University of the West of England and BSRIA

HEATING CONTROLS INTERNATIONAL EVIDENCE BASE AND POLICY EXPERIENCES

PREPARED FOR

UK Department for Business, Energy and Industrial Strategy

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Executive Summary

This report presents a synthesis in the form of narrative summaries of the international evidence base and policy experiences on heating controls in the domestic sector. The research builds on the former Department of Energy and Climate Change (DECC) commissioned (systematic) scoping review of the UK evidence on heating controls published in 2016 (Lomas *et al*., 2016), and the Rapid Evidence Assessment of smarter heating controls published in 2014 (Munton *et al*., 2014).

The report consists of two parts. Part 1 involves a (systematic) scoping review of the international evidence base on the energy savings, cost-effectiveness and usability of heating controls in the domestic sector. Part 2 contains the findings from an analysis of the policy experiences of other countries.

Part 1 of the review focused on an extended suite of heating control types including: Weather compensation (also known as outdoor reset), Time Proportional and Integral (TPI) controls, Zonal control, Programmable Thermostatic Radiator Valves (TRVs), Manual TRVs, Learning algorithms, Automation, Optimisation, Modulating room (or load compensating) thermostats, Communication protocols, Remote control (such as via an App), Occupancy sensors, Programmable thermostats, On/off switches, Boiler thermostats, Central timers, Room thermostats, Geolocation, Geofencing, and Hot water controls.

The search strategy for Part 1 was carried out using clearly defined searches across six databases including Scopus and Science Direct, grey literature sources and Google Scholar, identifying 992 academic publications (after screening for duplicates within databases), 61 grey literature and 114 documents using the BSRIA Market Intelligence library. In the first stage of filtering, the identified documents were screened for duplicates across databases and relevance based on their abstracts, resulting in 101 articles. In the second stage of filtering, the remaining documents were screened based on relevance and the application of inclusion and exclusion criteria. In the final stage of filtering, the remaining documents were subjected to a quality appraisal, which resulted in a total number of 38 documents in the final sample (see Appendices A and B for the list of documents). All documents that did not pass the quality appraisal were recorded and stored (see Appendix C for the list of documents).

Out of the total sample of 38, 19 documents reported energy savings potential of heating controls, 2 demonstrated cost-effectiveness whilst 17 examined usability. Energy savings are determined differently across varying countries and measured primarily through simulated modelling studies with a limited number of large-scale field trials. Field trials were mostly reported in the USA and primarily with a focus on the potential energy savings impact of ‘smart’ thermostats (see also 2.7.1). Cost-effectiveness is rarely researched in terms of a full comparison of the likely costs against the predicted savings. However, even cost savings are rarely reported and, in one case, evidence has centred on controls working in tandem with specific dual-tariff electricity models. Usability is examined mainly through modelling scenarios rather than trials and suggestions for the development of new interfaces based on these. Field trials on usability have mostly focussed on programmable and smart thermostats in the USA.

Overall, based on the documents included in the review, there seems to be limited evidence suggesting that, in general, better heating controls can save energy. Specifically, it is hard to quantify likely reductions, principally because of substantial variations in the baseline conditions and due to a paucity of real studies that consider householder heating behaviours. In comparison to the (systematic) scoping review of the UK evidence on heating controls whereby one large-scale field trial was found, the international evidence identified in this review includes several field-trials (mostly in the USA).

Part 2 of this report contains the findings from an analysis of the policy experiences of other countries. This involved document analysis (gathered non-systematically via 'call for evidence') on the policy, regulatory or legislative experiences of implementing heating controls in climatically relevant countries. The 'call for evidence' involved contacting experts in Portugal (3), Denmark (1), USA (6), New Zealand (2), Japan (1), France (6), Switzerland (2), Italy (1), Sweden (2), Ireland (2), Australia (1), Chile (1), EU (3), Germany (2), Netherlands (1), Norway (2) and Belgium (1). Experts included contacts from national energy agencies and international energy policy research institutes. They were contacted by email and asked if they could provide information on relevant documents relating to policy, regulatory and legislative experiences as well as evidence of underlying policy decisions on heating controls. The evidence received in the short timescales (November-December 2016) included either specific policy measures or case studies, however, did not include any evidence regarding policy decisions. Evidence included positions papers, case study impact reports, building regulations, website links and institutional summary reports in German, French, English and Portuguese, which were translated where relevant. The identified evidence was screened per country based on relevance and quality screening criteria appropriate for a non-systematic review (see also 3.6).

Most of the evidence on policy measures focuses on incentivising utility providers (such as in the USA and, to some extent, Ireland and the Netherlands). In other countries, such as Germany, heating controls are considered as part of a wider set of efficiency measures (both in terms of heating systems and building fabric). With regards to impacts or policy experiences, a number of field trials in the USA that consider the implications of incentivising utility providers to install smart thermostats quantify energy savings and carbon emissions. However, the comparative savings potential is difficult to methodologically identify as the field trials contain diverse housing typologies, heating control functionalities, sources of fuel, occupancy and climatic conditions. Furthermore, a key aspect often not reported in most studies is the effect of the type of existing heating system on the operability, efficiency and reported savings potential of installing and using a certain smart thermostat.

Overall, across Parts 1 and 2, there is limited international evidence (high quality or otherwise) relating to the energy savings, cost-effectiveness and usability of heating controls. Table one summarises the results (of Part 1) by heating control type and uses the same tabular format as that used in the 2016 report on the UK evidence on heating controls for comparative purposes. In addition, the table includes information on the country the evidence originates from. Programmable/Smart thermostats have the highest level of international evidence (moderate to good), with two documents reporting energy savings and eight documents reporting the results of user-surveys or user-testing of controls. These studies, some moderate to large field trials or surveys, have largely been carried out in the USA, with a number sponsored by the USA Department of Energy. The next highest level of international evidence is for occupancy sensors (low-moderate). Four documents report energy savings from modelling of heating controls with improved occupancy detection. For all other control types the evidence level is low, very low or there is a lack of robust international evidence identified.

Table 1: Impact of different heating controls on energy saving, cost-effectiveness and usability – international evidence

Control Type	Country	Impact on Energy Saving	Cost-effectiveness	Usability	Confidence
Programmer/timer (inc. digital)	N/A	Lack of robust evidence	Lack of robust evidence	Lack of robust evidence	N/A
Room Thermostat	Czech Republic	Lack of robust evidence	Lack of robust evidence	Smart-home control system – no testing **(Sysala *et al.,* 2016)**	Very Low
Manual TRVs	Italy	2% - 10% annual energy savings on heating for a 12 apartment building- modelling **(Monetti *et al.*, 2015)**	Cost savings of €2300/year for a 12 apartment building- modelling **(Monetti *et al.*, 2015)**	Lack of robust evidence	Very Low
Programmable TRVs	N/A	Lack of robust evidence	Lack of robust evidence	Lack of robust evidence	N/A
Weather Compensation	USA	Moderate size trial of control improvements in 42 units in a 3 building complex – 10-15% savings of energy consumption for space heating across complex due to outdoor reset control changes **(Dentz *et al.*, 2014)**	Moderate size trial of control improvements in 42 units in a 3 building complex – Payback time of less than 3 years for improved outdoor reset control **(Dentz *et al.*, 2014)**	N/A	Low
TPI	N/A	Lack of robust evidence	Lack of robust evidence	N/A	N/A
Zonal Control	N/A	Lack of robust evidence	Lack of robust evidence	Lack of robust evidence	N/A
Automation	UK	Modelled smart home energy management system for electrified heating - up to 9% carbon emission savings over a single month trial **(Rogers *et al.*, 2011)**	Modelled smart home energy management system for electrified heating – up to 15% cost savings over a single month trial **(Rogers *et al.*, 2011)**	Lack of robust evidence	Very Low

Control Type	Country	Impact on Energy Saving	Cost-effectiveness	Usability	Confidence
Remote Control (via App)	N/A USA and UK USA	Lack of robust evidence Modelling of thermostat use behaviour with a sample 82 homes – "using setback and infrequent overrides" group uses 65% less on average energy than other groups **(USA) (Urban and Gomez, 2013)** Modelling smart schedules with data from 8 houses and 3 datasets for over 100 homes – 0.2kWh – 1.0kWh savings of daily electrical (HVAC) energy consumption, 1% - 5% **(Iyengar *et al*., 2015)**	Lack of robust evidence	Lack of robust evidence User testing with 31 users of programmable controls – 74.2% of users were successful in task, 90% of those who failed were aged over 60 **(UK) (Combe and Harrison, 2014)** Usability tests with six users of two thermostat models - highlights importance of good design **(USA) (Meier *et al*., 2010a)** Study of 17 adults and 39 children interest **(USA) (Horn *et al*., 2015)**	N/A
Programmable/Smart Thermostats	USA USA Netherlands		Lack of robust evidence	User testing with 31 users of five types of thermostats showed highest success rates with good visibility, feedback and consistency **(Peffer et al., 2012 and Meier et al., 2011a)** A survey across 57 cities showed thermostat functions are often not used **(USA) (Meier *et al*., 2010a)** Thermostat functions not used - **Guerra-Santin and Itard (2010)** survey of 7000 households (Netherlands)	Modest – Good

Control Type	Country	Impact on Energy Saving	Cost-effectiveness	Usability	Confidence
	USA			Online survey via crowdsourcing platform showed features are not used or disabled **(Pritoni *et al.*, 2015)**	
Boiler Thermostat	N/A	Lack of robust evidence	Lack of robust evidence	Lack of robust evidence	N/A
Hot Water Controls	N/A	Lack of robust evidence	Lack of robust evidence	Lack of robust evidence	N/A
Optimisation	N/A	Lack of robust evidence	Lack of robust evidence	N/A	Very Low
Whole system optimisation	Ireland (Germany/EU)	On average 7kWh/m2/yr energy saving for test buildings through whole system optimisation (uses data from German OPTIMUS project) **(Ahern and Norton, 2015)**	Lack of robust evidence	N/A	Very Low
Learning algorithms	Switzerland/ Germany	6%-10% annual energy savings for algorithms using setback thermostats across modelling studies **(Kleiminger *et al.*, 2014)**	Lack of robust evidence	N/A	Low
	Slovakia	MPC thermostat outperforms intelligent thermostat with savings of 9%-17% for modelling a single residential building **(Drgona *et al.*, 2015)**			
	Switzerland	Small scale trial in 10 homes of an MPC controller – 28% savings energy **(Lindelof *et al.*, 2015).**			

Control Type	Country	Impact on Energy Saving	Cost-effectiveness	Usability	Confidence
Geolocation	N/A	Lack of robust evidence	Lack of robust evidence	Lack of robust evidence	N/A
Geofencing	N/A	Lack of robust evidence	Lack of robust evidence	Lack of robust evidence	N/A
On/off switches	N/A	Lack of robust evidence	Lack of robust evidence	Lack of robust evidence	N/A
Occupancy sensors	USA USA USA Switzerland/ Germany	Modelling a "smart thermostat" with occupancy sensors in 8 homes – 28% average saving of residential (HVAC) energy consumption **(USA) (Lu *et al*., 2010)** Modelling with occupancy sensing and prediction on data of 4 users movements – 8.3% to 27.9% average saving of electrical (HVAC) energy consumption **(Hong and Whitehouse, 2013)** Single house test modelling occupancy sensors – 23.6 % saving of energy consumption from heating over 24 hours **(USA) (Gupta *et al*., 2016)** 6%-17% annual energy efficiency savings depending on the type of building across modelling studies **(Kleiminger *et al*., 2014)**	Lack of robust evidence	Lack of robust evidence	Low – Modest
Central Timers	N/A	Lack of robust evidence	Lack of robust evidence	Lack of robust evidence	N/A

1 Introduction

1.1 Background and problem definition

Household energy use accounts for almost 60% across the EU and more than a quarter of all energy used in the UK (Palmer and Cooper, 2013). Space heating accounts for almost 67% of energy consumption across average European homes (Odyssee-Mure, 2012) and 69% in UK households (DECC, 2015). Reducing energy consumption and its associated carbon dioxide emissions due to space heating has the potential, therefore, to make a significant contribution to the UK Government's overall carbon reduction strategy.

This report was commissioned by the UK Department for Business, Energy and Industrial Strategy (BEIS) to review the international evidence base and policy experiences of other countries with regards to domestic heating controls. This report builds upon Loughborough University's Heating Controls Scoping Review (Lomas *et al.,* 2016) commissioned by DECC, which reviewed the UK evidence base on domestic heating controls. In addition, this report follows a rapid evidence assessment of "How heating controls affect domestic energy demand" by Munton *et al.* (2014), also commissioned by DECC. The 2016 Loughborough Scoping Review (Lomas *et al.,* 2016) reported the findings of 32 UK documents on the energy savings, cost-effectiveness and usability of heating controls, and recorded and retained a number of international documents. This report repeats and extends the Loughborough searches to identify further international documents, update the UK evidence base and present the international evidence base.

1.2 Structure of report: Parts 1 and 2

Part 1 of the review includes a (systematic) scoping review on international domestic heating controls in terms of energy savings, cost-effectiveness and usability. Part 2 contains the findings of a non-systematic review that gathered evidence on the policy, regulatory or legislative experiences of heating controls in climatically relevant countries. This includes evidence obtained from contacting (37) experts in Portugal (3), Denmark (1), USA (6), New Zealand (2), Japan (1), France (6), Switzerland (2), Italy (1), Sweden (2), Ireland (2), Australia (1), Chile (1), EU (3), Germany (2), Netherlands (1), Norway (2) and Belgium (1).

1.3 Aims and objectives of report: Parts 1 and 2

For Part 1, the project aimed to collect, analyse, synthesise and assess the international evidence base on domestic heating controls by meeting the following objectives:

- Use systematic evidence review techniques to collect all prior international studies on domestic heating controls from academic, grey and industry sources (focused on climatically relevant countries as outlined in 2.3). In addition to collecting international studies, the review focused on the following suite of heating control technologies: Weather compensation (also known as outdoor reset), Time Proportional Integral (TPI) controls, Zonal control, Programmable Thermostatic Radiator Valves (TRVs), Manual TRVs, Learning algorithms, Automation, Optimisation, Modulating room (or load compensating) thermostats, Communication protocols, Remote control (such as via an App), Occupancy sensors, Programmable thermostats, On/off switches, Boiler thermostats, Central timers, Room thermostats, Geolocation, Geofencing and Hot water controls
- Assess the quality of previous studies and discuss the strengths and weaknesses of both those that pass or fail the quality assessment (section 2.5 outlines the process for quality appraisal)
- Synthesise studies to determine the energy savings, cost-effectiveness and usability of different types of heating controls and discuss the current state of knowledge, including identifying where the main evidence gaps are

For Part 2, the project aimed to review the policy experiences of other countries with regards to domestic heating controls by meeting the following objectives:

- Contact identified experts in climatically relevant countries for evidence of any policy, legislation or regulation on domestic heating controls (and non-domestic where applicable)
- Evaluate and classify the content of evidence based on:
    - Whether evidence provides details of policy, legislation or regulation
    - Whether impact is discussed in terms of carbon emissions, energy savings or energy bills and how metrics are used
- Assess the quality of studies based on appropriate and agreed appraisal and evidence assessment criteria
- Synthesise findings to determine different types of policy experiences, decisions and impact

2 Part 1 Methodology

2.1 Overview

The review of existing international evidence on domestic heating controls and their energy savings, cost-effectiveness and usability was conducted using systematic evidence review techniques (search strategy, inclusion criteria, quality assessment, data extraction and synthesis). The review included searching academic databases, grey literature sources, government publications and institutional reports. The review followed guidelines developed by the Government Social Research Service (GSR, 2013), 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 undertaken through several stages as shown in Figure 1.

To ensure the robustness of the review protocol, a pilot test was undertaken to check that the document filtering process was correctly applied and repeatable. Testing of search strings was carried out on a sample of databases by 3 researchers to ensure the same number of initial search results (and the same results) were obtained. Researchers agreed inclusion and exclusion criteria across databases and the search strings were adapted as necessary. Further quality assurance checks were carried out following screening stage 1 and screening stage 2 with 2 researchers cross-checking passed documents. The scoring of the 138 documents which had passed both screening stages 1 and 2 against the BEIS quality assessment scale (see Figure 3) was cross checked by 5 researchers. Finally, the draft and final report was quality assessed and signed off by a senior analysist in the team and by the Head of Department (outside the team).

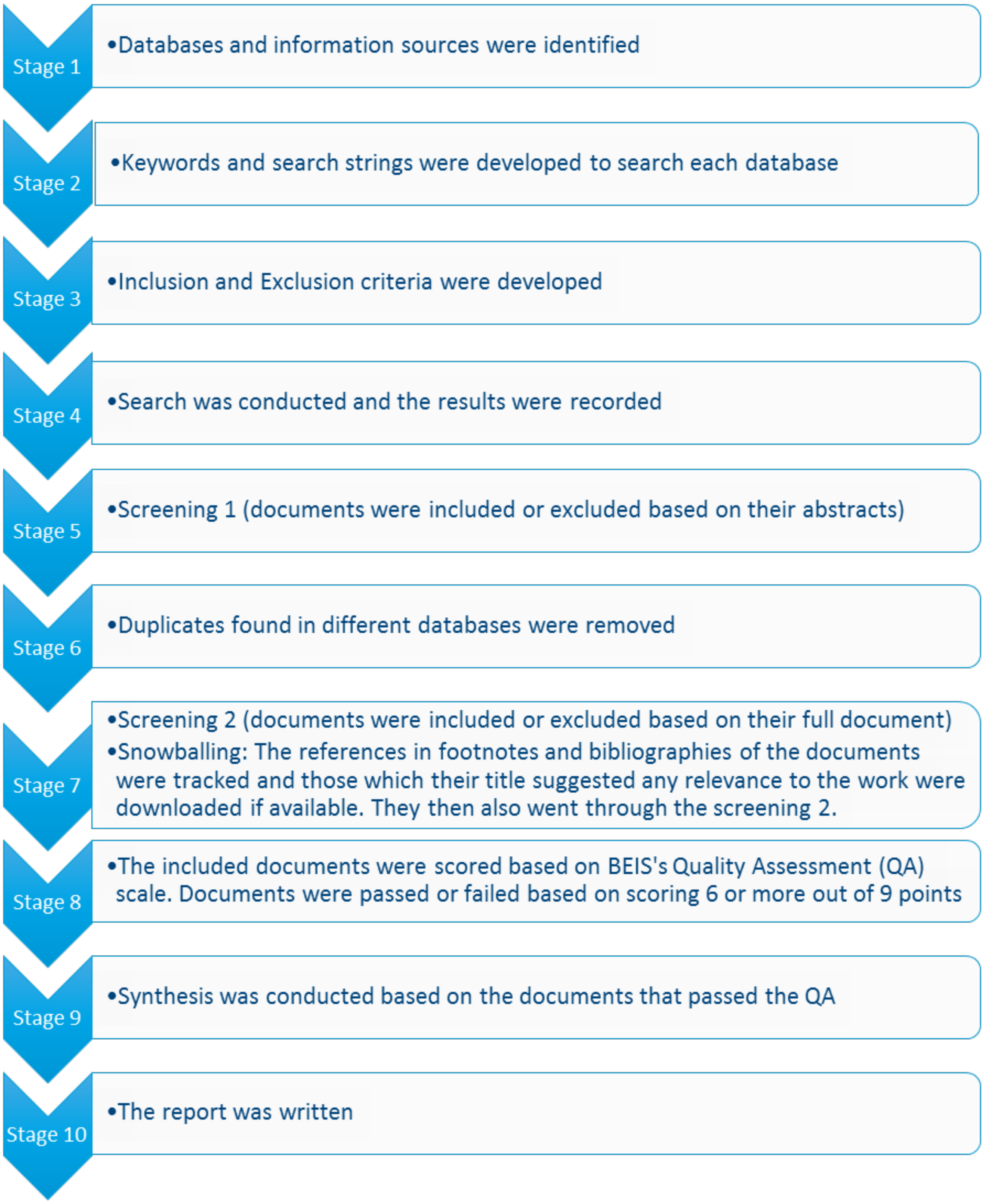

Figure 1: Key phases of review for Part 1

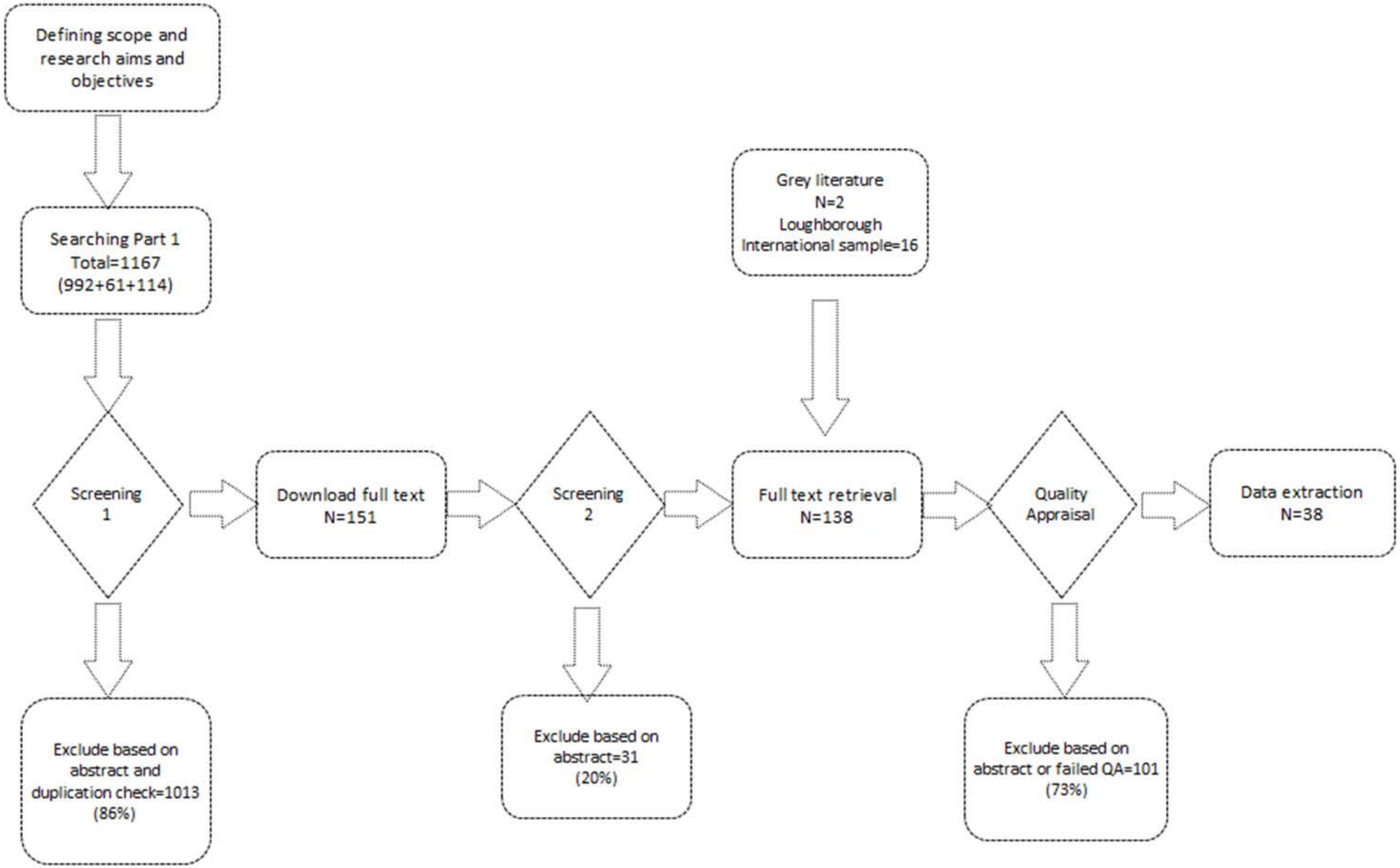

Figure 2 The search strategy and filtering stages to produce the final sample

2.2 Databases and sources

The search was conducted using the following academic databases and grey literature 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.

