



UK Government

# Home Energy Monitoring Studies - Literature Review

Homes for Net Zero



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# Executive Summary

This literature review, carried out at the start for the Homes for Net Zero (HfNZ) project, aims to set out lessons learned from previous energy intervention monitoring studies and to support planning to get the most out of the project.

Few studies of the scale of HfNZ have been carried out in the past. Most research has been undertaken as part of general policy evaluation with limited resource and few purpose designed studies have been undertaken. In this review we describe major studies in the UK since 2000 and additionally gather examples from other countries and smaller scale studies. We discuss both projects which simply observed energy use and temperatures in the home, and those that assessed energy efficiency interventions, as the learning from both is relevant for HfNZ. We describe the design of these studies, and the consequent monitoring strategies. We introduce several options to calculate counterfactual energy use in order to assess the energy savings from an intervention.

HfNZ provides an opportunity to design an intervention study to avoid the pitfalls of previous projects. Key challenges faced by historical studies have been:

- Insufficient sample size to provide statistically significant evidence of energy saving
- Limited monitoring instrumentation due to cost
- Poor reliability of data. This includes lack of data about which interventions occurred at what times, and poor collection of contextual data
- Insufficient monitoring periods, in particular if there is no pre-intervention monitoring

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# 1. Introduction

This Literature Review forms the output from Work Package 1 of the Homes for Net Zero project for the Department of Energy Security and Net Zero (DESNZ). The work was led by Clare Hanmer of UCL on behalf of the EDOL (Energy Demand Observatory and Laboratory) team at UCL and Oxford University. Substantial input was also received from the Energy Systems Catapult team working on HfNZ.

## 1.1 Homes for Net Zero

Homes for Net Zero (HfNZ) is a research project to improve the evidence bases on the options for homeowners to transition to a home that is compatible with Net Zero policy aims. The project will focus on monitoring 1,000 owner-occupied, gas-heated homes, predominantly with solid walls. Phase 1 of the project will deliver 140 physical interventions, 100 behavioural interventions and maintain a counterfactual group of 760 homes. The physical interventions will include heating system improvements and upgrades, professional draught-proofing and replacing/upgrading old or poorly installed loft insulation.

## 1.2 Purpose of Literature Review

The focus of this review of existing academic and grey literature is on the following questions (from DESNZ ITT):

- What methods have previous household energy monitoring studies used and what were the lessons learnt?
- What monitoring methods have been used in previous household energy monitoring studies and what were the lessons learnt?

This literature review is intended to inform the monitoring (WP3), data collection (WP6) and data analysis (WP7) work packages, by exploring methods used and lessons learned in previous projects.

## 1.3 Overview of document

This literature review starts by describing historical studies which monitored energy use in homes and assessed the impact of energy efficiency interventions. We draw on information from these historical studies to develop the next two sections. Section 3 discusses how the studies were designed to answer specific research questions and

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Section 4 provides more detail about the monitoring equipment used to gather quantitative data. Each section concludes with lessons learnt from previous studies to inform Homes for Net Zero Phase 1. Section 5 provides a short overview of general principles for providing energy efficiency information and advice for households and an introduction to the roadmap concept, which will be developed in future project deliverables.

## 1.4 Context: British solid wall homes with gas heating

The scope of HfNZ is privately owned, gas-heated homes, predominantly with solid walls, in England and Wales. It is likely that the majority of these will have been built before 1919 (when cavity wall construction became common).

The English Housing Survey (DLUHC, 2022) shows that 65% of English homes are privately owned and 23% of these were built before 1919. The 2021 census reported that around 74% of households use mains gas central heating as their only heating system (Stewart, 2023) and 89% of English homes have a boiler heating system, with the most common type being a condensing-combination boiler (59.4% in 2021) (DLUHC, 2022) .

The decision-making process for the installation of energy efficiency measures in private homes is different to that for rented properties. The “landlord-tenant problem” (that the landlord is generally responsible for energy efficiency investment while it is the bill-paying tenant who gains the benefit (Petrov and Ryan, 2021)) may disincentivise investment in rented property. On the other hand, social landlords may have efficiency and cost benefits from retrofits at scale, which are not available to individual homeowners. It should be noted that many large-scale retrofit trials have been carried out in social-rented rather than privately owned housing. Privately owned properties tend to have lower energy efficiency ratings than social rented across most property types (ONS, 2023).