Compendex: Compendex is a comprehensive interdisciplinary engineering database with over nine million records referencing over 5,000 engineering journals and conference materials dating from 1969.

Proquest: (including Civil Engineering Abstracts, Avery and Ante) is a content holder of all types, preserving and enabling access to their rich and varied information. Those partnerships have built a growing content collection that now encompasses 90,000 authoritative sources, 6 billion digital pages and spans six centuries. It includes the world’s largest collection of dissertations and theses; 20 million pages and three centuries of global, national, regional and specialty newspapers; more than 450,000 ebooks; rich aggregated collections of the world’s most important scholarly journals and periodicals; and unique vaults of digitized historical collections from great libraries and museums, as well as organizations as varied as the Royal Archives, the Associated Press and the National Association for the Advancement of Colored People.

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 and pre-prints.

Energy Citations: The ***Energy Citations Database (ECD)*** was created in 2001 in order to make scientific literature citations, and electronic documents, publicly accessible from U.S. Department of Energy (DOE), and its predecessor agencies, at no cost to the user. This database also contains all the unclassified materials from Energy Research Abstracts. Classified materials are not available to the public. *ECD* does include the unclassified, unlimited distribution scientific and technical reports from the Department of Energy and its predecessor agencies, the Atomic Energy Commission and the Energy Research and Development Administration. The database is usually updated twice per week.

Academic Search Elite: *Academic Search Elite* is a rich resource spanning a broad stretch of academic subjects with thousands of full-text journals and abstracted and indexed journals. Information is easily attainable for the most complex term papers.

Science Direct: Science Direct is a website which provides subscription-based access to a large database of scientific and medical research. It hosts over 12 million pieces of content from 3,500 academic journals and 34,000 e-books. The journals are grouped into four main sections: *Physical Sciences and Engineering*, *Life Sciences*, *Health Sciences*, and *Social Sciences and Humanities*. Article abstracts are freely available, but access to their full texts (in PDF and, for newer publications, also HTML) generally require a subscription or pay-per-view purchase.

Institutional, Governmental and Organizational sources: The following organizations and institutions were included in grey literature searching: The Precourt Energy Efficiency Centre at Stanford, Berkley and Opower; in Portugal - ADENE Agência para a Energia-Portuguese Energy Agency and in Germany the EnergieWende. The following conference proceedings were also searched: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Chartered Institution of Building Services Engineers (CIBSE), European Council for an Energy Efficient Economy (ECEEE), American Council for an Energy-Efficient Economy (ACEEE), Behaviour, Energy & Climate Change (BECC) and European Conference on Behaviour and Energy Efficiency (Behave).

2.3 Search strategy and inclusion criteria

The search criteria were internationally inclusive. However, given the tight timescale, results were filtered to prioritise evidence that relates to countries with climatic zones that are similar to current and projected UK climate conditions (Jenkins *et al*., 2009). Köppen-Geiger (Kottek *et al.,* 2006) category classifications including Cfb (maritime temperate) Csa and Csb (Mediterranean) classifications were applied. In many cases, such as the USA, these countries will include an extended range of climate conditions, broadening the coverage of research and policy experience. Evidence relating to countries that fall entirely outside these selection criteria was recorded and stored pending further investigation if deemed of particular value.

After conducting preliminary searches to assess the effectiveness of different search terms, the research team agreed the search strings shown in Table 2 with BEIS. To ensure the robustness of the review protocol, a pilot test was undertaken to check that the document filtering process was correctly applied and repeatable. Testing of search strings was carried out on a sample of databases by 3 researchers to ensure the same number of search results (and the same results) were obtained. Researchers agreed inclusion and exclusion criteria across databases and the search strings were adapted as necessary. Further quality assurance checks were carried out following screening stage 1 and screening stage 2 with 2 researchers cross-checking passed documents. The scoring of the 138 documents which had passed both screening stages 1 and 2 against the BEIS quality assessment scale (see Figure 3) was cross checked by 5 researchers.

Table 2 List of academic database search strings and terms

Database	Search strings and terms
Scopus	**Repeat Loughborough Search:** 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) **UWE added terms/countries Search:** TITLE-ABS-KEY (heating OR hydronic) AND TITLE-ABS-KEY TITLE-ABS-KEY (heating OR hydronic OR “hot water”) AND TITLE-ABS-KEY (control OR controls OR remote OR zonal OR compensator OR compensation OR automat* OR tpi OR “time proportional integral control*” OR fuzzy OR (trv AND (programmable OR manual)) OR (“thermostatic radiator valve*” AND (programmable OR manual)) OR (thermostat* AND (room OR boiler OR “modulating room” OR “load compensating” OR programmable) OR geolocation OR geofencing OR “central timer*” OR “communication protocols” OR “learning algorithms” OR automation OR optimisation OR “weather compensation” OR “outdoor reset” OR “occupancy sensors” OR (boiler AND (timer OR programmer))) AND TITLE-ABS-KEY (dwelling* OR residential OR home* OR domestic OR apartment OR house*) AND TITLE-ABS-KEY (energy OR cost* OR usability OR user OR occupant* OR behaviour OR behavior OR interaction OR reaction OR practice OR policy) AND TITLE-ABS-KEY (“uk” OR “united kingdom” OR california OR chile OR australia OR japan OR germany OR portugal OR france OR netherlands OR denmark) 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”)) AND TITLE-ABS-KEY (dwelling* OR residential OR home*

Database	Search strings and terms
	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 OR policy) AND TITLE-ABS-KEY (“uk” OR “united kingdom” OR california OR chile OR australia OR japan OR germany OR portugal OR france OR netherlands OR denmark) 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”)
Compendex	**Repeat Loughborough search:** ((((((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)) **UWE added terms/countries Search:** (with and without AND(countries): (((((((heating OR hydronic) WN KY) AND ((control OR controls OR remote OR zonal OR compensator OR compensation OR automat* OR tpi OR “time proportional integral control*” OR fuzzy OR (trv AND (programmable OR manual)) OR (“thermostatic radiator valve*” AND (programmable OR manual)) OR (thermostat* AND (room OR boiler OR “modulating room” OR “load compensating” OR programmable)) OR geolocation OR geofencing OR “central timer*” OR “communication protocols” OR “learning algorithms” OR automation OR optimisation OR “weather compensation” OR “outdoor reset” OR “occupancy sensors” 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 OR policy) WN KY))AND ((“uk” OR “united kingdom” OR california OR chile OR australia OR japan OR germany OR portugal OR france OR netherlands OR denmark)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))

Database	Search strings and terms
Proquest (inc Ante and Avery)	AB,TI(heating) and AB,TI("Time Proportional Integral" or tpi or controls or control or ((remote or zonal or "hot water") and control) or "Thermostatic Radiator Valve" or (trv and (programmable or manual)) or (thermostats and (room or boiler or "load compensating" or "modulating room" or programmable)) or thermostat* or (central and timer*) or "on/off switches" or "weather compensation" or "outdoor reset" or "learning algorithm" or automation or optimisation or optimization or "communication protocols") and AB,TI(dwelling* or residential or home* or domestic or apartment) and AB,TI(energy or cost* or user or occupant*) and not AB,TI("heat pump" or wind or "Non-residential" or "Non-domestic" or "District" or Air-con*) and YR(2010-2016)
Google Scholar	**UWE search repeats Loughborough searches** changing "heating" for "hydronic" and "domestic" for "residential" or "home" or "dwelling" or "house" or "apartment" or "homes" or "dwellings" or "houses" or "apartments" with extension of additional "OR" terms as follows: allintitle: heating domestic control OR controls OR thermostat OR remote OR zonal OR compensator OR compensation OR automat OR tpi OR trv OR timer OR programmer OR programmable OR manual OR weather OR compensation OR outdoor OR reset OR radiator OR valves OR communication OR protocols OR occupancy OR sensors OR switches OR room OR geolocation OR geofencing OR hot OR water
Energy Citations	allintitle: heating residential control; thermostat; allintitle: heating house control; thermostat;
Academic Search Elite	AB heating OR AB thermostat AND (AB domestic OR AB residential OR AB apartment or AB dwelling) OR AB trv OR AB tpi AND AB controls or (AB zonal and AB control) OR (AB weather and AB compensation) OR (AB outdoor or AB reset)
Science Direct	UWE added database and terms search:tak(heating) and tak(tpi or controls or control or ((remote or zonal or (hot and water)) and control) or "Thermostatic Radiator Valve" or (trv and (programmable or manual)) or (thermostats and (room or boiler or "load compensating" or "modulating room" or programmable)) or thermostat* or (central and timer*) or "on/off switches" or "weather compensation" or "outdoor reset" or "learning algorithm" or automation or optimisation or optimization or "communication protocols") and tak(dwelling* or residential or home* or domestic or apartment) and not tak("heat pump" or wind or "Non-residential" or "Non-domestic" or "District" or Air-con*)

Additionally, the following grey literature sources were searched including: The Precourt Energy Efficiency Centre at Stanford, Berkley and Opower; in Portugal, ADENE Agência para a Energia-Portuguese Energy Agency; and in Germany, the EnergieWende). The following conference proceedings were also searched including the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Chartered Institution of Building Services Engineers (CIBSE), European Council for an Energy Efficient Economy (ECEEE), American Council for an Energy Efficient Economy (ACEEE), Behaviour, Energy and Climate Change (BECC) and Behaviour and Energy Efficiency (BEHAVE). The sites were searched using search keywords including heating controls, domestic, residential, energy savings, cost savings and usability in English, German and Portuguese.

2.4 Inclusion and exclusion criteria

Criteria to select or exclude documents were applied in two screening stages. Stage 1 involved screening based on abstracts, while Stage 2 involved screening full documents. These inclusion and exclusion criteria were developed based on the aim and scope of the project and also using BEIS's quality assessment scale. They are shown in Tables 3 and 4.

Table 3: Inclusion criteria used for PART 1 Sample

Inclusion Criteria
Screening 1
Documents that are written in English, Portuguese, Spanish or German
Documents that are UK, German, California, Portugal, Australia or Chile based
Documents that are available and accessible online within the project's timeframe
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: Weather compensation (also known as outdoor reset); Time Proportional Integral (TPI) controls; Zonal control; Programmable Thermostatic Radiator Valves (TRVs); Manual TRVs; Learning algorithms; Automation, Optimisation; Modulating room (or load compensating) thermostats; Communication protocols; Remote control (such as via an App); Occupancy sensors; Programmable thermostats; On/off switches; Boiler thermostats; Central timers; Room thermostats; Geolocation; Geofencing and Hot water control
Screening 2
Documents that when read in full, meet all the criteria set for the screening 1 AND actually provide an evidence base

Table 4 Exclusion criteria used for PART 1 Sample

Exclusion Criteria
Screening 1 and 2
Documents that report new method(s) for controlling domestic heating but do not evaluate their energy saving potential, effectiveness or usability Documents that only study the effect of heating controls on energy demand along with other energy efficiency measures Documents that only provide a cost-savings estimate in relation to a specific variable electricity tariff
Documents that are a shorter version of another document already included
Documents that fall outside the search timeframe 2010-2016

During searching the databases and through snowballing, several documents were identified which met all the inclusion criteria for Screening 1 except being in non-climatically relevant countries. These documents were stored separately and did not go through Screening 2, quality assessment or the final synthesis.

2.5 Quality Appraisal

The reporting and research quality of the included documents were assessed using BEIS's quality assessment scale (Figure 3). Each document was scored out of total of 9 and those which scored 6 or above 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 4 shows the distribution of the scores that the documents received following assessment against the quality assurance scale.

Reporting Quality

- 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?

Research Quality

- 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 3: BEIS's quality assessment scale

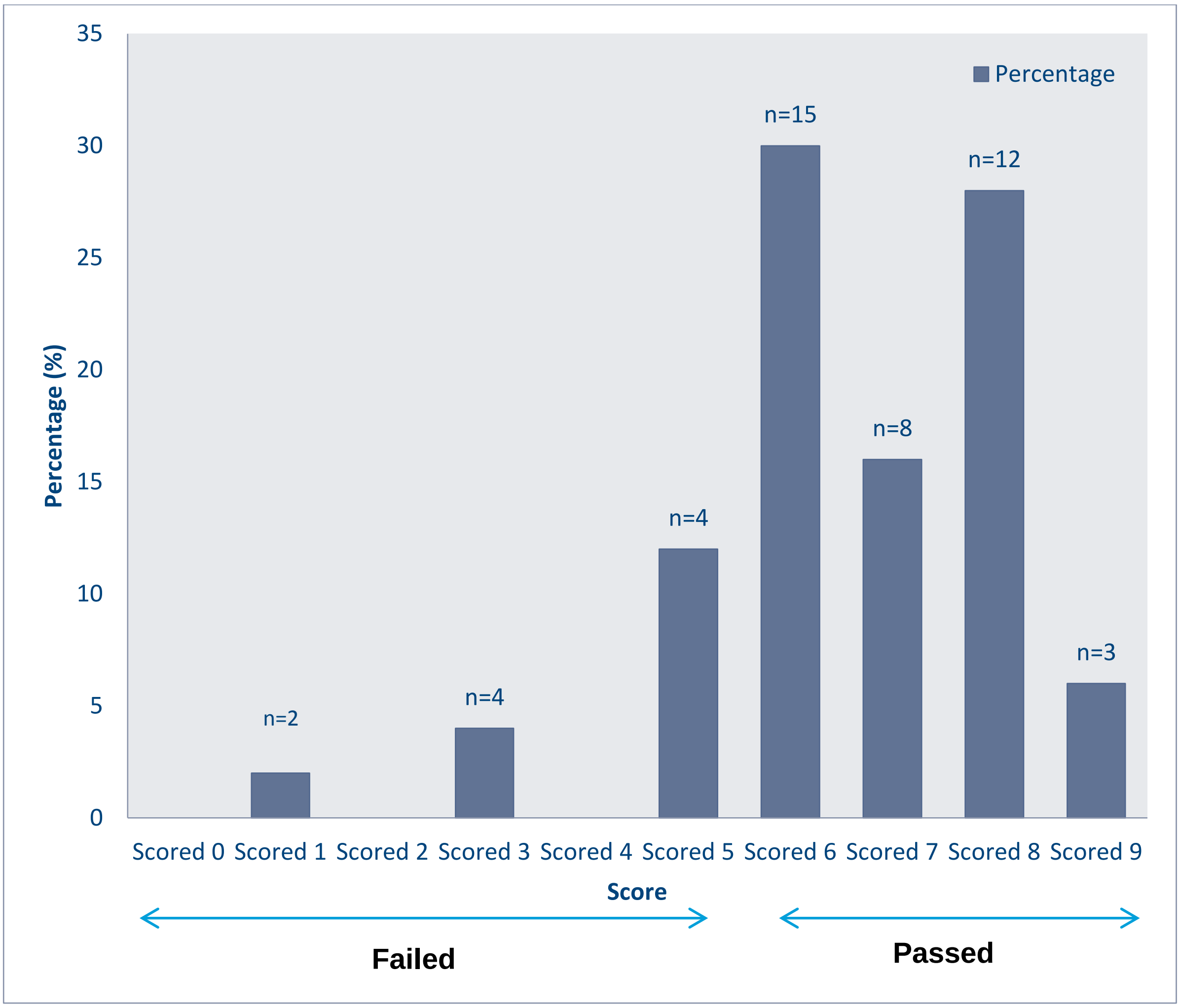

Figure 4: Distribution of scores for the documents reaching the final stage of filtering

2.6 Synthesis

Documents that passed the quality appraisal were classified by country, type of heating controls and focus (see Appendix A). Once classified, all final documents were analysed thematically and reviewed by appropriate team experts. Results of the synthesis are discussed in detail in section 2.7.

2.7 Main findings: UK updates and Key international evidence

Further to the Heating Controls Scoping Review carried out by Loughborough University on the UK evidence base, this review has been extended to cover:

1) New UK research published subsequent to the Loughborough review
2) International research, primarily focussing on countries deemed climatically similar to the UK
3) An extended list of heating control technologies including: Weather compensation (also known as outdoor reset), Time Proportional Integral (TPI) controls, Zonal control, Programmable Thermostatic Radiator Valves (TRVs), Manual TRVs, Learning algorithms, Automation, Optimisation, Modulating room (or load compensating) thermostats, Communication protocols, Remote control (such as via an App), Occupancy sensors, Programmable thermostats, On/off switches, Boiler thermostats, Central timers, Room thermostats, Geolocation, Geofencing and Hot water controls

The new UK work on energy savings or cost effectiveness that has been identified is not of great relevance to the UK context. One study (Ahern and Norton, 2015) extrapolates data from a German study (OPTIMUS) in order to estimate potential savings from heating optimisation at a European-scale. The other (Rogers *et al*., 2011) considered a control system that could respond to a hypothetical system that provided information on varying electricity prices and carbon impacts. No new UK energy/cost savings work was identified that had a direct relevance to the current UK situation.

More studies identified from the UK examined the usability of controllers. Combe and Harrison (2014) conducted a review of usability studies that carried out tests on users. Stevenson *et al*. (2012) designed and tested a matrix tool for assessing the usability of controls, and Revell and Stanton (2016) analysed how current heating system designs were sub-standard and might be improved by using different theoretical design principles. Rather than looking at the actual usage of controllers, Wade *et al*. (2016) considered the role of installers with regard to the take-up and usage of heating controls.

The following sections discuss the relevant international research in relation to energy savings, cost effectiveness and usability reported in the literature since 2010.

2.7.1 Energy Savings, Cost Savings and Cost-effectiveness

An updated (systematic) scoping review of the UK and international evidence on the potential energy savings and cost-effectiveness of heating controls identified a total of 21 articles out of which 2 were on cost-effectiveness. The identified evidence is examined based on methods of measurement taking into consideration the different international cultural and social contexts. Table 5 shows range of measurements methods used to analyse potential energy savings or cost effectiveness impact of diverse heating controls.

Table 5 Key methods of measurement across evidence

Method	*Type of heating control*	*Countries*	*Articles (n)*
Computer modelling	TRVs, Model Predictive Control algorithms, Programmable, intelligent and smart thermostats, occupancy prediction, and smart homes	Ireland/EU, Slovakia, Germany, Switzerland, Italy, UK and USA	12
Full-scale experiments	Programmable thermostats	USA	1
Small and large-scale trials in real occupied homes	TRVs, Model Predictive Control Algorithms, Outdoor Reset control	Switzerland and USA	3
Other approaches	Thermostats, zone control, automated sensors, wireless communications.	USA	5

Loughborough University's Heating Controls Scoping Review (Lomas *et al*., 2016) identified limited UK evidence based on large scale field trials, and concluded that, due to the absence of this type of robust evidence, the energy saving and cost-effectiveness potential of heating controls is difficult to determine with any confidence. Difficulties are mainly described as being in a lack of evidence covering measurements of either isolated energy savings or cost-effectiveness potential of heating controls as opposed to when viewed largely as part of wider holistic set of improvement strategies.

Similarly, the analysis carried out for this report also recognises the difficulty in separating the specific energy savings or cost-effectiveness control interventions can have. In addition to not being able to isolate the potential impact of a particular control, comparability between studies and international contexts encountered limitations. For instance, reported savings can be associated with different space heating systems such as central heating, hydronic/steam heating and heating, ventilation and air conditioning

(HVAC), or in different types of residential buildings supplied by a range of fuels (for example, gas, electricity and oil). It can be unclear as to whether reported energy savings relate to the whole home energy budget (all fuels), only to the fuel used for heating, only to the heating component of that energy type, and/or whether reported savings only apply to the heating period or to the whole year. In addition to this, particularly in modelling research, studies do not always make it clear that the work presented relates to a particular climate/country. In the summaries below, where a specific geographic locale for the work has not been stated, the country of the (main) authors has been stated and assumed to be the relevant location for the work (affecting 3 documents from the sample of 21 documents). The synthesis presented here is based on a total of 21 articles that report energy savings or cost-effectiveness. The majority (14) are based in the USA, with the remaining 7 articles in different countries within the European Union (EU) (including the UK).

Space and water heating in the USA is less homogenous than in the UK where the vast majority of households (>80%) have gas central heating systems. In the USA, residential buildings have gas heating systems, steam powered/hydronic heating, heat pumps and/or electric resistance heating (US Department of Energy, 2016). North America has a range of different climates in comparison with the UK and the range of heating systems partially reflects this, but considering the findings of identified documents is important as the UK may experience changes to its climate, or there may be a significant move towards electric heating and cooling in future years.

The USA evidence focuses primarily on the energy saving potential of smart thermostats, driven historically by the Environmental Protection Agency and its ENERGY STAR programme. Despite the long-term promotion of both manual and programmable thermostats, the potential energy savings were historically reported not to have been realised (Energy Star, 2014). Most studies reported that the lack of savings were mostly a result of unforeseen user behaviour in either not using thermostats at all or, when using controls, largely disabling energy saving features. Current research in the USA tends to be focussed on the latest range of smart thermostats enhanced by the inclusion of many additional features such as of occupancy sensors, setback strategies, or outdoor reset controls. Smart thermostats differ from manual and programmable ones in several ways (see Figure 5).