## 1.5 Scope

This literature review for Phase 1 of Homes for Net Zero concentrates on the simple interventions to reduce heating energy use to be studied in this phase of the project, i.e.:

- Heating system improvements
  - hydraulic balancing
  - heat distribution system flushing
  - lowering flow temperatures
- Heating system upgrades

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- upgraded emitters, providing sufficient capacity for low temperature operation
  - Energy efficiency improvements
    - Professional draught proofing
    - Replacing/upgrading old or poorly installed loft insulation

With the exception of upgraded emitters (in preparation for the installation of a heat pump or other low temperature heat source), these are all measures that can be carried out independently, in any order, and each measure will reduce energy use in its own right or in combination with others. The technical discussion in this literature review is therefore framed around individual measures to save energy rather than a journey to net zero.

The academic literature on monitoring energy use in the home and assessing the impact of energy efficiency measures dates back to the 1990s and earlier. This review considers documents published after 2000, with a particular focus on recent studies which take advantage of updated technologies (especially smart meters and streaming / Internet of Things technologies) as these are considered most relevant for the work of HfNZ. No literature which is based entirely on simulations or other model-based studies is included since empirical study of actual homes is fundamental to HfNZ.

The focus is on measurements and trials in the UK, but literature from other countries with temperate climates and similar housing and heating configurations is also referenced where it appears particularly relevant. Both observational studies (which simply monitor energy use and conditions in homes) and intervention studies (which investigate the impact of an energy efficiency measure or measures) are included.

The scope of the literature review covers both physics/engineering and social science perspectives (considering building and occupants as socio-technical system). It touches on occupant survey design and how quantitative and qualitative data from surveys can be linked to smart meter and other energy data. It is not limited to just the scope of property and intervention types that HfNZ will tackle. There is a general body of literature on study design for intervention studies much of which has been driven by medical research which this field can learn many important lessons (see for example CEBM (2023)). However, what is often considered the gold standard of study design, the randomized control trial is not applicable in energy and building research. No attempt has been made to review this method in this document.

For general information about study design relative to energy and building research the reader is recommended to read the feasibility reports produced for the Longitudinal UK Energy Survey (Cooper et al., 2014) .

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## 2. Monitoring and intervention studies

This section of the report introduces the historical energy monitoring and retrofit assessment studies which will be referenced in later sections where more details are given of trial design and monitoring equipment.

### 2.1 Historical studies

#### 2.1.1 Observation studies

This subsection outlines studies that did not include measurements both before and after interventions and were carried out in the last 20 years. The studies have a range of objectives and scales, which are reflected in the different monitoring configurations (see section 4), but all monitored internal temperature, generally in combination with relative humidity and external temperature. This section introduces the background of the projects. More detail on research design and monitoring approaches is provided in subsequent sections.

The ‘Energy Follow-Up Survey’ (EFUS) is large-scale, government funded energy monitoring and survey of a sub-sample of English Housing Survey (DLUHC, 2022) homes. EFUS 2017 (BRE, 2021) involved monitoring temperature and energy use in more than 2,500 homes representative of the overall building stock, including temperature monitoring in several rooms.

The only other observational, national representative longitudinal study in the UK is the Smart Energy Research Lab (SERL) Observatory which monitors half-hourly electricity and gas, plus modelled external temperature in 13,000 GB homes. This has shown the impact different EPC ratings as well as COVID Lockdowns and the Cost-of-Living crisis have on metered energy use (Zapata-Webborn et al., 2023b, 2023a). SERL is being expanded to include other monitoring such as internal temperature under a new project, the Energy Demand Observatory and Laboratory (EDOL).