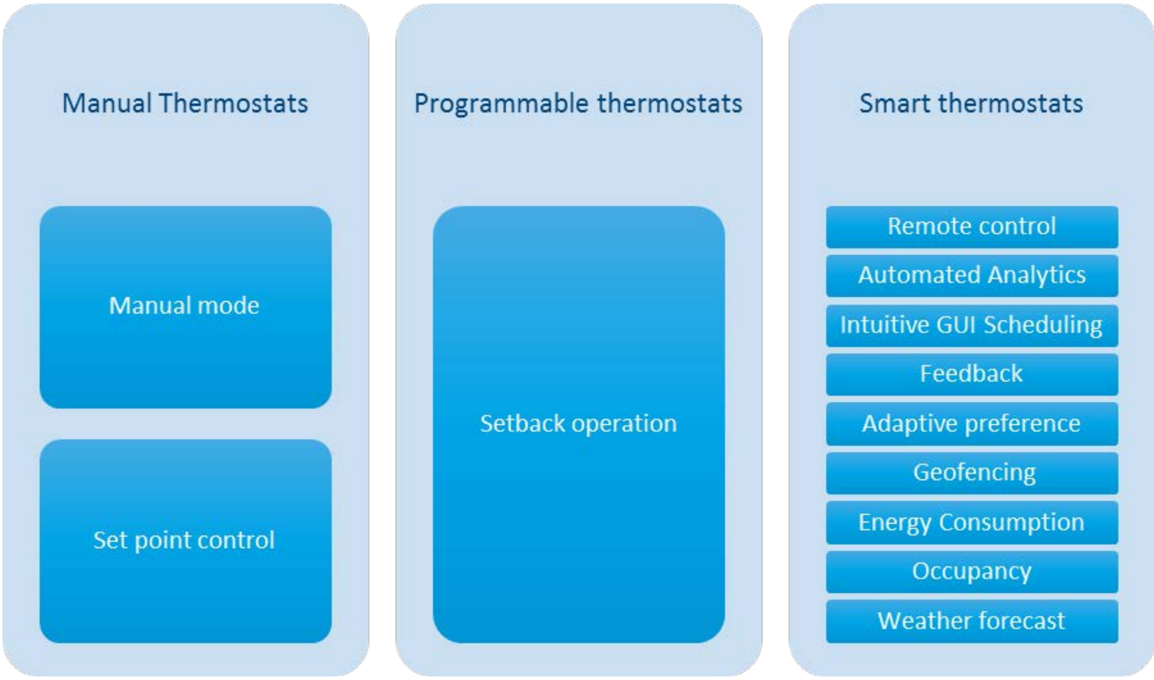

Figure 5 Thermostat categorisation (adapted from Robinson *et al*., 2016)

Within the EU, residential building types, climatic conditions, as well as heating system types, fuel sources and cultural context are extremely heterogeneous. These large differences exist both within and between countries. This makes comparability of any studies very difficult. The final sample of selected documents contains case studies from Italy (1 document), Slovak Republic (1 document), Switzerland and Switzerland/Germany (2 documents) and the UK (1 document) – one being on EU-wide savings estimates (based on German data).

Overall energy savings are reported in different ways across the studies. In some instances, emphasis is placed on improvements in energy efficiency (for example, Gupta *et al*., 2016), in others as cost savings or energy consumption reductions. In addition, savings are reported at different scales from national scale, neighbourhood or urban to single house. The different approaches will be compared in this synthesis.

Computer modelling

Out of the European studies identified, five rely on modelling of responses to heating controls. Of the twelve studies from the United States, seven rely on modelling responses to heating controls. As identified elsewhere in this report, even where the same essential method has been used, there is no standardisation regarding either the research questions and methodologies or the case studies and baseline used. The European studies are considered first.

Ahern and Norton (2015) used results from the 2003-8 German OPTIMUS project (http://www.optimus-online.de/) that examined whole heating system optimisation (consisting of insulation of pipework, adjustments to pumping power, hydraulic balancing via TRVs and "Commissioning of any pre-existing control devices for example weather compensated flow controller and adjusting heating operating times" (Table 1: Optimization interventions applied in the OPTIMUS study, p 201, Ahern and Norton, 2015). No details were reported regarding settings for the TRVs or heating controls. OPTIMUS's comparison of 30 test buildings with 45 controls indicated that whole system optimisation could achieve (on average) 7 kWh/m^2/yr in energy savings. However, the savings were unevenly distributed. Virtually no savings were apparent through the optimisation process in the oldest dwellings constructed before the installation of thermal insulation was made mandatory. This was seen as being due to heating system optimisation enabling higher internal temperatures to be provided in poorly insulated dwellings resulting in little or no reduction in energy consumption. In some of the older dwellings surveyed, optimisation measures resulted in a slight increase in heat energy consumption due to a now homogeneous heat distribution being achieved in all rooms. Ahern and Norton (2015) extrapolated these findings across the whole of the EU to estimate potential heat energy savings ranging from 1-19% depending on dwelling type, age, location and initial heat energy consumption. Based on their conclusions they recommended 1) Plumbers needed to be better trained and equipped to ensure appropriate optimisation of heating systems, and 2) that governments consider regulatory measures for heating system upgrades and replacements, subsidy schemes and audit programmes.

Drgona *et al.* (2015) modelled the potential performance of Model Predictive Control algorithms (in Slovakia) as a means of improving basic binary (on-off) heating controls. Their review work suggested that where MPC thermostats completely replace binary thermostats they can actually outperform 'intelligent' thermostats by 17% in non-insulated buildings and 28% in insulated ones. However, the control modelled by Drgona *et al.* used an MPC 'governor' as an adjunct to a standard binary thermostat (as opposed to a replacement). This set up was only modelled for a single residential building, but over the modelled period daily savings of energy were estimated to vary between 9% and 17% (though no indication was given of the presumed heating fuel).

Kleiminger *et al.* (2014) focussed specifically on a review and assessment of the effectiveness of occupancy prediction algorithms for smart thermostats (in Switzerland). They concluded that of the main algorithms assessed Krumm and Brush's Presence Probabilities (Krumm and Brush, 2011) performed best, but was only just ahead of Scott *et al.* (2010) (Pre-Heat) and two heuristic prediction strategies based on Lu *et al.*'s (2010) Smart Thermostat (Mean Arrival Time and Minimum Distance Mean Arrival Time). Kleiminger *et al.*

(2014) concluded that significant efficiency gains were achievable through occupancy prediction, but the size of these was heavily dependent on structure of building, occupancy and weather conditions. Annual savings ranged from 6% to 17% depending on building type. Savings almost doubled for poorly insulated buildings. The 25% of households with the lowest occupancy have a 4-5 times greater potential for efficiency gains than those with highest occupancy. Lower temperatures and cloudy skies reduce efficiency gains and increase comfort loss as it takes longer to heat up the building and the authors cite similar studies (Ingersoll and Huang, 1985 and Manning *et al*., 2007) which showed 6% to 10% savings using setback thermostats in cool and temperate climates.

Monetti *et al.* (2015) modelled the impact of introducing TRVs into a single early 19th Century building in Turin that had been converted into 12 apartments, each with around 5 rooms (leading to 60 separate thermal zones). Several different scenarios were used, including one with different TRV settings for a variety of room typologies (e.g. living room, bedroom etc.). No data on actual occupant behaviour was known. The building was supplied by district heating, with a district heating substation in the basement. The results suggested the possibility for 2% to 10% energy savings on heating. Cost savings were also estimated and they found that on the basis of the building being served by the district heating network, approximately 2,300 €/year may be saved across all 12 apartments in the building. However, if it weren't for the district heating grid, higher savings, around 14,000 €/year, might be achievable for a full installation cost of €15,484 (energy from the district heating network was costed at 0.12 €/kWh with an energy saving of 9.11 kWh/m^2).

Rogers *et al.* (2011) modelled the effect of smart home energy management systems in the context of electrified heating connected to a smart grid (UK) that provided not just variable pricing, but also information on real-time carbon footprint of electricity. They showed (that under the scenarios modelled that their system could predict cost and carbon emissions to within 9% and show that over a single month trial, that it could reduce these by 15% and 9% respectively.

In the US context, Lu *et al.* (2010) tested the effectiveness of a smart thermostat, which could automatically sense occupancy and sleep patterns. They evaluated their approach using whole-house thermal simulation modelling provided by the U.S. Department of Energy's EnergyPlus simulator. Their study is proposed as a framework to evaluate different thermostat algorithms under different household and climate conditions. To investigate the impact of occupancy patterns on thermostat performance in modelling they collected occupancy data by deploying sensors in eight homes. In addition, they carried out occupant surveys in 41 homes (the locations of the monitored houses and survey respondents are not reported) and obtained two public smart home datasets: the Kasterton and Tulum home monitoring data sets (Van Kasteren *et al.,* 2008, and Cook and Schmitter-Edgecomb, 2009). They compared the smart thermostat against a baseline algorithm using the household data sets and found that the smart thermostat saved energy through three main components: fast reaction, deep setback and preheating, when the thermostat was tested using different climatic zone weather data. The average residential HVAC energy savings for heating and cooling for the smart thermostat across the three components was 28%. The report compares this to commercially available baseline approaches which save 6.8% of residential HVAC energy consumption on average. They also calculate potential national energy savings suggesting that installation of smart thermostats in all US houses with HVAC could save on average 38.2% of the electricity used nationwide for heating and cooling. The size of the sample for data collection and limitations in modelling (the presence of pets or plant is not considered, and only one type of heating equipment is evaluated) make the evidence of potential savings in this instance limited.

Hong and Whitehouse (2013) also modelled automated control of HVAC systems based on occupancy prediction, highlighting how programmable thermostats waste energy due to not knowing when to turn on and turn off if they have not been programmed to do so. The study focusses on predicting an occupant's arrival home. The study proposes a model which pairs patterns of arrival and departure with historical commuting timelines using historical occupancy GPS data and occupancy prediction. The historical data is analysed to identify similar days in the past in terms of the person's commute in order to calculate the distribution of arrival times and predict future arrival times. The model is evaluated on a data set from another study (Chon *et al.,* 2012) comprising four users' daily movements over a period spanning from 120 to 180 days. HVAC energy use is wasted whenever there is an early or late prediction either because the room is heated when it doesn't need to be or because of the stage of HVAC heating required (fast reaction) to heat the home quickly. The penalty for an early prediction was found to be 1.5kW/hour and for a late prediction 4kWh. In percentage terms the evaluation of the model on a dataset of 4 users was found to save between 8.3% and 27.9% of HVAC energy (electricity) consumption in comparison with the baseline, with a 14.9% to 59.2% lower miss time (when the prediction was wrong). Calculation of the penalty cost of late or early predictions is dependent on weather and the house heat loss rate and a limitation of the energy saving calculations (other than small number of user data sets modelled) is the omission of weather data from the study.

Perez and Burger (2014) carried out real time simulation using Model Predictive Control of a home, electric heating system with a cloud enabled thermostat that monitors outdoor weather conditions. A single home with six sensor nodes deployed was used for modelling and controlling. The controller performance is compared to a traditional HVAC deadband (eliminates the possibility of simultaneous heating and cooling) controller and the study reports a 31% reduction in heating costs in comparison. This is due to shifting the time of electricity use to avoid peak and partial-peak energy prices. The amount of energy consumed by both is similar so there is no evidence presented of energy savings from this approach (and indeed actual consumption may have been permitted to increase and still achieve cost savings).

Urban and Gomez (2013) analyse data from a field study on how occupants use thermostats (Sachs *et al.* 2012). The study included 82 residential rental units with metered gas heating in an apartment block in Massachusetts. Occupants were left to use the thermostats however they wanted. This study used computer simulation to isolate the effects of thermostat behaviour from other sources of variability using the observed temperature histories and set point schedules in whole building simulations. They generated heating schedules for different apartments and found several results. For instance, occupants preferred warmer temperature than those prescribed by the ASHRAE 90.2 standard. Also, variations in heating energy consumption between units were significant, varying more than ten-fold, and this finding was born out in simulations where the apartment heating schedules were applied. Assigning the variety of heating schedules into four categories identified that the heating schedule group which used both setback schedules and infrequent manual overrides consumed 65% less energy on average as the other categories, but only 25% of the sample fell in this group. The study suggests the results show the importance of modelling behavioural variability in thermostat schedules due to the large influence of occupant behaviour.

Gupta *et al.* (2016) present an end-to-end framework, BEES, designed to enable collection of occupant feedback on thermal preferences data which can be fed-back into the system to improve the energy efficiency operation of a building. The BEES approach also uses a set of distributed sensors and beacons to collect real-time data on zones of occupancy, optimises occupant thermal comfort and minimises cost, and models correlations between different thermal zones. When tested in a residential setting over a 24-hour period (one of the faculty member's homes in Waterford, New York) with the BEES system employed, there was a 23.6% saving of HVAC energy (electricity) for heating.

Ivanov *et al.* (2013) report on an EnergyWise Smart Meter pilot with a sample of 1000 households in the city of Andover, Minnesota, 125 of whom had smart thermostats installed. All households had advanced meters which collected energy usage data, but only the treatment group had IHDs and smart thermostats. This study is largely focused on modelling peak load shifting of electricity use in summer for cooling, but does report that households in the treatment group reduced their energy use on 'red alert days' when the temperature was turned up, by an average of 0.47 kW, a 15% reduction of peak time HVAC energy (electricity) use.

Iyengar *et al.* (2015) present iProgram, a system for inferring smart schedules for programmable thermostats from smart meter data to reduce run-time and energy consumption. The design of the system allows for a targeted occupancy detection approach. Evaluation of iProgram as a web system using data from over 100 homes in the US from the ECO (Beckel *et al.,* 2014), UMass Smart (Barker *et al.,* 2012) and Pecan Street (Pecan Street, 2015) datasets, as well as results from a user study of 8 anonymous homes, identified improvements in occupancy detection and energy savings. Average daily HVAC energy (electricity) savings were 0.2kWh to 1.0kWh for heating and cooling, equivalent to 1-5% reduction in an average U.S. home.

Small and large scale trials in real occupied homes

A number of studies from the USA have been sponsored by the USA Government's Department of Energy. Most of these focus on the usability of programmable thermostats (see section 2.7.2), but some quantify energy savings using different approaches. Dentz and Ansanelli (2015) consider thermostatic radiator valves (TRVs) in a small-scale trial study carried out in a multi-family building in Flushing, New York. The building has hydronic/steam heating and occupants do not pay for heating directly. All apartments had TRVs installed and two apartments underwent a "one-pipe steam" TRV retrofit. Data loggers were used to monitor space and radiator heating temperatures in these two apartments. Unlike in the UK, TRVs are not widely accepted by the residential retrofit market in the north eastern United States even though Dentz and Ansanelli's (2015) review of the literature identified reported saving as high as 15% (McNamara, 1995). In this study, analysis of heating fuel utility bills did not show savings at either the unit or building level. Several reasons other than TRV performance were put forward for the discrepancy with earlier studies such as McNamara (1995): existing problems with the steam heating system, TRV sensor location issues, occupant's behaviour, particularly in continuing to open windows, and a failure to optimize boiler control set points.

In an earlier study, Dentz *et al.* (2014) report on a trial in a 42-unit complex of three low-rise multi-family buildings in Cambridge, Massachusettes. Interventions included replacing boiler controls with systems that offer temperature setback or outdoor reset control (ORC). One building's controls were replaced with Intech 21 controller and indoor temperature sensors, and two with Tekmar 274 controller with no sensors but capable of night-time setback. A billing analysis comparing bills before and after the installation of controllers with ORC showed the new control system saved a significant amount of space heating energy, an over-all weather-adjusted reduction of gas consumption of 10-15%. They also calculate that this would lead to a payback time on the control system of three years. The analysis for the controllers with the indoor temperature cut-off control showed significant savings in the one building where it was tested with a reduced boiler runtime of 28%. All the savings were achieved at night which the report suggest means the ORC controller worked adequately on its own during the daytime, reducing run-time and, hence, energy consumption.

The only European field trial identified was by Lindelöf *et al*. (2015). This tested a "non-invasive add-on module for existing heating controllers that implements an adaptive, model-predictive heating control algorithm". The add-on used an adaptive MPC algorithm that relied on monitoring building properties rather than needing a full thermal model for the building. The trial was undertaken in ten separate buildings in Switzerland (eight single family homes and two apartments). There were a wide mixture of heating systems, including whether control valves or central thermostats were present, fuel types (wood pellets, solar thermal, oil and gas) and heat distributors (radiators and underfloor heating). The system was tested in every building, with alternate periods of at least two weeks of operation with and without the add-on. Overall, energy savings of 28% (error margin of ± 4% - one standard deviation) were identified, however, these varied significantly across the test sites, with four out of the five highest energy saving buildings being built pre-1970 and being presumed to have much less insulation.

Full-scale experiments

Suter & Shammin (2013) carried out a full-scale experiment over two years to measure the impact of different treatment-levels on a sample of 24 single-family homes rented to undergraduates at Oberlin College in Ohio, USA. There were three experimental treatments: installation of programmable thermostats, addition of attic insulation and provision of financial incentives for energy conservation. The sample of houses was split into four groups - one for each treatment level and a control group. In the first year, programmable thermostats were installed in six out of 24 homes. An econometric model of household natural gas consumption found no evidence of energy savings in the programmable thermostat group. In year 2, three of the houses in the treatment group were also given financial incentives. This combination of treatments saw the largest reduction in energy use in the experiment showing that programmable thermostats were only effective when combined with financial incentives, with an observed reduction of average internal temperatures of 4.3 degrees Fahrenheit. A limitation of the study is that pre-treatment data was not collected: a recommendation for future research.

Other proposed methods of quantification and measurement of savings potential

This final section considers some studies (all from the USA) which do not fall in the previous sections but offer information on measuring and comparing the effectiveness and energy saving potential of heating controls.

Daken and Meier. (2016) asks 'Do Connected Thermostats Save Energy' and outlines a procedure for calculating a hybrid performance metric of connected thermostats using data from the installed base of thermostats. This is proposed as a first effort at finding a way to quantify savings from thermostats, if they exist, using data available in the USA. Energy savings from a particular thermostat are not reported. Meyers *et al.* (2010) present a scoping study that takes a broad look at different energy saving technologies including programmable thermostats, smart meters and outlets, zone heating, automated sensors and wireless communication. The study discusses the potential role of these different technologies to reduce wastage, considering cost and payback time but does not report energy savings. The document estimates energy wastage from inefficient delivery and conversion of energy in US homes due to thermostat oversetting estimated at 2.5% of primary energy is wasted on oversetting of thermostats for both heating and cooling.

Blasing and Schroeder (2013) report on energy, carbon-emission and financial savings from thermostat control and estimate the savings that can be achieved by reducing settings by 1 °F. The report discusses the role of different weather systems across the US on the potential savings that could be achieved through thermostat control. Across the entire USA, they estimate that this change in setting in residential properties could save 0.198 EJ (ExaJoules) (equivalent to 55 TWh) of energy from heating (across electricity, gas and oil) with accompanying carbon savings of 2.899 teragrams (Tg) and monetary savings of $2,313m (approximately $29 per household/$11 per person).

Xu *et al.* (2014) report an energy saving alignment strategy for achieving energy efficiency. The strategy uses data from a case study of a 1084-apartment public housing complex in New York called Amsterdam Houses. Occupant HVAC thermostat setting preference distributions were estimated from U.S. Residential Energy Consumption Survey (RECS) (2009) statistics and classified into 5 groups. The model aligned these 5 groups with 5 matching categories of indoor operative temperature in the public housing complex to maximise energy efficiency and thermal comfort. When the groups were aligned by preferred summer thermostat setting the model estimated the Amsterdam Houses project could save 3.7% of their total primary energy demand.

A limited amount of work in the USA has also been carried out on the cost effectiveness potential of heating controls with one study identified analysing electrical HVAC systems in the context of variable electricity tariffs. For example, Harding and Lamarche (2016) carried out a large-scale randomised control trial where 1,011 customers were switched to a Time-of-Use (TOU) pricing structure and put in different treatment groups. The report found that web portals and in-home displays (IHDs) were significantly less effective than smart thermostats at encouraging householders to change electricity usage to off-peak times. However, in order to focus on work of greater relevance to the UK, this has not been considered widely within this report.

The following section discusses the usability issues of various heating controls as identified in this report.

2.7.2 Usability

According to the international standard, ISO 9241-11 (2015) usability is "*the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use*". In this context effectiveness, can be referred to as the "*completeness and accuracy with which users achieve specified goals*"; efficiency as the *"the speed (with accuracy) with which this work can be done*"; and satisfaction as the "*user's comfort, positive attitude and acceptability of a product or a system during the interaction with the user interface of a product or a system*". It is widely acknowledged that usability is a crucial component in the success or failure of a product or a system. The term "usability" emerged in the 1980s and is now adopted by numerous disciplines to measure the user experience associated with the interface of a product or a system. One of the usability research pioneers, J. Nielsen, defines usability as the question of how well a user may utilise the functionality of a system as opposed to the functionality itself (Nielsen 1993). For heating controls usability describes how easily a person is able to use the control, including turning it on or off and adjusting temperature and timing settings (Lomas *et al*., 2016).

This review summarises the evidence accumulated from the selected evidence that investigates usability in relation to heating controls. This includes but is not limited to research on visibility, identification and accessibility of temperature controls, adjustment of room temperature by means of controls and understanding of the feedback provided after adjustment. We cover the topic in the context of different countries, control technologies and concerns related to interaction with heating controls. The final sample of selected documents contains case studies from USA (9 documents), UK (4 documents), Netherlands (2 documents), Czech Republic and Switzerland (1 document each). In the context of heating controls majority of the documents from our sample discuss novel control functionalities for thermostats and only a few documents focus on more complex household smart controls that among other functionalities also provide means to control heating.

Methods of Measurement

The final sample of our literature review on usability consists of 17 documents. We classify them further based on their methods of assessment. Table below shows number of documents found for each of these methods.

Table 6 Number of documents with focus on usability based on their method

Method	***Country***	***Number included in review***
Reviews	UK , USA	4
Expert Evaluation	UK, US, Switzerland	4
Controlled Usability Assessment	UK, USA	4
Real World Usability Trials	US, Netherlands	5
Other Approaches	Czech Republic, UK	2

Reviews

Four studies were included in our sample, which provide reviews on the usability of heating controls. Combe and Harrison (2014) focuses on reviewing the literature and the guidelines on usability of heating controls in general. In their work the authors stress the fact that the usability of heating controls forms a particular gap in the existing research, despite usability issues being highlighted in early 1980s. The investigation of most recent technologies raises a concern that despite poor understanding of the usability of existing systems further complexity is being rapidly added to such systems.

The other three review articles (Peffer *et al.,* 2011, Peffer *et al.*, 2012 and Meier *et al.,* 2010 and 2011b) mainly focus on reviewing research and literature related to residential programmable thermostats as these are predicted to take over the market in USA. The authors conclude that there has been very little research undertaken by thermostat manufacturers to address usability issues and acknowledge the opportunities for improved usability such as access through web portals and voice recognition. However, at the same time, the increasing functionality of thermostats which is going beyond simply controlling heating can introduce further usability challenges.

Expert Evaluation

We identified below discussed documents that use expert evaluation of the usability of heating controls in their research methods. Expert evaluations are understood as methodologies or prototype models developed to evaluate and better understand usability and usability criteria.

Based on their review as discussed above, Combe and Harrison (2014) also propose a way to develop a heating control interface prototype. They apply the usability guidelines from ergonomics, general device usability, computer–human interfaces and building control sources published in Peffer *et al.* (2012). The purpose of their study is to develop a prototype heating control interface for domestic buildings. The control interface aims to allow simple programming of such heating controls to make them more usable and potentially more effective. The aim of their study was to demonstrate how a domestic control interface could be developed to result in a simple and usable solution without compromising on functionality. The details of controlled usability assessment carried out in the document are discussed in the section below.

The document by Revell and Stanton (2016) discusses how designs of residential heating systems could fail in the way they communicate their function to householder. The authors present a 'user mental models' approach to design as an alternative. Another valuable document drawing on expert evaluation method is by Von Bomhard *et al*. (2014). The authors discuss solutions for European heating systems (referring to a German case study conducted by BMWi in 2012) and based on key requirements for a heating and ventilation information system design an intuitive user interface that aims to assist residents to achieve energy-efficient heating and improved comfort.

Stevenson *et al*. (2012) focus on the usability of "touch point" controls ("touch point‟ controls represent everything in the home that the user physically touches in order to provide environmental and comfort control; these include heating and hot water controls) in two evaluation case studies conducted in UK low carbon housing stock. The authors developed a functional usability assessment matrix to visually measure critical control features of heating systems. An expert researcher as well an ordinary user evaluated each "touch point" control product. The conclusions highlight the necessity of more robust design and detailed evaluation of "touch point" control products to take into account user engagement.

Controlled usability assessment

In this section, we discuss the four studies that carried out small-scale testing in controlled environments. We explore how these studies reflect upon usability issues, country context, housing type, technology and fuel mix.

To validate their prototype heating control interface as discussed above, Combe and Harrison, (2014) conducted a small group user testing in UK. The study consisted of 31 users aged between 23 and 78 years old. The authors recorded that 74.2% of users were successful in programming the prototype control. Around 90% of the participants who failed the task were aged over 60 years old. This raises an issue about whether older people may still have difficulty using their system despite improvements and whether there should be more research targeting the older population.

Meier *et al*. (2010a) report on a small usability test on programmable thermostats in the USA. They selected six users and tested their interactions with two different thermostat models. Further discussions with users revealed problems with understanding the meaning of labels and most of the users preferred a touch screen to a button model. Peffer *et al.* (2012) and Meier *et al.* (2011a) in their studies on measuring usability of programmable thermostats conducted a laboratory testing on five types of thermostats on a sample of 31 participants aged from 18 to 65 in USA. Their tests proved to be successful in supporting the methodology developed to differentiate the usability of different thermostat interfaces. Test results show that subjects had the highest success rate of task completion with the thermostats designed in accordance with the following guidelines: good visibility of available actions, feedback, and consistency.

Real world usability trials

In this section, we discuss studies that performed a large-scale evaluation in real-world settings.

Brounen *et al*. (2013) conducted a detailed survey of 1,721 Dutch households (no information provided on housing type) to see whether there is a link between the extent of energy awareness and energy conservation behaviours among the residents. They examined the extent to which households are aware of their energy consumption, understand the energy efficiency properties of their homes and adjust their behaviour appropriately. From their survey, they draw conclusions that approximately 50% of households in the sample were aware of their energy consumption. However, many households in their sample failed to use temperature control as a means of saving energy. Their results imply that energy literacy and awareness could be unrelated to conservation behaviour.

Horn *et al*. (2015) conducted a study to understand children's involvement with heating controls in particular thermostats. 17 adults and 39 children from diverse range of neighbourhoods participated in their study with programmable thermostats. The findings of the study show that children rarely (and often never) touch thermostats in homes, which is due to two factors: children have no interest in thermostats and parents do not allow them using them. The authors suggest that the usability of thermostats could be enhanced to make it easy to use for younger generations.

Meier *et al*. (2010a) attempted to determine the critical usability characteristics of programmable thermostats (PTs), and conducted an online survey that collected responses across 57 cities in US. From the results of the survey they concluded that programmable functions of thermostats were not used often (89% of respondents rarely or never adjusted the thermostat to set a weekend or weekday program). A similar study on programmable thermostats by Sachs *et al*. (2012) focuses on exploring whether people with a high usability thermostat are more likely to use energy saving features than people with a low usability thermostat. Based on thermostat usability research conducted by Meier *et al*. (2010b), the authors choose the VisionPRO TH8000 by Honeywell as the high usability thermostat and the RTH221B – a basic programmable model by the same manufacturer as low usability thermostat. For the experimental testing of PTs the authors recruited households from a 96-unit multi-family building in Revere, Massachusetts, USA. The participants were randomly assigned to the high or low usability thermostats.

The analysis focused on: night-time setbacks, daytime setbacks, vacation holds, and reprogramming. All these types of interaction are reported to potentially lead to energy savings. The analysis of data from the experiment shows that usability did not appear to influence energy saving behaviours of the study participants. The authors concluded that increasing the usability of PTs is increasing the ability to save energy. However, to achieve energy saving behaviour, this ability needs to be be combined with users' motivation and policy educational interventions.

Pritoni *et al*. (2015) report on an online survey on thermostat usage via a crowdsourcing platform and collected data from 152 subjects across 38 states in USA. Of the respondents about 40% of those that owned PTs did not use the energy-saving programmable features and one third of them disabled or overrode the programmable features. Respondents also mentioned finding the user interfaces of thermostats to be confusing.

Another study conducted in Netherlands by Guerra-Santin and Itard (2010) focussed on determinants and effects of occupants' behaviour on heating consumption. Data used for analysis was collected from a household survey of 7,000 households in the Netherlands. The housing types covered were detached, semi-detached, terraced, corner houses, maisonettes (two floor flats), and flats. Based on that data this study drew a comparison between households with programmable and manual thermostats. The results did not show statistically significant differences in terms of hours of use. However, further analysis showed that households with programmable thermostats took fewer deliberate actions and were likely to leave control to the thermostat itself. This was taken as implying that the radiators in households with PTs were turned on for more hours than in the case of manual thermostats. In order to more effectively achieve energy savings, the authors recommend introducing automatic thermostats that would react to the presence of occupants instead of pre-programmed timetables.

Alternative views on usability

In this section, we discuss studies that present an alternative perspective on usability concept. Sysala *et al.* (2016) present a novel complex smart-house control system with a user-friendly interface for easy control that is accessible from any room in the house or, the authors claim, from any place in the world. The heating module of the system is equipped with heating sensors and allows programming of temperature of individual rooms as well as setting a weekly heating schedule. They argue that the advantage of such a system is energy cost optimisation due to efficient use of heating. However, they provide no evidence yet of experiments to test this system.

The article by Wade *et al*. (2016) discusses usability of heating controls from central heating installers' influence. This study is based from data gathered from survey conducted in UK. Data suggests that over half of UK householders left the choice of heating control to the installer. Empirical data shows that heating installers suggest suitable heating controls for particular types of occupant (for instance mechanical devices are most often installed for older people, while smart heating controls are perceived to be suitable for technologically savvy users and programmable digital controls are perceived to be suitable for working people and families) but they also provide guidance on how to operate installed heating controls and suggest appropriate settings. This work demonstrates that "heating installers can script the types of devices that end users receive and the ways in which they will likely be used thereafter". Based on their conclusions the research recommends that policy-makers need to consider the extent to which heating installers could encourage better use of heating controls.

2.8 Conclusion, limitations and areas for future research

This review has identified very little published research in the way of studies on energy saving benefits resulting from the installation of heating controls in real world situations, with a single study identified in Europe (Lindelöf *et al.*, 2015) and two from the USA (Dentz and Ansaneli, 2015 and Dentz *et al*., 2014). Even within these studies, there are a very wide variety of housing and heating systems tested (making it difficult to assess variations over a comparable sample) and limited consideration of the impact on results due to variation in user behaviours as opposed to the technologies themselves. Within all the studies (modelled or trials) it is evident that the scale of actual energy savings will be hugely dependent on the baseline conditions of the properties where controls are installed or updated, the nature of the heating system to which controls are added, and existing patterns of heating behaviours and energy use. Two studies identified, reported that savings were likely to be significantly greater in poorly insulated houses (Lindelöf *et al.*, 2015 and Kleiminger *et al.*, 2014). However, Drgona *et al.* (2015) cited work on smart thermostats that resulted in greater energy savings occurring in well-insulated households. Ahern and Norton's (2015) reporting of the OPTIMUS study suggested that heating system optimisation in older properties was found to result in the potential for rebound as heat delivery to poorly insulated part of houses increased (though this may have been more to do with improvements to pumps than the controls themselves).

Energy savings from use and installation of heating control technologies were examined and discussed internationally in several ways. Most studies emphasised the need for tailored approaches to installing heating controls dependant on particular climatic locations, housing typology, age and type of build as well as fuel mix (and in one case looking at views of installers, on the type of occupant). Several studies from the USA modelled the potential for increased energy savings and improved performance of programmable thermostats through using various means of occupancy prediction to avoid early or late system start-ups (Lu *et al.,* 2010, Hong and Whitehouse, 2013 and Perez and Burger, 2014).

There is also only limited evidence on the cost-effectiveness of heating controls, with three studies reporting quantified cost savings and examining 3 different types of controls. Monetti *et al.* (2015) estimate savings from installation of TRVs in a 12 apartment building in Italy. Dentz *et al.* (2014) report the payback time for an improved heating controller with outdoor reset control in the USA. UK based Rogers *et al*. (2011) estimate cost savings over a single month trial of a smart home energy management system. As with energy savings the cost-effectiveness is dependent on the baseline condition of the properties where the new controls are installed. In addition, it is difficult to compare findings between countries with different currencies and energy systems.

Regarding evidence on usability of heating controls, we identified a final sample of 17 documents. Most studies were carried out in the USA (9 documents) and the rest (8 documents) were conducted in EU. From the EU research, four documents used data from UK case studies. We observe that all the research on usability of heating controls in USA concentrated on studying programmable thermostats. Peffer *et al.* (2012), citing statistics from the US Department of Energy, claim that in US, thermostats control about 9% of national energy use.

There is insufficient robust evidence to draw a conclusion on how housing type can influence interactions with heating controls. Whilst US studies on usability have tended to focus on programmable and smart thermostats, a few EU studies in the sample considered usability of other types of heating controls such as low-carbon housing "touch point" controls (Stevenson *et al.,* 2012), smart thermostats (Von Bomhard *et al.*, 2014) and smart house programmable controllers (Sysala *et al.*, 2016).

With such a significant share of energy use being devoted to home heating, it becomes increasingly important to understand not only the thermostat technologies (whether it might technically lead to savings, or whether they are considered 'usable') but also how the occupants interact with them and the impacts that this can have. Peffer *et al.,* (2013) claim that, theoretically, programmable thermostats can reduce energy consumption by 5-15%. However, the evidence based on surveys, controlled and real world trials in USA and EU suggests that in practice there are little or no savings found compared to manual thermostats as residents tend not to use potentially energy saving features of programmable thermostats (and, indeed, a shift from manual to programmable timers can easily be understood to have the potential to increase heating usage).

The research agrees that, in general, usability of heating controls along with energy literacy and awareness do not directly influence conservation behaviour (Sachs *et al.*, 2012 and Brounen *et al.*, 2013), but only facilitate it (as there needs to be some additional motivation to save energy even beyond tacit cost savings). A number of real world trials and surveys indicate that user interfaces of heating controls need improvements and that there are unlikely to be 'one size fits all' solutions. Studies show, for instance, that older people have more difficulties using programmable thermostats than younger generations (Combe and Harrison, 2014). Wade *et al.* (2016) demonstrate however, that installers already recognise this, and tend to recommend different controllers based on their perception of the likely users.

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3 Part 2 Methodology

3.1 Overview

Part 2 focussed on analysing the policy experiences of other countries and draws on documents identified non-systematically and through expert contacts in different countries. The analysis focused on assessing the evidence base in order to capture:

- The range of international approaches taken in policy in relation to the use of heating controls and the identification of control types
- The metrics used to discuss success of the effectiveness of policies on heating controls once implemented
- The regulatory, technical and cultural context within which the policies have been implemented that may have affected their success
- Consumer experiences on heating controls – what evidence is there on effective policies, legislation and regulations that focus on maximising the opportunities for domestic and non-domestic (where relevant) consumers to adopt heating controls measures?
- Policy impacts – what evidence exists on the impacts of policies on heating controls on carbon emissions, energy savings and energy bills?

Overall there were three key stages to Part 2 (contacting experts, reviewing grey literature (out of which 8 websites, links and governmental sources and 10 institutional documents were in German, Portuguese and French) and analysing and quality appraising) as illustrated in Figure 6. Experts (37) were identified through team contacts with international and national energy agencies and energy research institutes such as ADENE in Portugal, Deutsche Energie-Agentur GmbH (DENA) in Germany, Centre for Sustainability University of Otago, Jyukankyo Research Institute, EDF, UC Davis, Energy Trust Oregon, NTNU, Duneworks, Efficient Energy International, Lawrence Berkeley National Laboratory, University of Sydney, VERCO, University of Wellington, IEA Demand Side Management Programme, European Alliance of Companies for Energy Efficiency in Buildings, Architects Council of Europe and Institute for Applied Research Germany.

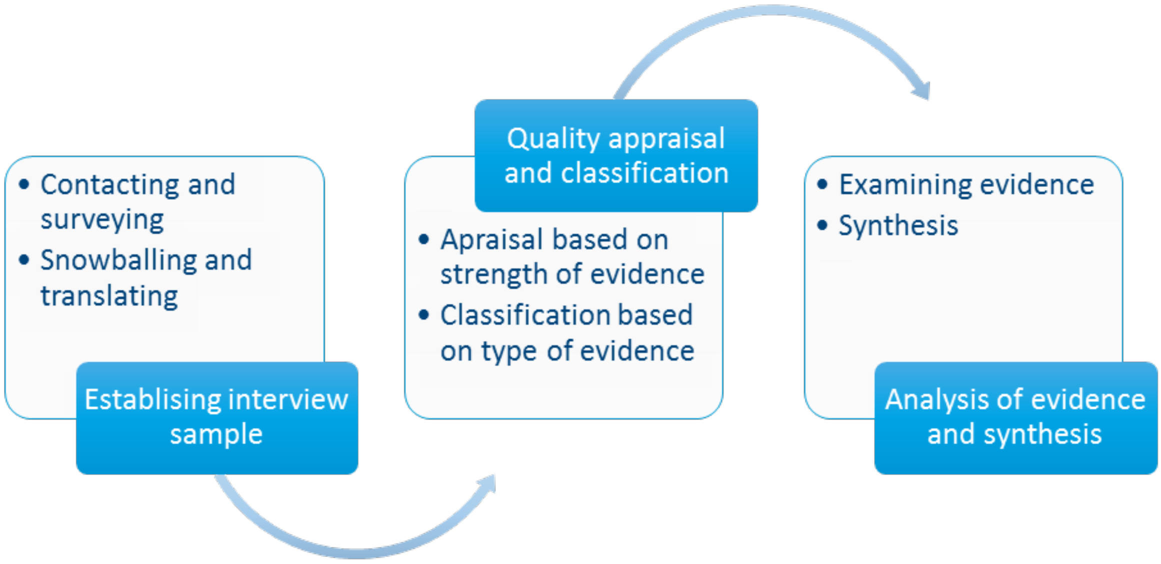

Figure 6: Key phases in Part 2 review

3.2 Sources and search terms

For the grey literature searches, heating control keywords were combined with policy, legislation and regulation keywords in English, German and Portuguese. Search terms (in English) were then refined in discussion with BEIS. Sources used could be classed as: journal papers, conference proceedings or grey literature. The search strategy for conference papers was to read through article titles of conference proceedings such as ASHRAE, CIBSE, ECEEE, ACEEE, BECC and Behave. Relevant papers were identified first by reading titles in each year's proceedings within specified timeframe (2010-2016) and then abstracts for those titles that appeared relevant. We also identified authors of articles in the proceedings who are working in the field who may be aware of relevant grey literature and listed them for contact via the probing email using questions illustrated in Figure 7.

In addition, the following institutional/organisational databases (BSRIA, ODYSSEE/MURE, ECEEE, ACEEE, BEHAVE, ASHRAE, CIBSE, EnergieWende, DENA, Fraunhofer Institute, PRECOURT ENERGY EFFICIENCY CENTRE, BERKLEY AND OPOWER, ADENE in PORTUGAL) were searched in English, Portuguese and German where applicable based on use of keywords: heating controls and policy, regulations, carbon emissions, cost savings, financial savings, energy savings, impact.

A probing email was sent to the identified experts asking them to list any relevant policy, regulatory or legislative documents related to domestic heating controls that they are aware of. We also consulted professional organisations including the EU Architects Council of Europe Workgroup and CIBSE. Within the email we explained our interest and provided list of three questions that could be answered fully further via phone call if necessary (see Figure 7).

Questions used in survey

Do you know anything about policy and legislative experience around heating controls in:
Your Country or Other countries (please list)

Please briefly describe these in terms of:
Legislation, Policies, Evidence Base and/or Impacts and evaluation

Would you be able to direct us to any documents describing these we would be very grateful (in English, Portuguese, Spanish or German)

Figure 7: Questions used in survey

3.3 Inclusion and exclusion criteria

The approach for selecting countries was based on their climatic similarity to current and projected UK conditions (Köppen-Geiger category classifications Cfb (maritime temperate) Csa and Csb (Mediterranean)). In many cases, such as the USA, selected countries experience an extended range of climate conditions, broadening the coverage of research and policy experience. Evidence relating to countries that fell entirely outside these selection criteria were be recorded and stored pending further investigation if deemed of particular value. Exclusion and inclusion criteria are illustrated in Tables 7 and 8.

Table 7: Inclusion criteria for Part 2 Sample

Documents that are written in English, Portuguese, Spanish or German
Documents that are UK, German, USA, Portugal, Australia or Chile based
Documents that are available and accessible online within the project's timeframe
Documents that their title or abstract indicate any evidence base for one or more types of domestic heating controls policy, legislation or regulation in terms of either (1) impact on carbon emissions (2) energy savings or (3) energy bills.
Documents that when read in full, meet all the criteria set for the screening 1 AND actually provide an evidence base discussed in 4.

Table 8: Exclusion criteria for Part 2 Sample

Exclusion Criteria
Documents that report policies, legislation or regulations for controlling domestic heating but do not evaluate their energy saving potential, carbon emissions impact or energy bills.
Documents that are a shorter version of another document already included
Documents that fall outside **the search timeframe 2010-2016**

3.4 Quality Appraisal

For grey literature, to obtain a collated sample of reports for Part 2, a different appraisal technique to Part 1 was used. When appraising international evidence and its transferability to the UK context the following was considered:

- What are the factors that contribute and determine the success of the policy (including addressing barriers, other regulatory issues, market structure and historical or cultural factors)?

- What is the impact of external factors (for example, high fossil fuel prices, home ownership structures, or availability of natural resources)?
- Would a policy (or aspects of the policy) work within the contemporary UK in terms of regulatory, legislative or technical measures?
- Is there evidence to indicate which is the most suitable delivery/engagement agent, or of the advantages of a particular configuration of national and local action that could be transferred to a UK context?

There are three key components to the appraisal and evidence assessment: the study's relevance to the review question, the appropriateness of its methods in the context of this specific review, and the quality of the execution of these methods (Gough, 2007). Evidence once appraised was discussed and classified using four categories for assessing research credibility found to be appropriate for a non-systematic review including:

- **Very Strong** - High quality body of evidence, large in size, consistent, and contextually relevant. We are very confident that the evidence of policy experiences does or does not have the effect anticipated. The body of evidence is very diverse and highly credible, with the findings convincing and stable.
- **Strong -** High quality body of evidence, large or medium in size, highly or moderately consistent, and contextually relevant. We are confident that the policy experience does or does not have the effect anticipated. The body of evidence is diverse and credible, with the findings convincing and stable.
- **Medium** - Moderate quality studies, medium size evidence body, moderate level of consistency. Studies may or may not be contextually relevant. We believe that the evidence of policy experience may or may not have the effect anticipated. The body of evidence displays some significant shortcomings.
- **Limited** - Moderate-to-low quality studies, medium size evidence body, low levels of consistency. Studies may or may not be contextually relevant. We believe that the policy experience may or may not have the effect anticipated. The body of evidence displays very significant shortcomings.

3.5 Synthesis

Documents that met the appraisal criteria were classified based on country, focus and heating control type (See Table 9). Relevant information was extracted for each country and synthesized as discussed in section 3.6 below.

Table 9 Classification of evidence identified for Part 2

Country	Heating Control technology	Evidence of policy, regulation or legislation	Study method	Evidence of Impact Case study
Ireland	Motorised valves, programmer	Limited	Small field trial	Medium
USA (Oregon)	Smart thermostats	Medium	Medium field trial	Strong
USA (Massachusets)	Boiler controls	Limited	Small field trial	Medium
USA (Florida)	Smart thermostats	Limited	Medium field trial	Medium
Germany	Thermostatic radiator valves, Optimisation	Limited	National projected and small trial	Medium
France	Room thermostats and thermostatic radiator valves	Limited	None found	None found
Netherlands	Smart thermostats with TOON (Quby)	Limited	Large field trial	Medium
New Zealand	Not known	Limited	Limited	Limited

3.6 Main findings: International evidence

The evidence searched for Part 2 included policy, regulatory and legislative experiences of heating controls as well as policy decisions underlying evidence of policy implementation (as outlined in section 3.2). In the short timescales, most of the gathered evidence for Part 2 of the report include: a) types of policy measures focusing on heating controls and b) policy experiences related to energy savings or carbon emissions of heating controls. Although searches carried out included identifying documents for evidence of policy decisions, there was a lack of evidence that emerged that demonstrated rationale for policy decisions.

In terms of the policy and/or regulatory landscape it was found that most countries have requirements associated with the minimum performance of boilers and air-conditioning systems. Examples include minimum boiler-efficiency levels and in some cases, such as Germany, a ban on old inefficient boilers (Lawson, 2015). Within the USA there are several utility programme incentives to implement energy efficiency measures including installation and use of heating controls such as smart thermostats. Section 3.6.1 illustrates some of the regulatory codes and policy incentive programmes in the USA and EU followed by insights from Ireland and Germany. These countries were identified in the short project timescales to have medium to strong evidence as discussed below. Countries such the Netherlands and New Zealand were identified to have only one of the aspects (either regulations or case studies) and are included in the review, however, Portugal, Denmark, France, Japan, Switzerland, Sweden, Norway, Italy, Chile, Belgium, Australia and Norway were identified in the timescale to have no or very limited evidence and are not included in the analysis.

3.6.1 Policy measures - narrative insights

The following discussion outlines key policy measures related to heating controls in the USA, Ireland and Germany.

USA select policy measures regarding heating controls

According to the USA Energy Information Administration, the use of particular fuels for space heating varies widely across the United States with natural gas heating 50% of homes nationwide, heating oil prominent in the Northeast and electricity most widely used in the South (EIA, 2016). Though the majority of USA households depend on a central furnace to provide heat, there has been an increasing presence of heat pumps in particular southern states. Most states in the USA have regulatory policies as well as utility programme incentives that require the electric and gas utilities to invest in energy efficiency as a resource.

With regards to regulatory policies, there are specific building codes for particular heating systems. For instance, most USA States have specific residential code requirements for new air source heat pump installations. These codes require that a thermostat be installed with the heat pump system that can lock-out the backup electric resistance heating elements when the outdoor air temperature is above 40^{o}F (equivalent 4.4 ^{o}C) (WSUEP, 2010). For existing installations, there are utilities that offer financial incentives for adding this electric heat lockout. The International Energy Code, Section 503.2.4.1.1, states that, except during defrost mode, supplemental heat shall be locked out when compression heat can meet the load.

With regards to utility programme incentives, in a number of states, Senate bills have facilitated mechanisms for the creation of organizations that are mandated to invest funds received from utilities in energy efficiency measures related to heating controls. In Oregon, Senate Bills 1149 and 848 (OLA 1999, 2007) facilitated funding mechanisms for state organizations such as the Energy Trust that have a mandate to invest funds received from the utilities to implement cost-effective energy efficiency measures. The regulations do not specify the types of efficiency technologies and measures that can be supported, as long as cost effectiveness can be demonstrated. Oregon has a utility program incentive whereby a $50 rebate is provided for installation of smart thermostats such as Nest and Ecobee3 devices (ETO, 2016a). There is a separate incentive for heat pump controls to lock out backup electric heat when outdoor temperatures are above 35^{o}F (1.7 ^{o}C) (ETO, 2016b).

In most other states including Washington and California, the Idaho Initiative 937 applies whereby utilities directly administer energy efficiency programs and the energy efficiency measures are required to be reviewed and approved by a state regulator (Idaho Initiative 937, 2016). Nationally there are upcoming policies planned by the US Environmental Protection Agency (EPA)'s Energy Star programme to certify connected thermostats (i.e. thermostats connected to the internet, which includes smart thermostats) with Energy Star labels (Energy Star, 2014). Energy Star previously labeled programmable thermostats, but that label was withdrawn in 2009 after several studies showed that programmable thermostats did not save any energy over manual thermostats. Under the proposed certification scheme, product providers will likely be required to submit aggregate savings data and associated statistics to the EPA every 6 months to demonstrate savings achieved in the field.

EU policy insights

Heating controls are included in the overall energy calculation methods in the new EPBD standards (M480) - EN 15232 Energy Performance of Buildings – Impact of Building Automation, Controls and Building Management (Commission Regulation EU, 2014). The European Standard EN15232:2012 was created to establish conventions and methods for estimating the impact of building automation and control systems on energy performance and energy use in buildings. A building control assessment scheme implementing EN15232:2012 and a rating label has been developed by the trade association (eu.bac) to facilitate this. The assessment scheme and label are concerned with control capability rather than measured energy performance of systems and buildings, but they may have a role to play in determining how relevant data can be captured and transmitted to automatic monitoring schemes for continuing long-term analysis.

The studies below in three EU countries: Germany, Ireland and the Netherlands all describe the energy saving potential of various heating controls measures. All the case studies are part of a wider set of energy efficiency interventions, and although some case studies isolate the effect of heating controls, the savings are difficult to evaluate with confidence.

Irish policy measures regarding Heating Controls

According to the recent surveys carried out by Odyssee-Mure, Ireland's residential sector currently accounts for 27% of all energy usage in the country and emits 10.5 million tonnes of CO_2 annually being one of the highest in Europe (Odyssee-Mure, 2012). The most widespread housing typology in Ireland is a detached house making up approximately 42% of total housing stock. The Sustainable Energy Authority of Ireland (SEAI) has examined the energy saving potential of a diverse set of efficiency measures across all key sectors including residential. According to the SEAI the energy saving potential in 2020 of heating controls and efficient boilers in residential buildings are estimated to be 3.8Twh (SEAI, 2015a).

Although there are a number of policy measures that consider a comprehensive set of energy efficiency strategies, there are no singular incentives aimed at heating controls. The "Better Energy: Homes" scheme (SEAI, 2016) is designed with the key objective of facilitating and promoting various energy efficiency interventions in existing homes. The scheme operates by providing grant-aids and incentives including attic and wall insulation as well as efficient boilers and heating control measures. Each home that receives an energy efficient set of interventions is also rated with an official Building Energy Rating (BER). In addition, the "Better Energy: Communities" scheme provides grant aids with the aim to facilitate and promote the delivery of innovative energy efficiency projects in communities and other areas including energy poor homes.

These measures are included in Ireland’s third National Energy Efficiency Action Plan (NEEAP) collectively under the heading Residential Retrofit. The scheme aims to encourage utility providers to work with consumers and identify potential savings. For instance, there are obligations for utilities to deliver mandatory energy savings across the residential, energy poor and non-residential sectors (SEAI, 2015b). These measures are not considered in detail in this report as they do not isolate the potential effect or saving of particular heating controls.

German policy measures regarding heating controls

After the Fukushima nuclear accident in 2011, the German government adopted an official energy transition strategy, the *Energiewende*, which included a nuclear phase-out by 2022 and renewable electricity goals of 35% by 2020, 40-45% by 2025, 55-60% by 2035 and 80% by 2050 (Die Bundesregierung, 2016). The *Energiewende* comprises six laws and one ordinance, focussing on areas such as grid expansion and upgrading, renewable energy and funding mechanisms for creating a system widespread energy transition.

According to the *Energieeinvesparverordnung*, new and/or existing buildings must undergo energy upgrades by 2050 by which time specific heating energy needs should only be around 20 kWh/m^2 (Hillebrandt *et al.,* 2015). Policy measures mostly include demonstration projects at different scales from city, district to neighbourhood. The German Federal Government launched the National Action Plan on Energy Efficiency (NAPE), a comprehensive strategy to further increase Germany's energy efficiency, on 3rd December 2014 (NAPE 2016). The strategy comprises several new instruments and working processes. The Climate Action Programme 2020, also adopted on 3rd December 2014, contains additional measures to increase Germany's energy efficiency in order to reach the 2020 climate target (BMWi, 2014).

Several initiatives supported by the BMWi (Federal Ministry for Economic affairs and energy) and implemented by DENA (German Energy Agency) serve the purpose of implementing measures whereby utilities are obliged to provide information regarding energy efficiency measures to consumers with every bill. In addition, the BMWi is funding several initiatives such as heating system inspections. In particular, a comprehensive communication campaign on energy efficiency was launched in May 2016. Information was provided to banks and other financial institutions to distribute loans in support of energy efficiency (BMWi, 2014).

Regarding heating controls, use of outdoor or indoor thermostats has been mandatory since 1978 with older systems required to be retrofitted since 1997. Weather compensation is reported to be mandatory in retrofit projects since 2002, whilst TRVs have been mandatory since 1978 (Lawson *et al.,* 2015). However, in the limited timescale for this review no evidence was found on any policies that focused incentives on heating controls; instead emphasis has usually been placed on demonstration projects and retrofit upgrade grants.

3.6.2 Impact case study experiences

USA Insights:

Across the USA there have been a number of impact case studies, from small to large scale field trials, focusing on the potential energy savings impact of smart thermostats as well as improvements in boiler controls. This section focuses on evidence identified in three states (Massachusetts, Florida and Oregon) with climatic differences as well as diverse housing and heating systems typologies as illustrated in Table 10.

Table 10: Illustration of key policy measures in selected states

Location/type of climate/year of study	Type of heating control	Method of measurement/size of sample	Type of building/fuel mix	Reported savings
Florida/hot humid climate/2014-15	Nest and Lyric smart thermostats	Surveyed billing data pre/post retrofit measures/28 installations	mix of 1-2 storey homes / heat pumps	Energy savings (heating) 9.5% peak demand reduction of 16% 4-5pm
Massachusetts/humid continental/2013-14	Boiler controls	Field test in 42 apartments	Apartments in masonry buildings/ hydronic	Up to 1-% energy savings (heating)
Oregon/oceanic climate/2013-14	Nest smart thermostats	Surveyed installers, residents and billing data 174with installed NEST thermostats/299 comparison homes	Air source heat pumps	781kWh per year average/4.7% annual electricity usage

In Massachusetts, Dentz *et al.,* (2014) report the energy saving bill implications of retrofitting boiler controls in the (CAST) housing development located in Cambridge, MA (also noted in Part 1 section 2.7.1). The development has (3) three-storey masonry buildings consisting of 9-18 apartments within each building. All apartments were heated by gas using multiple boilers and controls that reset supply water temperature based on outdoor temperature. Building facility managers are responsible to ensure minimum space temperatures for each apartment of 68°F during the day and 64°F at night during heating season. This requirement is in accordance with the Massachusetts Department of Public Health (2012). Each apartment had one or two non-electric actuator zone valve controllers to regulate water flow through baseboard heaters.

The aim of the project was to assess and quantify the effect of various boiler control measures including outdoor reset improvements, indoor cut off and night time set back. The retrofit strategy included replacing boiler controls throughout with controls capable of night setbacks with no indoor temperature sensors. In one of the buildings the new boiler control system allowed for remote tracking and control of all parameters as well as setbacks. It also included wireless temperature sensors in all apartments that provided input into the control algorithm.

Outdoor reset interventions in one building reported heating energy use decreased by 10% with opportunities to further introduce savings by lowering the reset curve. Monthly gas bill data was compared to pre-retrofit weather-normalised data. Indoor cut off interventions in one building reported similar results, whilst night-time setback in one building proved to be ineffective. Thermostatic radiator valves were seen to offer a solution to overheating and imperfect distribution of heat in some apartments. TRVs were installed in two apartments with uncertain results. Building-wide data did not indicate any energy savings and space temperatures reported from apartments and studies were inconclusive.

The study in Florida carried out by Parker *et al.,* (2016) used an established method of analysing retrofit influences based on response to weather (ASHRAE, 2002). Overall the effect of installing Nest and Lyric smart thermostats were reviewed in 28 installations. The results indicate average energy savings on heating costs of 39kWh/year savings given Florida's heating season (that is limited). According to the study, analysis undertaken on billing found that annual savings of $60 at $0.12/kWh with payback of Nest installation four years with annual rate of return of 24% was feasable.

A similar study by the Energy Trust of Oregon evaluated the 'Existing Homes programme' Nest thermostat heat pumps control energy saving potential (ETO, 2014). The programme offered incentives to contractors to install advanced controls to exiting heat pumps. The Energy Savings Trust of Oregon (ETO) was formed in 2002 governed by the Oregon Public Utilities Commission. Customers of all key Oregon utilities pay a dedicated percentage of their income from utility bills towards supporting a variety of energy efficiency and renewable energy savings measures. The aim of the pilot was to assess the energy saving potential of installing smart thermostats utilising the heat pump balance point setting, which controls how frequently the heating system cuts out the backup resistance heat. The balance point was installed and set by installers to "Max savings' to minimise reliance on backup heat to achieve the target temperature.

The survey included 5 interviews with installers, surveys with 110 residents and billing analysis (no available data on how many homes). Billing data was constructed using a number of data sources such as heat pump characteristics, preliminary weather normalised annual electrical savings attributable to NEST 781kWh per year and equivalent 12% of heating load. According to the Energy Savings Trust the highest savings were reported in homes with largest occupancy, those occupied by younger occupants as well as 'manufactured' homes.

Germany: One of the most prominent residential heating intervention projects in Germany is OPTIMUS. The project objectives included analysis of potential energy savings from optimising various heating system components including controls (though these appeared to have a minor effect). The project reported energy savings of 20% could be achieved. Under the OPTIMUS study (Jagnow and Wolf, 2008), data for 75 dwellings with installed heat and electricity meters, was analysed after the 2002/2003 heating season. In total 19 single-family dwellings and 11 multi-family/apartment dwellings with relatively high heat consumption were selected for some or all of the optimization interventions. The heat energy consumption characteristics of 45 non-optimised and 30 optimised systems were monitored over the 2003/2004 and the 2004/2005 heating season, designated heating season A and B. It was reported that radiators were oversized by a ratio of 1.7, boilers by 1.8 and circulator pumps by a ratio of 3, leading to over- consumption of energy. By optimising these heating systems through both control and hydronic balancing (including resizing pumps) significant energy savings are reported to be possible to be achieved.

The Fraunhofer Institute for Building Physics (IBP) conducted a 14-month simulation study on the energy saving potential of Tado smart thermostat (Kersken and Sinnesbichler, 2013). Based on use of calculations the study was carried out on a typical single-family house and a typical apartment with five rooms. In addition, the report compared two types of building construction types. The results of the study report savings of up to 24% based on the use of the automatic presence detection. Furthermore, turning down the heating based on the weather forecast is reported to potentially add another 7% to the savings. However, the study is based on scenario prediction rather than large scale field trials.

Ireland: In the case of Ireland, the European CONCERTO project SERVE (Sustainable Energy for the Rural Village Environment) within the European Research Framework Programme (FP6 and FP7) is designed to demonstrate benefits of a community-wide approach to energy efficiency interventions. In the framework of the project, 400 buildings were retrofitted to improve their energy performance and approximately 500 renewable energy heating systems were installed (Kenny, 2010). In addition, the project supported 50 new eco-buildings to be supplied by renewable energy based district heating system.

A total of 346 dwellings were upgraded (approximately 55,000 m^2) with a two-zone seven-day programmer (time & temperature) control and boiler interlock; time and temperature control of electric immersion heating for hot water; and either one additional zone control or three TRVs. The space heating controls in a typical house were, prior to retrofit measures, based on a single time/thermostat unit that did not allow separate zones or separate hot water time control. Though each home had tailored approaches as there were variations in house typology as well as existing heating systems, in most cases upgrades were made to heating controls as well.

Typically, direct reduction in energy consumption achieved from upgrades to heating controls are isolated and reported individually for each home. In most cases this is suggested to be 2,000 kWh per annum, reporting an average saving of €180 though evidence is difficult to evaluate as many analysis parameters are not reported in detail.

Netherlands: A study carried out recently by Vrije Universiteit Amsterdam (Ramondt, 2015) reports on the energy savings associated with Toon, an in-home energy display that distinguishes itself by combining energy consumption feedback with expanded smart features such as a programmable thermostat and the ability to show social and historical energy consumption comparisons. The study involved a survey of 76,000 households, of which at least 5,300 had a Toon installed. The main result, estimated yearly savings between 5.1% and 6.1% on gas and between 2.6% and 3.2% on electricity. Savings are shown to continue to reduce, however, between three months and up to two years after installation. A sub-population analysis shows that smaller households tend to save more, indicating that the Toon stimulates habitual behaviour change rather than investment in major home improvements.

The part that the combination of smart thermostats and smart meters could play a) in improving understanding of the effectiveness of policy and b) improving householder confidence in investing in energy saving measures was noted in 2014 study by Quby (who developed the Toon smart thermostat referred to above) and energy consultancy Ecofys. Data availability was found to be key to both aspects and importantly, this requires user consent for access to data held in the devices to allow cloud based analysis and added value services such as comparison with other households and tailored insights and advice on potential energy saving behaviours, system maintenance contracts and investments using big data techniques.

The adoption of the technology in significant numbers (Quby have a user base of 250,000 households in the Netherlands) has principally been as a result of promotion by Dutch energy utility Eneco who have provided the Toon thermostat at reduced or zero cost depending on the length of the energy supply contract agreed with the consumer. The experience of the Toon study indicates that sufficiently large numbers of current users of smart thermostats will agree to such access to allow robust assessment of policy initiatives and meaningful comparisons with similar households. The Quby report also promotes collaboration with governments, academic institutions and other organisations to use the available data as a “Living Lab” to improve understanding of consumer energy consumption and the opportunities to increase efficiency.

The potential size of the domestic smart system market makes it particularly attractive for developers of systems and associated services and offers further potential to be extended into the small non-domestic building sector. The latter trend was noted as a threat to larger commercial system providers in BSRIA's 2015 report on the market for Building Automation and Control Systems in the Netherlands. The report notes, however, the existence of significant associated concerns around data security of these connected systems.

New Zealand: A brief review was carried out of the New Zealand Building Code (New Zealand Ministry of Business, Innovation and Employment, 2014) in order better to understand the context of energy regulation of domestic buildings in New Zealand. A "Simple House" Acceptable Solution (New Zealand Department of Building and Housing, 2010) is available for single storey household units that are limited in size, form, location (limited by wind exposure, snow zones, proximity to geothermal bores etc.), materials and proximity to property boundaries. Energy performance is controlled through minimum R-values for building elements and it should be noted that *"there is no requirement under the Building Code for heating to be provided to this simple house"*. If the Simple House approach is not appropriate, domestic, and other buildings with a floor area of less than 300 m^2, are assessed using the NZS 4218 standard with offers three compliance options. Thermal regulation in New Zealand is thus focussed on the performance of the building fabric. Controls are effectively disregarded in the assessment methodology and appear currently to be ignored as a means of implementing policy on energy saving.

Since 2009, the New Zealand government have been running a programme (Warm Up New Zealand) to subsidise the costs of retrofitting insulation and/or clean heating (typically electric heat pumps) to pre-2000 homes (Grimes *et al.,* 2012). A broad range of benefits were anticipated: improved energy efficiency, improved comfort, positive health outcomes and an increase in employment and production at a time of depressed economic activity.

Controls are not referred to in the programme, however, the analysis of the effectiveness of the measures is a potentially useful case study for the assessment of policy interventions. A series of impact studies against each of the anticipated benefits were carried out and published in a series of papers between 2011 and 2012 culminating in a final paper that examined the overall cost-benefit of the programme. This found that, based on changes in metered energy consumption and independently measured health costs, whilst energy savings were very modest (and of little individual benefit), health benefits represented 99% of total benefits (and were of benefit to society in general). This consideration of the broader impacts of an "energy saving" policy reveals considerable economic value that would be missed in narrower studies that focus on energy savings alone.

3.7 Conclusions, limitations and areas for future research

Overall, most of the evidence identified in the short timescales of the project included policy measures (in the USA) and impact case studies consisting of medium to large scale field trials (also in the USA). Although there are a number of field trials conducted in European and other international contexts (as described in 3.6.2), it was difficult to determine the existence or likelihood of an actual corresponding policy measure in some countries (Netherlands, Germany, Ireland and New Zealand). However, for the purposes of identifying areas of future research, evidence from these countries was included in the synthesis.

Although searches carried out included identifying evidence of underlying policy decisions, in the timescale there was insufficient evidence found that demonstrated rationale for policy decisions. It is also acknowledged that there are limitations in the non-systematic characteristics of the method employed such as potential bias in evidence provided by 37 experts contacted. The quantifiable potential of a policy measure on the carbon or energy savings of a particular heating control has also been limited, and in most cases, non-sufficiently robust. This is unsurprising as it is widely recognised that there are significant issues with the quality of data on energy use particularly in the residential sector (IEA 2014). Data consistency and availability related to different types of fuel are also an issue that is reflected in this review.

Most of the policy measures that isolate the potential impact of a particular heating control discussed in this review include incentivising utility providers (such as in the USA and some extent Ireland and the Netherlands). In Oregon (USA), senate bills have facilitated utility programme incentives for the installation of smart thermostats as well as separate incentives for heat pumps controls. Similar incentives are reported in other states as well (as discussed in section 3.6). Although most identified evidence has come from the USA, similar incentives are reported in Ireland such as the National Energy Efficiency Action Plan (NEEAP) collectively which is reported to aim to encourage utility providers to work with consumers and identify potential savings. In other contexts, such as Germany, heating controls are considered as part of a wider set of efficiency measures (both in terms of heating systems and building fabric).

With regard to impact or policy experiences a number of field trials in the USA consider the implications of incentivising utility providers (to install smart thermostats) are quantified with regards to energy use and carbon emissions. Two field-trials (in Oregon and in Florida) analyze the energy saving potential of installing smart thermostats. However, the comparative savings potential is difficult to methodologically identify as the field trials contain diverse housing typologies, sources of fuel, occupancy as well as climatic conditions. In addition, savings are reported either as heating/cooling only, as energy savings more broadly or as peak demand reduction. For instance, in Oregon savings are reported to be 781kWh per year average/4.7% annual electricity usage, whilst in Florida energy savings (for heating) are reported as 9.5% peak demand reduction. In addition, sample sizes are very different. In Florida the sample included 28 installations, whilst in Oregon the sample was much larger and consisted of 174 installations. In addition to the USA, another large scale field trial came from the Netherlands involving installation of 'Toon' in at least 5300 of 76,000 surveyed households. The main result, estimated yearly savings between 5.1% and 6.1% on gas and between 2.6% and 3.2% on electricity. Evidence of reported energy savings of smart thermostats was also identified in Germany. The Fraunhofer Institute undertook a modelling study into the energy savings potential of a smart thermostats Tado reporting potential energy heating savings of up to 24%.

Limited evidence was identified that include other heating controls. Limited evidence was identified in Ireland reporting energy savings achieved through retrofitting and upgrading heating systems as part of the project SERVE. As the sample of homes (346) differed in both construction and heating system upgrades were tailored to individual dwellings and included (where appropriate) two-zone seven-day programmer (time & temperature) control and boiler interlock; time and temperature control of electric immersion heating for hot water; and either one additional zone control or three TRVs. Savings isolating impact of upgrading heating controls are not separated clearly as the project is part of a large scale set of efficiency retrofit measures. Another European case study included a large scale field trial in Germany. The German OPTIMUS study involves optimising heating systems through both control and hydronic balancing (including resizing pumps). The results reported indicate potential energy savings (20%), however, limited evidence was identified regarding the different baseline conditions across the sample database.

Another field-trial analysing impact of upgrading boiler controls was found in Massachusets, USA. The field-trial consisted of a sample of 42 apartments and involved replacing boiler controls throughout with controllers capable of night setbacks with no indoor temperature sensors. In addition, TRVs were installed in two apartments with uncertain results. Building-wide data did not indicate any energy savings and space temperatures reported from apartments and studies were inconclusive.

4 Overall conclusions

Out of all the heating controls considered in the identified evidence in both Parts 1 and 2 of this review, smart thermostats have been the most prominent. Still, uncertainty remains about the energy savings or cost effectiveness they produce. Interpreting this body of research is a challenge due to three key factors: availability of data, contextual issues related to the sample, as well as diverse functionality options associated with smart thermostat design.

First, smart thermostats, with their capability to integrate home energy consumption data with data on occupancy and environmental conditions, offer potential to export detailed information that can be analysed centrally and fed back to the householder as added services. Potential added services include as discussed in report sections above, fault detection, energy tariff optimisation, comparisons with similar homes and tailored energy saving advice or central control mechanisms such as load shedding. This data has also been used as a source of information to analyse energy savings across significant numbers of homes as discussed in the Netherlands case study example. There is clearly the potential to exploit this data for a variety of purposes, including analysis of the effectiveness of policy interventions. However, there are associated data ownership and privacy issues which deserve exploration so that maximum benefit can safely be extracted.

Second, contextual issues include methodological concerns associated with the wide variability in study design, sampling bias related to convenience samples, self-selected participants, and a lack of valid comparison groups. This review has considered the results of a large set of diverse country contexts and inherent housing typologies, different home ownership potential factors, as well as various the fuel mix. Not only does this wide variety of baseline conditions make it hard to evaluate the existing evidence, it will also make it very difficult to successfully predict the impact of installing technologies in any given house. Although building models might (but not always) be able to reasonably estimate a building's thermal properties, the exact set up, configuration and condition of the heating system will be hard to ascertain. On top of this, there is also the behaviour of occupants to consider.

Third, the studies reported include multiple brands of smart thermostats with diverse functionality capabilities and user interfaces. In addition, there are currently limited widely accepted definitions or accounts of smart thermostats (sometimes referred to as intelligent or connected thermostats). A more nuanced understanding of how utility operators, installers as well as residents are interacting with both smart thermostats as well as associated remotely collected and analysed data is needed to better understand how this interaction affects efficiency savings.

On the basis of the evidence reviewed, there appears to be a strong case against considering heating controls in isolation from other aspects of the heating system (including thermal properties of the building). The German OPTIMUS study in particular has demonstrated that the impact of controls is very much linked to (and probably conditional on) more substantial elements of the heating system (e.g. boilers, pumps, radiators and pipework). The US studies in particular, also highlight the extent to which thinking about the effectiveness of controls is dependent on whether heating systems are gas-powered (as is currently most common in the UK) or run on electricity (as is most common in the US, and is planned in the UK).

A potential shift to increased electrical heating in the UK (predominantly via heat pumps) would radically alter the terrain in which heating controls need to be considered. This was particularly highlighted by the high number of studies identified in the scoping stages of this review that focussed on load-shifting and cost-savings in the context of variable electricity tariffs. However, this raises a very significant issue regarding differences in the use of heating controls that was not clearly addressed by any of the studies reviewed. This is to do with basic advised heating patterns between different heating systems. For example, heat pumps and underfloor heating work best in highly insulated properties, and in these situations it is recommended that heating systems be left on 24-hours a day (potentially with a small degree of setback). Research shows that this pattern of heating is not currently common in the UK (e.g. Huebner et al., 2013). This is likely due to both poor insulation standards and the general prevalence of gas-powered central heating utilising radiators. Therefore, any consideration of policy development with regard to heating controls needs to consider, as a matter of importance, plans for future developments in the nature of heating systems and home insulation, with particular regard to developing appropriate user understandings of controls that will be relevant in the long-term.

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APPENDIX A

Document Title	Energy, carbon-emission and financial savings from thermostat control
Author(s), Publisher, Year	Blasing, T.J., Schroeder, D., Energy, Carbon-emission and Financial Savings from Thermostat Control. (No. ORNL/TM-2013/55). Oak Ridge National Laboratory (ORNL), 2013
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	2	1	1	1	1	8	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☒	**Usability** ☐

Abstract/Summary

It is generally agreed that there is no single solution to the problem of reducing energy use and the gaseous and particulate emissions arising there from. The problem must be approached from several angles. Notably, Pacala and Socolow (2004) have suggested 15 “wedges” each aimed at reducing carbon emissions; selection of which wedges to use, and the degree of implementation for each, is left to policymakers or individuals. One of the more ambitious, but demonstrably achievable, ways to reduce energy use involves “zero energy” houses (ZEHs), which use little energy compared to most homes, or may be net producers of energy (Torcellini et al., 2006). Less ambitious measures provide correspondingly reduced benefits, in terms of energy and carbon savings, for individual households. These measures include use of compact fluorescent lights, windows that transmit light but not heat, and walls composed of structural insulated panels. Most of these measures save money over a period of years, if not almost immediately. The March 2009 issue of National Geographic Magazine had a feature article on energy savings starting in the home. It was shown that in many cases one can save energy, carbon emissions, and money all at the same time. Among the easiest approaches to energy, and cost, savings for most people is the adjustment of thermostats to save energy. Here we estimate savings of energy, carbon, and money in the United States of America (USA) that would result from adjusting thermostats in residential and commercial buildings by about half a degree Celsius downward during the heating season

and upward during the cooling season. To obtain as small a unit as possible, and therefore the least likely to be noticeable by most people, we selected an adjustment of one degree Fahrenheit, (1°F) which is 0.56 degree Celsius (0.56°C). This is the gradation used almost exclusively on thermostats in the USA and is the smallest unit of temperature that has been used historically. Heating and/or cooling of interior building space for personal comfort is sometimes referred to as space conditioning, a term we will use for convenience throughout this work without consideration of humidity. Thermostat adjustment, as we use the term here, applies to thermostats that control the indoor temperature, and not to other thermostats such as those on water heaters. We track emissions of carbon only, rather than of carbon dioxide, because carbon atoms change atomic partners as they move through the carbon cycle, from atmosphere to biosphere or ocean and, on longer time scales, through the rock cycle. To convert a mass of carbon to an equivalent mass of carbon dioxide (thereby including the mass of the 2 oxygen atoms in each molecule) simply multiply by 3.67. Our results are a set of factors for scaling a 1°F thermostat adjustment to the resulting savings of energy, carbon emissions, and money. Larger adjustments than 1°F will result in correspondingly larger savings increases as long as the indoor temperature does not closely approach the outdoor temperature, in which case savings would be reduced. Thermostat adjustments are easy to make, and the resulting comfort level can be determined by building occupants. We investigated only the residential and commercial sectors of the economy, where about half the total energy used goes for heating, ventilation and air conditioning according to the Residential and Commercial Energy Consumption Surveys conducted by the Energy Information Administration (EIA) of the United States Department of Energy (EIA, 2005, 2005a). The industrial sector uses large amounts of energy for manufacturing purposes such as machine drives, electrochemical processes, coking, and process heat, but less than 10% of the energy used by the industrial sector is used for heating and cooling (EIA, 2006).

Document Title	iProgram: Inferring Smart Schedules for Dub Thermostats
Author(s), Publisher, Year	Iyengar, S., Kalra, S., Ghosh, A., Irwin, D., Shenoy, P., Marlin, B., Proceedings of the 2nd ACM International Conference on Embedded Systems for Energy-Efficient Built Environments. Seoul, South Korea. ACM, pp. 211-220, 2015
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	2	1	1	1	1	7	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☒	**Usability** ☐

Abstract/Summary

Heating, ventilation, and air conditioning (HVAC) accounts for over 50% of a typical home's energy usage. A thermostat generally controls HVAC usage in a home to ensure user comfort. In this paper, we focus on making existing "dumb" programmable thermostats smart by applying energy analytics on smart meter data to infer home occupancy patterns and compute an optimized thermostat schedule. Utilities with smart meter deployments are capable of immediately applying our approach, called iProgram, to homes across their customer base. iProgram addresses new challenges in inferring home occupancy from smart meter data where i) training data is not available and ii) the thermostat schedule may be misaligned with occupancy, frequently resulting in high power usage during unoccupied periods. iProgram translates occupancy patterns inferred from opaque smart meter data into a custom schedule for existing types of programmable thermostats, e.g., 1-day, 7-day, etc. We implement iProgram as a web service and show that it reduces the mismatch time between the occupancy pattern and the thermostat schedule by a median value of 44.28 minutes (out of 100 homes) when compared to a default 8am-6pm weekday schedule, with a median deviation of 30.76 minutes off the optimal schedule. Further, iProgram yields a daily energy saving of 0.42kWh on average across the 100 homes. Utilities may use iProgram to recommend thermostat schedules to customers and provide them estimates of potential energy savings in their energy bills.

Document Title	Energy savings across EU domestic building stock by optimizing hydraulic distribution in domestic space heating systems
Author(s), Publisher, Year	Ahern, C., Norton, B., Energy and Buildings, 91, pp. 199-209, 2015
Country	EU

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	1	1	2	1	1	8	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☐	**Usability** ☐

Abstract/Summary

The objective of this work is to quantify the resultant savings across the EU from the optimization of existing system components in domestic space heating distribution systems to maintain comfort levels. Heat energy savings are shown to range from 1% to 19% depending on dwelling type, age, location and initial specific heat energy consumption. Total potential savings across the sector amount 22.6 Mtoe, a reduction of 7.3%; 53% of these from a reduction in pumping power required by heating distribution systems and 47% of these from a reduction in the heat energy consumed by heating systems. Note- Argues that heating systems are often over sized; mentions study in Germany by Jagnow et al (2006) of 92 dwellings whereby boilers were found to be oversized to the peak load heat by a ratio of 1.8; also radiators were typically oversized by a ratio of 1.7. The study argues that energy savings in domestic heating systems of 23Twh can be achieved across EU by 2020 if existing stock of fixed pumps were replaced with the high efficiency variable speed type circulators with an Eco Design Directive energy efficiency index in the range of 0.20-0.30.

Document Title	Hydronic Heating retrofits for low rise multifamily buildings: Boiler control replacement and monitoring
Author(s), Publisher, Year	Dentz,J., Henderson,H, Varshey,K, National Renewable Energy Laboratory (NREL), Golden, CO (United States), 2014
Country	USA

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	1	1	0	1	1	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☒	**Usability** ☐

Abstract/Summary

The ARIES Collaborative, a U.S. Department of Energy Building America research team, partnered with Neighbor Works America affiliate HRI of Cambridge, Massachusetts to implement and study improvements to the central hydronic heating systems in one of the nonprofit's housing developments. The heating control systems in the three-building, 42-unit Columbia Cambridge Alliance for Spanish Tenants (CAST) housing development were upgraded in an effort projected to reduce heating costs 15%–25%. HRI recognized that heating fuel use per square foot per heating degree day in the development was excessive compared to its other properties of similar construction. Although a poorly insulated thermal envelope contributes to high energy bills, adding insulation to the exterior walls was not a cost-effective or practical option for Columbia CAST, given the desire to maintain the building's historic exterior and to avoid disrupting the residents. A more cost- effective and readily available option was improving heating system efficiency.

Efficient operation of the heating system faced several obstacles, including inflexible boiler controls, failed thermostatic radiator valves, and disregard by residents of recommended thermostat set points. Boiler controls in all three buildings were replaced with systems that offer temperature setbacks and one that controls heat delivery based on apartment temperatures in addition to outdoor temperatures. This is the final report of a 3-year project, including two and one half winter monitoring seasons. During the first season various control settings and system configurations were altered as the systems were adjusted to maximize

comfort and energy savings. During the second and third seasons, control settings were adjusted a few times on schedules intended to provide data to compare various techniques, including indoor temperature controls and nighttime setbacks.

A utility bill analysis shows that after implementing control techniques, overall weather- normalized energy consumption for heating was reduced by approximately 10%–31% and the average savings across the three buildings was approximately 19%. Indoor temperature cut off was estimated to reduce boiler runtime (and by extension heating fuel consumption) by 28% in the one building in which it was implemented. Daytime and nighttime data were analyzed separately because they had different indoor cutoff thresholds and different reset curves. Nearly all the savings were obtained in the nighttime, which had a lower indoor temperature cutoff (68°F) compared to daytime (73°F). This implies that the outdoor reset curve selection was appropriately adjusted for this building for daytime operation. Nighttime setback of heating system supply water temperature had no discernable impact on boiler runtime or gas bills.

Document Title	Do Connected Thermostats Save Energy?
Author(s), Publisher, Year	Daken, A. A. and Meier, A. K. (2016) ACEEE Summer Study on Energy Efficiency in Buildings. [online] Pacific Grove, California: ACEEE, pp. 2-1 - 2-12. 2016.
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	1	1	1	1	1	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☐

Abstract/Summary

Connected thermostats (CTs) manage HVAC systems in over four million homes. Widely varying strategies are used by these thermostats to reduce HVAC energy use. Thermostat vendors claim savings of up to 20%; however, there is no accepted procedure to evaluate the effectiveness of these strategies. Presently, consumers (and utilities) have no way to identify the most effective CT products. We developed a method to quantify HVAC energy savings from a CT and assign a savings metric to CT products based on the method. The method collects indoor temperature and HVAC run time data from thermostats, plus publicly available local weather data. Temperature data is then regressed against HVAC run time to develop a unique HVAC- thermal model for each home. CT savings are expressed as percentage HVAC run time reduction from that with an assumed constant temperature baseline. To assign a metric value to a product (hardware plus service), savings from a large number of homes using the product are aggregated via a specific procedure. The method is being tested on large groups of thermostats from several vendors. Many of the strengths and weaknesses of this approach have been identified and will be discussed, along with anticipated future improvement of the method.

Document Title	Impact of low investment strategies for space heating control: Application of thermostatic radiators valves to an old residential building.
Author(s), Publisher, Year	Monetti, V., Fabrizio, E., Filippi, M., Energy and Buildings, 95, pp. 202-210, 2015
Country	Italy

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	0	1	2	1	1	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☒	**Usability** ☐

Abstract/Summary

With an old mean construction age, Italian buildings are considered as long-lasting goods; 75% and 17% of Italian live respectively in buildings built before 1990 and before 1950. The potential energy savings that can be achieved from the refurbishment of existing dwellings are clearly high. To this regard, the European Directive EPBD recast defines a comparative framework to improve buildings energy performance aiming to the nearly zero energy target by 2020. It is thus important to point out energy retrofit actions to be widely applied to the whole existing buildings stock and to be cost optimal. This paper analyzes the application of space heating control devices such as thermostatic radiators valves (TRVs) on an old existing multi-family building in Turin by means of the EnergyPlus dynamics simulation code. Measured data of the energy supplied by the district heating network were used for calibrating the model. In order to evaluate the impact of the TRVs, simulations were performed with and without TRVs. The application of the dynamic energy simulation to different patterns of TRVs use was proved to bring back significant energy savings from a minimum of 2% up to a maximum of 10%.

Document Title	Returns to residential energy efficiency and conservation measures: A field experiment
Author(s), Publisher, Year	Suter , J. F. , Shammin, M.R., Energy Policy, 59, pp. 551-561, 2013.
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	0	1	2	1	1	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☒	☐	☐	☐	☒	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☒	**Usability** ☐

Abstract/Summary

Residential energy conservation is a key component of contemporary energy and climate change policy in the US and elsewhere. Comparisons of the relative effectiveness of measures aimed at reducing residential energy consumption are made challenging, however, by the endogeneity of technology and energy use decisions. In this paper we describe a novel small-scale field experiment that uses randomized treatments to estimate the returns to three types of energy conservation measures in institutionally owned homes. The results from the experiment indicate considerable reductions in natural gas consumption associated with the installation of attic insulation and the provision of incentives for conservation. The results are supported by observations of ambient indoor temperature data, which show that households receiving incentives significantly reduce their temperature settings— especially when coupled with access to a programmable thermostat. The study will ideally provide guidance for institutions and communities considering energy efficiency measures and for future researchers designing randomized experiments to study residential energy use.

Document Title	Thermostatic Radiator Valve Evaluation
Author(s), Publisher, Year	Dentz, J., Ansanelli, E., National Renewable Energy Laboratory (NREL), Golden, CO (United States), 2015.
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	2	1	1	1	1	8	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☒	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☒	**Usability** ☒

Abstract/Summary

A large stock of multifamily buildings in the Northeast and Midwest uses hot water or steam for space heating. Typically, residents do not pay for heat directly (i.e., heating fuel serves a central plant and use is not submetered). Losses from these systems are typically high, and a significant number of apartments are overheated much of the time. This is often evidenced by open windows on winter days. Controls and distribution are often faulty, and improving them can be more cost effective than replacing boilers.

Thermostatic radiator valves (TRVs), which have been in use for many decades, are one potential strategy to combat this problem. They are commonly used in Europe and in other markets such as commercial buildings, but have not been widely accepted by the residential retrofit market in the northeastern United States. Anecdotal evidence suggests that heating systems engineers and contractors have a variety of opinions about their effectiveness, illustrating a lack of consensus on this potentially important energy efficiency measure. A review of the limited available literature revealed that, in one study, heating fuel savings as high as 15% was achieved through TRV retrofits.

In this project, the U.S. Department of Energy Building America team, Advanced Residential Integrated Energy Solutions, sought to better understand the current usage of TRVs by key market players in steam and hot water heating and to conduct limited experiments on the effectiveness of new and old TRVs as a means of controlling space temperatures and reducing heating fuel consumption. The project included a survey of industry

professionals, a field experiment comparing old and new TRVs, and cost-benefit modeling analysis using BEopt™ (Building Energy Optimization software). Radiator and apartment space temperature data were collected and analyzed for two similar apartment units in a building that underwent a one-pipe steam TRV retrofit. Space temperature comparisons were made across the pre- and post-TRV installation heating periods and between rooms equipped with old or new TRVs in an attempt to show the comparative effectiveness of each vintage of TRV. Analyses of the heating fuel utility bills before and after the building-wide TRV installation were conducted to quantify potential savings.

The results of the field experiment and utility bill analysis did not show energy savings at either the unit or the building-wide level. The results provided inconclusive answers to the original study questions but provided valuable insight into common steam system imbalance and resident behavior issues that are critical to address in conjunction with TRV retrofits. Specific issues identified included steam distribution imbalance, possible TRV sensor location issues, a persistent window-opening habit, and a failure to optimize the boiler control set points as part of the TRV retrofit. The lack of heating fuel savings underscored the need to include whole steam system commissioning alongside or as a prerequisite to TRVs. Failed air vents and uneven steam main venting are critical to address either in conjunction with or before a TRV installation. Monitoring existing space temperatures before a retrofit strategy is chosen would allow the consultant and building owner to better assess the potential benefits of a whole-building TRV retrofit, selective installation of TRVs in some units, or simply balancing the steam distribution venting.

Document Title	Predicting household occupancy for smart heating control: Acomparative performance analysis of state-of-the-art approaches.
Author(s), Publisher, Year	Kleiminger, W., Mattern, F., Santini, S. Energy and Buildings, 85, pp. 493-505, 2014.
Country	Switzerland and Germany

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	2	1	2	1	1	8	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☐

Abstract/Summary

This paper provides a comparative study of state-of-the-art means of predicting occupancy for smart heating control applications. We focus on approaches that predict the occupancy state of a home using occupancy schedules – that is, past records of the occupancy state. We ran our analysis on actual occupancy schedules covering several months for 45 homes. Our results show that state-of-the-art, schedule-based occupancy prediction algorithms achieve an overall prediction accuracy of over 80%. We also show that the performance of these algorithms is close to the theoretical upper bound expressed by the predictability of the input schedules. Building upon these results, we used ISO 13790-standard modelling techniques to analyse the energy savings that can be achieved by smart heating controllers that use occupancy predictors. Furthermore, we investigated the trade-off between achievable savings (typically 6–17% on average) and the risk of comfort loss for household residents.

Document Title	Field tests of an adaptive, model-predictive heating controller for residential buildings
Author(s), Publisher, Year	Lindelof, D., Afshari, H., Alisafaee, M., Biswas, J., Caban, M., Mocellin, X. and Viaene, J., Energy and Buildings, 99, pp. 292-302, 2015
Country	Switzerland

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	0	1	2	1	1	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☒	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☐	**Usability** ☐

Abstract/Summary
Conventional weather-compensated heating controllers are often configured to deliver more heating than necessary, resulting in energy losses. Furthermore, they cannot take into account future climate conditions, and yield less than optimal thermal comfort. We have developed a non-invasive add-on module for existing heating controllers that implements an adaptive, model-predictive heating control algorithm. This algorithm helps the heating controller deliver a heating energy just sufficient for maintaining thermal comfort, resulting in energy savings. In this paper we report on the energy savings measured on ten buildings equipped with this device. By monitoring the space heating energy during the 2013-2014 heating season, and by periodically alternating between the new controller and the reference controller, we establish the energy signature of all buildings with both controllers. The comparison of the energy signatures yields the relative energy savings achievable with the new controller. These energy savings are positive for all test sites, with a mean of 28 %± 4% (standard error of the mean).

Document Title	The Smart Thermostat: Using Occupancy Sensors to Save Energy in Homes
Author(s), Publisher, Year	Lu, J., Sookoor, T., Srinivasan, V., Gao, G, Holben, B, Stankovic, J., Field, E., Whitehouse,K., Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems (SenSys'10) , 2010
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	1	1	1	1	1	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☒	☐	☐	☒	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☒	**Usability** ☐

Abstract/Summary

Heating, ventilation and cooling (HVAC) is the largest source of residential energy consumption. In this paper, we demonstrate how to use cheap and simple sensing technology to automatically sense occupancy and sleep patterns in a home, and how to use these patterns to save energy by automatically turning off the home's HVAC system. We call this approach the smart thermostat. We evaluate this approach by deploying sensors in 8 homes and comparing the expected energy usage of our algorithm against existing approaches. We demonstrate that our approach will achieve a 28% energy saving on average, at a cost of approximately $25 in sensors. In comparison, a commercially-available baseline approach that uses similar sensors saves only 6.8% energy on average, and actually increases energy consumption in 4 of the 8 households.

Document Title	A Case for Thermostat User Models
Author(s), Publisher, Year	Urban, B. and Gomez, C., Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association., pp. 1483-1490, 2013
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	1	1	0	1	1	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☐	**Usability** ☐

Abstract/Summary

Today's thermostat setpoint models naïvely assume fixed schedules, ignoring the reality of user control and its large variability. Better models must include more realistic user-behavior profiles to correctly evaluate the energy benefits of the next generation of thermostats against a realistic baseline. Data from a recent thermostat field study were analyzed to demonstrate the variation and patterns associated with manual adjustment of programmable thermostats and its consequences on observed and simulated energy consumption. A practical modeling technique for describing variable setpoint schedules was applied and compared with standard, fixed setpoint assumptions. Room air temperature data from 63 apartments near Boston, MA were used to generate unique hourly heating setpoint schedules. These observed temperature histories were then used to model the expected variation in energy use of an apartment due to manual thermostat adjustment. Significant differences in energy consumption were observed when variable setpoints were used instead of fixed setpoints, indicating the need for improving thermostat assumptions and updating models with more realistic schedules.

Document Title	MPC-Based Reference Governors for Thermostatically Controlled Residential Buildings
Author(s), Publisher, Year	Drgona, J., Klauco, M. and Kvasnica, M., 2015 IEEE 54th Annual Conference on Decision and Control (CDC). Osaka, Japan: IEEE, pp. 1334-1339, 2015
Country	Slovakia

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	1	1	1	1	1	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☐

Abstract/Summary

This paper tackles the design of a reference governor strategy based on model predictive control (MPC) which allows to improve economics of conventional relay-based thermostats in residential buildings. In this set up, MPC serves as a supervisory controller which generates optimal setpoints for the thermostat. The thermostat, which operates in an on/off manner, then controls the heating actuator that influences the indoor temperature. We show how to include the dynamical behavior of such a thermostat into the MPC optimization problem. Optimal setpoints can then be obtained by solving a mixed integer linear programming problem. Efficiency of the proposed strategy is verified on a simulation case study.

Document Title	Empowering Consumers Through Data and Smart Technology: Experimental Evidence on the Consequences of Time-of-Use Electricity Pricing Policies
Author(s), Publisher, Year	Harding, M. and Lamarche, C., Journal of Policy Analysis and Management, 35(4), pp. 906-931, 2016.
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	0	1	2	1	0	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☒	**Usability** ☐

Abstract/Summary

This paper investigates the extent to which technology used to automate household responses to time-of-use pricing for electricity leads to higher energy savings than simply providing households with information on current prices and quantities. Using a large randomized field trial, we find that informed households with "smart" thermostats achieve impressive reductions in consumption during on-peak periods of up to 48 percent, but also engage in substantial load shifting to off-peak hours. We also document the extent to which household responses to time-of-use pricing are heterogeneous and vary significantly by demographics, weather, and across the usage distribution.

Document Title	Scoping the potential of monitoring and control technologies to reduce energy use in homes
Author(s), Publisher, Year	Meyers, R. J., Williams, E. D. and Matthews, H. S., Energy and Buildings, 42, pp. 563-569, 2010.
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	1	1	2	1	1	8	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☐	**Usability** ☐

Abstract/Summary

This scoping study takes a broad look at how information technology-enabled monitoring and control systems could assist in mitigating energy use in residences by more efficiently allocating the delivery of services by time and location. A great deal of energy is wasted in delivering services inefficiently to residents such as heating or cooling unoccupied spaces, overheating/undercooling for whole-house comfort, leakage current, and inefficient appliances. We construct a framework to estimate different categories of inefficient energy services and the result of our initial estimate is that over 39% of residential primary energy is wasted. We next discuss how monitoring and control technologies could manage home energy use to reduce waste. Technologies considered here include programmable thermostats, smart meters and outlets, zone heating, automated sensors, and wireless communications infrastructures. The level of energy services delivered is assumed to remain unchanged, with all energy savings being realized through better management. A final discussion on barriers to adoption of these systems speculates that a lack of consumer awareness of the technologies, high costs due to lack of economies of scale, and difficult user interfaces are currently the major hurdles toward adoption.

Document Title	Enabling technologies and energy savings: The case of EnergyWise Smart Meter Pilot of Connexus Energy.
Author(s), Publisher, Year	Ivanov, C., Getachew, L., Fenrick, S. A. and Vittetoe, B., Utilities Policy, 26, pp. 76-84, 2013
Country	Minnesota, US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	1	1	2	1	0	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☐	**Usability** ☐

Abstract/Summary

We examine the demand impact of a smart meter pilot conducted by Connexus Energy from 2008 until 2010. We focus on the amount of peak time energy use reduction, either through forgone usage or load shifting to off-peak times, as a result of enabling technologies in the form of in-home displays and smart thermostats. The in-home display allows the treatment group members to voluntarily alter their power use during “red alert” (critical peak) days. The smart thermostats also installed for the treatment group enable the utility to reduce AC usage of that group during red alert days by remotely turning up the temperature setting by 3 degrees Fahrenheit (F) (i.e., a form of direct load control). We use hourly fixed effects models to examine peak time energy use changes in the summer of 2010. We find that treatment group members reduced their peak time energy use relative to the control group, which had no in-home displays or smart thermostats. Treatment group members who had the enabling technologies used, on average, 0.47 less kW, or 15% less energy, during peak hours on an average red alert day.

Document Title	Energy Saving Alignment Strategy: Achieving energy efficiency in urban buildings by matching occupant temperature preferences with a building's indoor thermal environment.
Author(s), Publisher, Year	Xu, X., Culligan, P. J. and Taylor, J. E., Applied Energy, Vol. 123 (2014), pp. 209-219, 2014
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	1	1	2	1	1	7	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☒	☐	☒	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☐	**Usability** ☐

Abstract/Summary

Existing strategies for residential energy savings through physical renovation or motivating occupant energy conservation behavior can be costly and/or have transitory effects. Focusing on multi-family dwellings, an important subset of the urban residential sector, we propose an Energy Saving Alignment Strategy (ESAS) that has advantageous cost-effectiveness and a long-lasting influence. By aligning the distribution of residents' thermostat preferences with the indoor temperature, ESAS aims to maximize thermal comfort and, accordingly, energy savings in multi-family buildings where indoor temperatures vary between apartments as a function of apartment orientation and floor level. Using a case study of a 1084-apartment public housing complex in New York, we classify both occupants' thermostat preferences and apartments' operative temperatures into five groups, and optimize energy efficiency by assigning each group of occupants to the group of apartments that best aligns with their thermostat preference. We test ESAS in eight cities representing all four U.S. census regions and six climate zones. Simulation results reveal 2.1-42.0% in energy savings compared to random apartment assignments depending on geographic location, with the highest energy reductions occurring in cities with mild climates, where the range of occupant thermostat preferences coincides with the natural indoor temperature range. We conclude by providing suggested guidelines on how ESAS might work in practice, and recommendations for extending ESAS research.

Document Title	BEES: Real-time occupant feedback and environmental learning framework for collaborative thermal management in multi-zone, multi-occupant buildings
Author(s), Publisher, Year	Gupta, S.K., Atkinson, S., O'Boyle, I., Drogo, J., Kar, K., Mishra, S. and Wen, J.T., Energy and Buildings, 125, pp.142-152, 2016
Country	USA

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	1	1	2	1	1	8	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☐	**Usability** ☐

Abstract/Summary

In this work we present an end-to-end framework designed for enabling occupant feedback collection and incorporating the feedback data towards energy efficient operation of a building. We have designed a mobile application that occupants can use on their smart phones to provide their thermal preference feedback. When relaying the occupant feedback to the central server the mobile application also uses indoor location techniques to tie the occupant preference to their current thermal zone. Texas Instruments sensortags are used for real time zonal temperature readings. The mobile application relays the occupant preference along with the location to a central server that also hosts our learning algorithm to learn the environment and using occupant feedback calculates the optimal temperature set point. The entire process is triggered upon change of occupancy, environmental conditions, and/or occupant preference. The learning algorithm is scheduled to run at regular intervals to respond dynamically to environmental and occupancy changes. We describe results from experimental studies in two different settings: a single family residential home setting and in a university based laboratory space setting.

Document Title	Adaptive home heating control through Gaussian process prediction and mathematical programming
Author(s), Publisher, Year	Rogers, A., Maleki, S., Ghosh, S. and Jennings, N. R. The Second International Workshop on Agent Technology for Energy Systems (ATES 2011), pp. 71-78, 2011
Country	UK

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	1	1	0	1	1	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☒	**Usability** ☐

Abstract/Summary

In this paper, we address the challenge of adaptively controlling a home heating system in order to minimise cost and carbon emissions within a smart grid. Our home energy management agent learns the thermal properties of the home, and uses Gaussian processes to predict the environ- mental parameters over the next 24 hours, allowing it to pro- vide real-time feedback to householders concerning the cost and carbon emissions of their heating preferences. Further- more, we show how it can then use a mixed-integer quadratic program, or a computationally efficient greedy heuristic, to adapt to real-time cost and carbon intensity signals, adjusting the timing of heater use in order to satisfy preferences for comfort whilst minimising cost and carbon emissions. We evaluate our approach using weather and electricity grid data from January 2010 for the UK, and show our approach can predict the total cost and carbon emissions over a day to within 9%, and show that over the month it reduces cost and carbon emissions by 15%, and 9%, respectively, compared to using a conventional thermostat.

Document Title	A Feasibility Study: Mining Daily Traces for Home Heating Control
Author(s), Publisher, Year	Hong, D., Whitehouse, K., 3rd International Workshop on Mobile Sensing, 2013
Country	Refers to US, UK and Canadian conditions

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	1	1	0	1	1	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/ Summary

HVAC systems take up the largest portion of utility bills in a home and they are also large electricity consumers nationwide. Recent work has been focused on automated control based on occupancy prediction, where some look into historical patterns while others leverage real-time position information of the occupant. We believe combining these two techniques could help predict when someone will come home. In this paper, we propose to look at an occupant's \landmarks" (time of leaving home and work) in history and make predictions of arrival times. Our approach requires the minimum efforts for heating controls from users. We evaluate the model on the data from 4 users and show the potential 8.3%-27.9% energy savings as well as 14.9%-59.2% reduction in miss time.

Document Title	Cloud Enabled Model Predictive Control of a Home Heating System
Author(s), Publisher, Year	Perez, H. E. and Burger, E. Project Report CE 290-2 Energy Systems and Control, 2014
Country	USA

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	1	1	0	1	1	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☒	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☒	**Usability** ☐

Abstract/Summary

This work creates a smart cloud-enabled thermostat for an electric home heating system. The objective is to optimize the operation of heaters to minimize the cost of electricity and maintain a comfortable temperature based on time-varying weather forecasts and electricity price data. This involves modelling and controlling the home through sensor deployment, Internet-based control system design, and smartphone application development. The goals of this project are to: a) monitor the real-time thermal conditions in an apartment, b) reduce peak loads on the power grid, c) make use of weather forecast data to predict heating requirements, and d) enable smart home technology development.

Document Title	Energy literacy, awareness, and conservation behavior of residential households
Author(s), Publisher, Year	Brounen, D., Kok, N. and Quigley, J. Energy Economics, 38, pp. 42-50, 2013
Country	Netherlands

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	2	1	2	1	0	8	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☐	☒	☐	☐	☒	☐	☐

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

The residential sector accounts for one-fifth of global energy consumption, resulting from the requirements to heat, cool, and light residential dwellings. It is therefore not surprising that energy efficiency in the residential market has gained importance in recent years. In this paper, we examine awareness, literacy and behavior of households with respect to their residential energy expenditures. Using a detailed survey of 1721 Dutch households, we measure the extent to which consumers are aware of their energy consumption and whether they have taken measures to reduce their energy costs. Our results show that "energy literacy" and awareness among respondents is low: just 56% of the respondents are aware of their monthly charges for energy consumption, and 40% do not appropriately evaluate investment decisions in energy efficient equipment. We document that demographics and consumer attitudes towards energy conservation, but not energy literacy and awareness, have direct effects on behavior regarding heating and cooling of the home. The impact of a moderating factor, measured by thermostat settings, ultimately results in strong variation in the energy consumption of private consumers.

Document Title	A review and application of usability guidelines relating to domestic heating controls
Author(s), Publisher, Year	Combe, N., Harrison, D., Intelligent Building International, 6(1), pp. 26-40, 2013
Country	UK

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	0	1	2	1	1	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☒	☒

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

Domestic buildings are currently responsible for nearly one-third of UK CO_2 emissions and the majority of these emissions are due to the large heat energy consumption of UK homes. Building occupants heavily influence this consumption by interacting with domestic heating controls. The poor usability of these controls has been widely documented and several sets of guidance produced. However, little has been done to validate this guidance or document its implementation. This article applies three sets of usability guidelines to the design of a heating control, aiming to produce a simple, usable and accessible interface. The interface developed was subsequently tested with 31 users (23-78 years old). The testing identified whether the design changes motivated by the guidance made had improved usability. The usability of the prototype system can be tentatively verified due to the high overall success rate, low average task completion time and low error rates observed. The subjective satisfaction ratings were also high and the help features were used infrequently, implying that the system was easy to use. Despite considerable design effort to improve usability further work is still required to make the heating controls more accessible to older users. If the buildings are to be both intelligent and sustainable then the control systems within domestic buildings need to be usable by the widest possible range of users.

Document Title	A review and application of usability guidelines relating to domestic heating controls
Author(s), Publisher, Year	Combe, N., Harrison, D., Intelligent Building International, 6(1), pp. 26-40, 2013
Country	UK

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	0	1	2	1	1	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☒	☒

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

Domestic buildings are currently responsible for nearly one-third of UK CO2 emissions and the majority of these emissions are due to the large heat energy consumption of UK homes. Building occupants heavily influence this consumption by interacting with domestic heating controls. The poor usability of these controls has been widely documented and several sets of guidance produced. However, little has been done to validate this guidance or document its implementation. This article applies three sets of usability guidelines to the design of a heating control, aiming to produce a simple, usable and accessible interface. The interface developed was subsequently tested with 31 users (23-78 years old). The testing identified whether the design changes motivated by the guidance made had improved usability. The usability of the prototype system can be tentatively verified due to the high overall success rate, low average task completion time and low error rates observed. The subjective satisfaction ratings were also high and the help features were used infrequently, implying that the system was easy to use. Despite considerable design effort to improve usability further work is still required to make the heating controls more accessible to older users. If the buildings are to be both intelligent and sustainable then the control systems within domestic buildings need to be usable by the widest possible range of users.

Document Title	Change the mental model, change the behavior: Using interface design to promote appropriate energy consuming behavior in the home
Author(s), Publisher, Year	Revell, K., Stanton, N., Advances in Ergonomics in Design. Springer International Publishing, pp. 769-778, 2016
Country	UK

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	2	1	2	0	1	8	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

This paper considers how designs of typical home heating systems fall short in the way they communicate their function to householders, and offers a ‘mental models’ approach to design as an alternative. Revell and Stanton (Appl Ergon 45:363–378, 2014) identified that inappropriate mental models of heating controls influenced users’ behavior strategies to conserve energy. Domestic energy accounts for approximately 30 % of UK consumption, and 60 % of this is as a result of space heating (DECC 2013). Previous work by the authors’ drives the focus of design changes at both the device and system level. Guidelines by Manketelow and Jones (Applying cognitive psychology to user-interface design. Chichester: Wiley, 83–117, 1987,) and Norman (The Design of Everyday Things, Basic Books, New York, 2002) are used to understand how existing devices may unintentionally ‘say the wrong thing’ and improve functional communication in the redesign. Feedback from a pilot study using a simulator to demonstrate the resulting ‘control panel style’ of heating operation is also provided.

Document Title	Designing for comfort - Usability barriers in low carbon housing
Author(s), Publisher, Year	Stevenson, F., Carmona-Andreu, I., Hancock, M. Windsor, London: Network for Comfort and Energy Use in Buildings 2012
Country	UK

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	2	1	2	1	1	8	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☒	☐	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

Recent research into occupant behaviour in low carbon housing indicates that for the same type of house, energy and water use can vary by up to fourteen times between different households. This paper assesses the usability of „touchpoint‟ controls in two contrasting building performance evaluation case studies. It situates the discussion within socio-technical theories of habit, practice, and emergent properties in products which facilitate easy and rewarding learning and thus durability. Key findings reveal poor design features and occupant lack of understanding including specific aspects of centralised mechanical heating and ventilation systems and some windows. Lessons learnt and recommendations are highlighted for design guidance and policy consideration, including 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	Monitoring and control system for a smart family house controlled via programmable controller
Author(s), Publisher, Year	Sysala, T., Pospichal, M., Neumann, P., Carpathian Control Conference (ICCC), 2016 17th International. IEEE, pp. 706-710, 2016
Country	Czech Republic

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	2	1	2	1	1	9	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

This article is focused on the control of houses, flats or apartments with the use of currently popular smart wiring. A control system is based on the programmable logical controller (PLC). There are possibilities for control heating, lighting, controlled access, security and air condition system but at present as the unusual possibilities also are television, satellite, radio and other multimedia control via infra-red (IR) modules or IP technology. The last goal is to create and describe a user friendly web application for whole house monitoring and control via tablet, mobile phone or computer.

Document Title	Designing an information system for residential heating and ventilation to improve comfort and save energy
Author(s), Publisher, Year	Von Bomhard, T., Wörner, D., Wortmann, F. Advancing the Impact of Design Science: Moving from Theory to Practice, Vol. 8463 of the series Lecture Notes in Computer Science, pp 398-402, 2014
Country	Switzerland

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	0	1	2	1	1	8	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☐	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☐

Abstract/Summary

Large amounts of energy are wasted because heating systems run round-the-clock even though residents are out or occupy only a small part of their home. Major reasons for this behaviour are the non-intuitive heating controls and missing direct feedback about the heating activity or even energy consumption. In addition, bad ventilation behaviour, e.g. tilted windows, may lead to unhealthy room climate as well as significant heat losses. To address these problems, we analysed the requirements for a supporting information system. We present a first prototypical implementation of an individual-room heating and ventilation system which combines automation, an intuitive user interface and supporting feedback. This should empower residents to achieve energy-efficient heating and improved comfort.

Document Title	How People Actually Use Thermostats
Author(s), Publisher, Year	Meier, A., Aragon, C., Hurwitx, B., Mujumdar, D., Peffer, T., Perry, D. and Pritoni, M. ACEEE Summer Study on Energy Efficiency in Buildings. Pacific Grove, Calif.: American Council for an Energy Efficient Economy, 2010
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	2	1	2	1	1	9	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☐	☒	☒	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

Residential thermostats have been a key element in controlling heating and cooling systems for over sixty years. However, today's modern programmable thermostats (PTs) are complicated and difficult for users to understand, leading to errors in operation and wasted energy. Four separate tests of usability were conducted in preparation for a larger study. These tests included personal interviews, an on-line survey, photographing actual thermostat settings, and measurements of ability to accomplish four tasks related to effective use of a PT. The interviews revealed that many occupants used the PT as an on-off switch and most demonstrated little knowledge of how to operate it. The on-line survey found that 89% of the respondents rarely or never used the PT to set a weekday or weekend program. The photographic survey (in low income homes) found that only 30% of the PTs were actually programmed. In the usability test, we found that we could quantify the difference in usability of two PTs as measured in time to accomplish tasks. Users accomplished the tasks in consistently shorter times with the touchscreen unit than with buttons. None of these studies are representative of the entire population of users but, together, they illustrate the importance of improving user interfaces in PTs.

Document Title	Facilitating Energy Savings through Enhanced Usability of Thermostats
Author(s), Publisher, Year	Meier, A., Aragon, C., Peffer, T., Perry, D. and Pritoni, M., Proceedings of ECEEE Summer Study on Energy Efficiency, 2011
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	2	1	2	1	1	9	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☒	☐	☐	☐	☒	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

Residential thermostats play a key role in controlling heating and cooling systems. Occupants often find the controls of programmable thermostats confusing, sometimes leading to higher heating consumption than when the buildings are controlled manually. A high degree of usability is vital to a programmable thermostat's effectiveness because, unlike a more efficient heating system, occupants must engage in specific actions after installation to obtain energy savings. We developed a procedure for measuring the usability of thermostats and tested this methodology with 31 subjects on five thermostats. The procedure requires first identifying representative tasks associated with the device and then testing the subjects' ability to accomplish those tasks. The procedure was able to demonstrate the subjects' wide ability to accomplish tasks and the influence of a device's usability on success rates. A metric based on the time to accomplish the tasks and the fraction of subjects actually completing the tasks captured the key aspects of each thermostat's usability. The procedure was recently adopted by the Energy Star Program for its thermostat specification. The approach appears suitable for quantifying usability of controls in other products, such as heat pump water heaters and commercial lighting.

Document Title	Thermostat Interface and Usability: A Survey
Author(s), Publisher, Year	Meier, A., Aragon, C., Peffer, T. and Pritoni, M., Lawrence Berkeley National Laboratory, 2010
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	2	1	0	1	1	6	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☐	☒	☐	☐	☐	☐	☒

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

Thermostats have controlled heating and cooling systems in homes for over sixty years. The home thermostat translates occupants' temperature preferences into system operation and displays system conditions for occupants. In this position of an intermediary, the millions of residential thermostats control a huge amount of fuel and electricity consumption. In the United States, for example, residential thermostats control approximately 50% of household end energy use, which corresponds to about 11% of the nation's total energy use (Energy Information Administration (EIA), 2008). The technologies underlying modern thermostats are experiencing rapid development in response to emerging technologies, new demands, and declining costs. Energy-efficient homes require more careful balancing of comfort, energy consumption, and health. Coordinating these concerns requires new capabilities from thermostats, including scheduling, control of humidity and ventilation, and ability to respond to dynamic electricity prices. Future thermostats will increasingly join communication networks inside homes. For these reasons, the success of the thermostat as an interface between occupants and the home's environmental systems deserves investigation. The first step in our research was to collect information about residential thermostats. It soon became apparent that the terms and symbols were an important aspect, partly because manufacturers and researchers had not settled on consistent definitions. For this reason we began by compiling a dictionary of terms, symbols, features, and icons associated with thermostats. We then investigated the history of thermostats so as to better understand their origins and relationship to heating, cooling, and other environmental controls. With this foundation, we

focused on the previous research related to the technologies, effectiveness, and usability of thermostats. The review is organized to address questions that we believed were necessary to understand prior to beginning our own research. The goal of the literature review was not to answer the questions; rather, we sought to describe the type and range of research as well as key results. In this way, previous research and conclusions could inform our—and others'—research plans. In the process of collection and compilation, we believe that we have gained new insights which are presented in the context. Finally, we discuss how new and anticipated features will address some of the problems that have been observed as well as respond to new technical and economic imperatives. The report is mostly organized to reflect these steps. However, the lists of features and symbols were moved to appendixes because of their unusual formatting requirements.

Document Title	Field Evaluation of Programmable Thermostats
Author(s), Publisher, Year	Sachs, O., Tiefenbeck, V., Duvier, C., Qin, A., Cheney, K., Akers, C. and Roth, K., Fraunhofer Center for Sustainable Energy Systems CSE, 2012
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	2	1	0	1	1	7	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☐	☒	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

In this study, a team from Fraunhofer Center for Sustainable Energy Systems (CSE) evaluated a low-cost and scalable way to reduce heating energy consumption using the energy-saving features of programmable thermostats (i.e., automatic daytime and nighttime setbacks). Even though these functions are available in most programmable thermostats, previous research at the Lawrence Berkeley National Laboratory (Meier et al. 2011) suggests that poor usability features of this product class could prevent their effective use, leaving their energy savings potential unrealized. We hypothesized that home occupants with high usability thermostats are more likely to use them to save energy than people with a basic thermostat. To test this hypothesis, we collected field data from 77 apartments in an affordable housing complex in Revere, Massachusetts, and applied a novel data analysis approach to infer occupant interaction with thermostats from nonintrusive temperature and furnace on–off state sensors. Our analysis of the data collected from January through March 2012 focused on four types of occupant interactions with thermostats that can lead to energy savings: nighttime setbacks, daytime setbacks, vacation holds, and reprogramming. Surprisingly, usability did not influence the energy saving behaviors of study participants. We found no significant difference in temperature maintained in apartments that had either high or low usability thermostats. The minimum and mean nighttime and daytime setback temperature was 70°F–71°F in both thermostat conditions—considerably higher than the energy saving default of 62°F. We also found that the proportion of households that used thermostat-enabled energy-saving settings was very low. Only 3% of households used

default nighttime setbacks, regardless of the thermostat usability. No households with high usability thermostats and only 3% of households with low usability thermostats used daytime setbacks.

Although many households used the permanent hold feature, it was used to maintain a high temperature and not to keep it at a constant low level when the apartment was unoccupied. The few cases of reprogramming that we found seem incidental and do not involve any meaningful lowering of the temperature to save energy. Although our results are limited to the specific study sample that we used, they demonstrate that thermal comfort is much more important to people than energy efficiency. This is particularly striking for affordable housing residents who pay their own heating bills. It implies that only people with a strong motivation to save energy or money or both can benefit from energy saving features of programmable thermostats. The rest of the population is likely to use them to maintain a comfortable temperature in their houses. The results of this project support previous research by Nevius and Pigg (2000), showing that installation of programmable thermostats alone does not lead to reliable energy savings. Effective use of energy saving features enabled by programmable thermostats depends on many factors besides usability. Our study demonstrates that home occupants strive to achieve thermal comfort in their homes regardless of what thermostat model they have. Without motivation to save energy, high usability alone is not enough to facilitate the use of energy saving features in programmable thermostats.

Document Title	How installers select and explain domestic heating controls
Author(s), Publisher, Year	Sachs, O., Tiefenbeck, V., Duvier, C., Qin, A., Cheney, K., Akers, C. and Roth, K., Fraunhofer Center for Sustainable Energy Systems CSE, 2012
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	1	1	2	1	1	7	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☐	☐	☒	☒	☐	☐	☐

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary
Though central heating controls have the potential to reduce the energy consumed through domestic space heating, their installation does not guarantee savings. End users do not always understand their controls, or operate them in an energy-efficient way, but there is little appreciation of why this is. Drawing on an ethnographic study, this paper investigates how installers select and explain central heating controls. With reference to the concept of technology scripting, which suggests that the assumptions made about users during the design of devices can influence their eventual use, it shows how heating installers also draw on certain user scripts. Through these means the paper illuminates the significant role that heating installers play in influencing the control products fitted into homes, and how they might be used. Though their use of these scripts is understandable, it is not always conducive to ensuring that central heating systems are operated in the most energy-efficient way. It is suggested that industry and policy-makers might engage with how installers understand users and revise current guidelines to foster better communication between them.

Document Title	Occupants' behaviour: determinants and effects on residential heating consumption
Author(s), Publisher, Year	Guerra-Santin, O., Itard, L., Building Research and Information. Vol. 38, no. 3, pp. 318-338, 2010.
Country	Netherlands

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	1	1	2	1	1	8	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☒	☒	☐	☐	☐	☐	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

What are the key determinants and effects of occupants' behaviour on energy use for space heating? Statistical analyses were carried out on energy use and self-reported behaviour data from a household survey in the Netherlands. Results showed that the number of usage hours for the heating system have a stronger effect on energy consumption than temperature setting. Small correlations were found between energy use and the ventilation system, since most households barely use the ventilation system. The main building characteristic determining behaviour is the type of temperature control. Households with a programmable thermostat were more likely to keep the radiators turned on for more hours than households with a manual thermostat or manual valves on radiators. In relation to household characteristics, the presence of elderly persons in the household proved to be a determining factor in the use of the heating system and ventilation. As a result of wide variations in preferences and lifestyle, occupant behaviour has emerged as an important contributor to energy use in dwellings. The results indicate that the type of heating and ventilation system has an influence on occupant behaviour.

Document Title	Kids and thermostats: Understanding children's involvement with household energy systems
Author(s), Publisher, Year	Horn, M., Leong, Z., Greenberg, M. and Stevens, R., International Journal of Child-Computer Interaction. Vol. 3-4 (2015), pp14-22, 2015.
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	1	1	2	1	0	7	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☐	☐	☒	☐	☐	☐	☐

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

We present a study of family practices around the use of thermostats to control residential heating and cooling systems. Our analysis is focused on the role of children and adolescents and factors that affect their participation in the management of household energy consumption. As ''smart'' technologies become more common in homes, our goal is to understand how we might involve parents and children together in learning about issues of environmental sustainability. Based on interviews with families, thermostat installers, and a thermostat designer, our findings suggest that thermostats tend to be adult-only devices. Children rarely (and sometimes never) adjust the temperature or program settings, and there appears to be limited opportunity for youth to become more involved as they get older. We encountered variation in family practices along dimensions such as age, economic situation, environmental attitudes, and type of heating and cooling equipment. Despite this variation, however, there was a pervasive lack of interest and awareness on the part of children, even among those who reported adjusting thermostats on occasion. Based on these findings, we discuss how this situation might be changed through the design of new technologies to raise awareness while creating more active and distributed participation.

Document Title	Facilitating energy savings with programmable thermostats: evaluation and guidelines for the thermostat user interface.
Author(s), Publisher, Year	Peffer, T., Perry, D., Pritoni, M., Aragon, C. and Meier, A., Ergonomics, vol. 56 (3), pp. 463-479, 2012
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	2	1	1	2	1	1	8	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☐	☐	☐	☒	☐	☒	☐

Discussed	**Energy Saving** ☒	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

Thermostats control heating and cooling in homes – representing a major part of domestic energy use – yet, poor ergonomics of these devices has thwarted efforts to reduce energy consumption. Theoretically, programmable thermostats can reduce energy by 5–15%, but in practice little to no savings compared to manual thermostats are found. Several studies have found that programmable thermostats are not installed properly, are generally misunderstood and have poor usability. After conducting a usability study of programmable thermostats, we reviewed several guidelines from ergonomics, general device usability, computer–human interfaces and building control sources. We analysed the characteristics of thermostats that enabled or hindered successfully completing tasks and in a timely manner. Subjects had higher success rates with thermostat displays with positive examples of guidelines, such as visibility of possible actions, consistency and standards, and feedback. We suggested other guidelines that seemed missing, such as navigation cues, clear hierarchy and simple decision paths.

Document Title	Energy efficiency and the misuse of programmable thermostats: The effectiveness of crowdsourcing for understanding household behavior
Author(s), Publisher, Year	Pritoni, M., Meier, A.K., Aragon, C., Perry, D. and Peffer, T., Energy Research & Social Science, vol. 8 (2015), pp. 190-197, 2015.
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	1	1	2	1	1	7	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☐	☒	☐	☐	☒	☐	☐

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

Programmable thermostats are generally sold as energy-saving devices controlling heating and cooling systems, but can lead to energy waste when not operated as designed by the manufacturers. We utilized Amazon Mechanical Turk, an online crowdsourcing service, to investigate thermostat settings and behavior in households. We posted a survey and paid respondents to upload pictures of their thermostats to verify self-reported data. About 40% of programmable thermostat owners did not use programming features and 33% had programming features overridden. Respondents demonstrated numerous misconceptions about how thermostats control home energy use. Moreover, we found that 57% of households were occupied nearly all the time, limiting the potential energy savings. The study revealed flaws in self reported data, when collected solely from traditional surveys, which raises concerns about the validity of current thermostat-related research using such data. “Ground truth” temperature data could now be available in homes with Internet-connected thermostats. Online crowdsourcing platforms emerge as valuable tools for collecting information that would be difficult or expensive to obtain through other means. Advantages over traditional surveys include low-cost, rapid design–implementation–result cycle, access to diverse population, use of multimedia. Crowdsourcing is more effective than alternative online tools due to easier recruitment process and respondents’ reputation system.

Document Title	Usability of residential thermostats: Preliminary investigations
Author(s), Publisher, Year	Meier, A., Aragon, C., Peffer, T., Perry, D., Pritoni, M., Building and Environment, vol. 46 (2011), pp. 1891-1898, 2011
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	1	1	2	1	1	7	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☐	☐	☒	☒	☐	☐	☐

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☐

Abstract/Summary

Residential thermostats control 9% of the total energy use in the United States and similar amounts in most developed countries; however, the details of how people use them have been largely ignored. Five parallel investigations related to the usability of residential thermostats were undertaken. No single investigation was representative of the whole population, but each gave insights into different groups or usage patterns. Personal interviews revealed widespread misunderstanding of thermostat operation. The on-line surveys found that most thermostats were selected by previous residents, landlords, or other agents. The majority of occupants operated thermostats manually, rather than relying on their programmable features and almost 90% of respondents reported that they rarely or never adjusted the thermostat to set a weekend or weekday program. Photographs of thermostats were collected in one on-line survey, which revealed that about 20% of the thermostats displayed the wrong time and that about 50% of the respondents set their programmable thermostats on “long term hold” (or its equivalent). Low-income families were visited and their thermostats photographed. Even though 85% of the respondents declared that they use programming features to automatically raise or lower the temperature, the photos indicated that 45% were in hold. Laboratory tests were undertaken to measure usability of thermostats. A measurement protocol was developed and a metric was created that could quantitatively distinguish usability among five thermostats. This metric could be used to establish minimum levels of usability in programmable thermostats and other energy-using devices with complex controls.

Document Title	How people use thermostats in homes: A review
Author(s), Publisher, Year	Peffer, T., Pritoni, M., Meier, A., Aragon, C. and Perry, D., Building and Environment, 46(12), pp.2529-2541, 2011
Country	US

Quality Assessment	**Reporting Quality Score**			**Research Quality Score**			**Total Score**	**Pass/ Fail**
	Q1(2pts)	**Q2**(2pts)	**Q3**(1pts)	**Q1**(2pts)	**Q2**(1pts)	**Q3**(1pts)	(9pts)	
	1	1	1	2	1	1	7	Pass

Quantitative Methods			**Qualitative Methods**				**Review**
Measurement	Modelling	Survey	Interview	Observation	Questionnaire	Other	Lit. Review
☐	☐	☐	☐	☐	☐	☒	☒

Discussed	**Energy Saving** ☐	**Cost-effectiveness** ☐	**Usability** ☒

Abstract/Summary

Residential thermostats control a substantial portion of both fuel and electrical energy- 9% of the total energy consumption in the U.S. Consumers install programmable thermostats to save energy, yet numerous recent studies found that homes with programmable thermostats can use more energy than those controlled manually depending on how-or if-they are used. At the same time, thermostats are undergoing a dramatic increase in capability and features, including control of ventilation, responding to electricity price signals, and interacting with a home area network. These issues warrant a review of the current state of thermostats, evaluating their effectiveness in providing thermal comfort and energy savings, and identifying areas for further improvement or research.

This review covers the evolution in technologies of residential thermostats; we found few standards and many features. We discuss studies of how people currently use thermostats, finding that nearly half do not use the programming features. The review covers the complications associated with using a thermostat. Finally, we suggest research needed to design-and especially test with users-thermostats that can provide more comfortable and economical indoor environments.

APPENDIX B

Document	Focus	Country	Geolocation	Generic Domestic Heating Controls	Hot Water Controls	Weather Compensation (outdoor reset)	Time Proportional Integral (TPI) controls	Zonal control	Programmable TRVs	Manual TRVs	Learning algorithms	Optimisation	Modulating room (or load compensating) thermostats	Communication protocols	Remote control (such as via an App)	Occupancy sensors	Programmable thermostats	On/off switches	Boiler thermostats	Central timers	Room thermostats	Geofencing	Scoring
Ahern, C. and Norton, B. (2015)	Energy Savings; Heating Systems	EU		✓					✓										✓		✓		8
Blasing, T.J. and Schroeder, D. (2013)	Zero energy houses, energy and cost savings, thermostat adjustment	US															✓		✓		✓		9
Brounen, D., Kok, N. and Quigley, J. (2013)	Energy efficiency, literacy, energy consumption and use, investment decisions	Nether-lands															✓		✓		✓		8
Combe, N. and Harrison, D. (2014)	Usability, guidelines, design, heating controls	UK		✓																			6

Document	Focus	Country	Geolocation	Generic Domestic Heating Controls	Hot Water Controls	Weather Compensation (outdoor reset)	Time Proportional Integral (TPI) controls	Zonal control	Programmable TRVs	Manual TRVs	Learning algorithms	Optimisation	Modulating room (or load compensating) thermostats	Communication protocols	Remote control (such as via an App)	Occupancy sensors	Programmable thermostats	On/off switches	Boiler thermostats	Central timers	Room thermostats	Geofencing	Scoring
Daken, A. A. and Meier, A. K. (2016)	Thermostats; energy savings	US		✓													✓						6
Dentz, J. and Ansanelli, E. (2015)	Thermostatic radiator valves - use installation and energy savings	US							✓	✓													8
Dentz, J., Henderson, H. and Varshney, K., (2014)	Multi-family building, boiler controls, trvs, set points disregarded, energy and cost savings	US				✓			✓	✓									✓				6

Document	Focus	Country	Geolocation	Generic Domestic Heating Controls	Hot Water Controls	Weather Compensation (outdoor reset)	Time Proportional Integral (TPI) controls	Zonal control	Programmable TRVs	Manual TRVs	Learning algorithms	Optimisation	Modulating room (or load compensating) thermostats	Communication protocols	Remote control (such as via an App)	Occupancy sensors	Programmable thermostats	On/off switches	Boiler thermostats	Central timers	Room thermostats	Geofencing	Scoring
Drgona, J., Klauco, M. and Kvasnica, M. (2015)	Model predictive control, economics, optimal setpoints	Slovakia										✓						✓	✓		✓		6
Guerra-Santin, O. and Itard, L. (2010)	Occupant behaviour energy use, temperature control	Nether-lands		✓						✓							✓						8
Gupta, S.K. et al., (2016)	Energy efficient operation of a building; mobile application to provide thermal preference feedback	USA		✓							✓				✓	✓							8

Document	Focus	Country	Geolocation	Generic Domestic Heating Controls	Hot Water Controls	Weather Compensation (outdoor reset)	Time Proportional Integral (TPI) controls	Zonal control	Programmable TRVs	Manual TRVs	Learning algorithms	Optimisation	Modulating room (or load compensating) thermostats	Communication protocols	Remote control (such as via an App)	Occupancy sensors	Programmable thermostats	On/off switches	Boiler thermostats	Central timers	Room thermostats	Geofencing	Scoring
Harding, M. and Lamarche, C. (2016)	Load shifting, time-of-use and energy saving	US															✓						6
Hong, D. and Whitehouse, K. (2013)	Energy savings, automated control and occupancy prediction, minimum effort for users	US, UK, Canada	✓	✓							✓	✓											6
Horn, M., Leong, Z., Greenberg, M. and Stevens, R. (2015)	Usability of thermostats, family practices around the use of thermostats	US																	✓		✓		7

Document	Focus	Country	Geolocation	Generic Domestic Heating Controls	Hot Water Controls	Weather Compensation (outdoor reset)	Time Proportional Integral (TPI) controls	Zonal control	Programmable TRVs	Manual TRVs	Learning algorithms	Optimisation	Modulating room (or load compensating) thermostats	Communication protocols	Remote control (such as via an App)	Occupancy sensors	Programmable thermostats	On/off switches	Boiler thermostats	Central timers	Room thermostats	Geofencing	Scoring
Ivanov, C. et al., (2013)	Load shifting, demand, energy saving	Minne-sota, US															✓						6
Iyengar, S., Kalra, S., Ghosh, A., Irwin, D., Shenoy, P. and Marlin, B. (2015)	HVAC, smart meters, energy bill savings, occupancy patterns	Massuc-husetts, US															✓						7
Kleiminger, W., Matterm, F. and Santini, S. (2014)	Energy savings, smart heating control applications, modelling	Switzer-land, Germany									✓						✓						8

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Lindelof, D. et al., (2015)	Model predictive heating controller, add-on, energy savings monitored, energy signature	Switzer-land		✓							✓												6
Lu, J. et al., (2010)	Smart thermostats; energy savings	US														✓	✓						6
Meier, A. et al., (2010a)	Testing usability of programmable thermostats, energy savings	US															✓						9

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Meier, A. et al., (2011a)	Procedure for measuring the usability of thermostats, heating and cooling systems, energy savings	US															✓						9
Meier, A. et al., (2011b)	Usability of programmable thermostats, survey	US		✓													✓						7
Meier, A. et al., (2010b)	Control of heating and cooling systems, review, usability	US															✓		✓		✓		6

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Meyers, R. J., Williams, E. D. and Matthews, H. S. (2010)	Scoping study realising energy savings through better, management of use of different controls	US		✓				✓							✓	✓	✓						8
Monetti, V., Fabrizo, E. and Filippi, M. (2015)	Thermostat radiators; energy savings	Italy		✓					✓														6
Peffer, T. et al., (2011)	Usability of programmable thermostats, review	US															✓						7

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Peffer, T. et al., (2012)	Testing usability of programmable thermostats usability, energy savings	US		✓													✓						8
Perez, H.E. and Burger, E. (2014)	Smart cloud-enabled thermostat, electric home heating system, modelling	US		✓		✓					✓	✓			✓		✓	✓			✓		6
Pritoni, M. et al., (2015)	Programmable thermostats; understanding household behaviour	US		✓													✓						7

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Revell, K. M. A. and Stanton, N. (2016)	Home heating systems, mental models, control design, usability.	UK		✓																			8
Rogers, A. et al. (2011)	Adaptively controlling home heating systems, timing of heating use, carbon and cost savings	UK	✓	✓		✓					✓	✓			✓		✓			✓			6
Sachs, O. et al., (2012)	Low-cost, scalable way to reduce heating energy consumption, poor usability, programmable thermostats.	US															✓		✓				9

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Stevenson, F., Carmona-Andreu, I. & Hancock, M., (2012)	Touchpoint controls, low carbon houses, user centred control design HVAC, usability	UK		✓																			8
Suter, J. F. and Shammin, M. (2013)	Programmable thermostats; energy conservation	US																					6
Sysala, T., Pospichal, M. & P., N. (2016)	Control, smart wiring, programmable logic controller, user-friendly, whole house monitoring	Czech Republic		✓											✓								9

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Urban, B. and Gomez, C. (2013)	Thermostat set point models, user behaviour model, energy consumption reduction.	US							✓	✓													6
Von Bomhard, T., Wörne, D. & F., W. (2014)	Energy waste, non-intuitive heating controls, supporting information systems.	Switzer-land		✓				✓															8
Wade, F., Shipworth, M. & Hitchings, R. (2016)	Installation, energy consumption reduction, installer scripts, policy makers	UK		✓																			7

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Xu, X., Culligan, P. J. and Taylor, J. E. (2014)	Energy saving alignment strategy (ESAS), thermostat preferences & indoor temperature, multi-family houses	US															✓		✓		✓		7

APPENDIX C

Document	Country/Focus	QA Scoring
Miklucak, T, Kapjor, A., Janota, A., Biro, O., (2012), *Exploring possibilities of predictive self-programming thermostats for energy savings*, Proceedings of 9th International Conference, ELEKTRO 2012	Slovakia/ Predictive self-prigramming thermostats, occupancy prediction, energy savings, simulation.	3
Yang, R., Newman, M. W (2012), *Living with an intelligent thermostat: Advanced control for heating and cooling systems*, UbiComp'12 - Proceedings of the 2012 ACM Conference on Ubiquitous Computing	US/ Intelligent systems, the Nest, machine learning, sensing and networking technology, mobile apps, energy savings	5
Vallati, A., Grignaffini, S., Romagna, M., Mauri, L. (2016), *Effects of different building automation systems on the energy consumption for three thermal insulation values of the building envelope*, EEEIC 2016 - International Conference on Environment and Electrical Engineerin	Italy/ Energy savings, thermal automation, control systems	3
BuildingAmerica (2014), Hydronic Systems: *Designing for Setback Operation*, Building America Program	US/ Heating loads and thermostat setback, hydronic system design, control design and choices	1
Combe, N., Harrison D. J., Way C.(2011), *Enabling sustainable user interaction with domestic heating controls*, Proceedings of the Research Students' Conference on "Buildings Don't Use Energy, People Do?" – Domestic Energy Use and CO2 Emissions in Existing Dwellings, 28 June 2011, Bath, UK	UK/ Energy savings, usable controls, inclusive domestic heating controls	5
Leblanc, C., Ghribi, M., Bouslimani A. (2011), *Remote Control and Energy management of a Residential Electric Heating*, International Journal on Recent Trends in Engineering and Technology	Canada/ Control and management electric heating platform, reduce energy consumption, internet, cellphone or local control.	3

Document	**Country/Focus**	**QA Scoring**
Baraniuk, C. (2014), Google's home invasion, New Scientist	US/ Smart thermostat; energy savings	1
Jassar S., Liao Z.Y. (2011), *Improve the control of residential heating systems*, Applied Mechanics and Materials	Canada	3
Sookoor, T., Whitehouse, K. (2013), *RoomZoner: Occupancy-based Room-Level Zoning of a Centralized HVAC System ACM*/IEEE International Conference on Cyber-Physical Systems, 2013	US/HVAC and CPs systems	5
Koehler, C, Ziebart, D.B., Mankoff J., Dey, (2013), TherML: Occupancy Prediction for Thermostat Control A.K., 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing, UbiComp'13,	US/mixed initiative systems	5