Other significant academic studies have included Stamford Brook (comparing actual energy used in four new build houses with design intentions (Wingfield et al., 2008)) and the CaRB project. The CaRB-HES survey was primarily intended to check energy modelling assumptions against conditions in actual homes, but data collected (for temperature in the living rooms of 275 homes) has also been drawn on to examine patterns of internal temperatures in winter (Huebner et al., 2015, 2013), and summertime overheating (Beizaee et al., 2013). Another project under the CaRB banner revisited 15 homes which had originally been monitored in 1990 to establish changes in energy use and occupant behaviour (Summerfield et al., 2007). In 2010 the 4M study logged

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temperatures in living room and main bedroom of 469 homes (Kane et al., 2015; Lomas and Kane, 2013).

Relevant studies in Europe include Galvin's (2013) account of monitoring of the space heating consumption of 60 apartments in Germany, investigating differences in heating behaviour and energy consumption, and Csoknyai et al.'s (2019) discussion of a project monitoring electrically heated homes at 3 locations in France and Spain. Pallonetto et al. (2022) describe very detailed monitoring of a single house in Ireland, representative of 40% of the Irish building stock.

Smaller scale research studies which combined quantitative and qualitative monitoring include Foulds et al. (2013) monitoring 16 new homes built to Passivhaus standards, and Tweed et al. (2014) examining thermal comfort in five homes. These detailed studies provide rich insights but also demonstrate the substantial resource needed for ethnographic approaches to qualitative data gathering.

Several studies have focused on summer temperatures inside the home, which may be a concern for new homes or those recently retrofitted, since improved insulation and airtightness may lead to summer overheating. Vellei et al. (2017) monitored summer temperatures in 55 social homes in Exeter and Morgan et al. (2017) provide information on 26 homes in Scotland.

The literature on thermal testing of unoccupied buildings is not included in this review, except to note that the SMETER trial evaluation (Loughborough University et al., 2020) used a variety of techniques based on co-heating tests to characterise the thermal performance of unoccupied social homes ahead of the trial of SMETER techniques (see below) once the tenants moved in.

An important source for domestic energy efficiency is NEED (DESNZ, 2023), a government database drawing together data from various sources about GB domestic energy use. This includes the impact of energy efficiency measures supported by ECO and government funding schemes such as Green Homes Grant, Home Upgrade Grant and Social Housing Decarbonisation Fund. Various datasets, including energy consumption data from suppliers, are linked together but internal temperature data is not included.

### 2.1.2 Assessing interventions

This subsection introduces studies which were not simply monitoring the home but also assessing the impact of some kind of energy efficiency intervention, generally combining physical measurements to assess energy savings (and/or improvements in thermal comfort) and a social science investigation of the residents' reaction to the intervention.

The Warm Front study in 2002 investigated the impact of a government-funded energy efficiency refurbishment scheme for low-income private sector dwellings. Energy consumption data was collected from 1255 pre-intervention, 1162 post-intervention and

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242 both pre- and post-intervention homes. Thermal comfort indicators were investigated in 2519 homes (Hong et al., 2009, 2006; Oreszczyn et al., 2006). The study design incorporated both longitudinal and cross-sectional analysis. The results showed that the programme was effective in increasing the mean indoor temperature and led to an increase in the proportion of households feeling thermally comfortable. The energy used for heating in many of the homes increased following the interventions, a result that was attributed to ‘comfort taking’ a concept which is discussed in Section 3.3 below.

Retrofit For the Future, which ran from 2009-2011, funded demonstrations of a variety of deep retrofit packages in social housing, testing innovative low or zero carbon technologies, retrofit methods and processes and monitoring equipment. 119 homes participated in a diverse range of retrofit projects, with a variety of monitoring approaches (Technology Strategy Board, 2013; Topouzi, 2016). Gupta et al. (2015) discuss reasons why only 3 out of 45 projects for which post retrofit emissions data was available met the expected CO<sub>2</sub> target in reality “despite generous funding and professional expertise”. These include the points that assessment of energy consumption before retrofit was not a defined project requirement and that, because of the fragmented nature of the project, the sharing of learning between the different teams involved was not optimal.

A suite of research projects under TEDDINET (Transforming Energy Demand Through Digital Innovation) focused on smart technology:

- IDEAL carried out very detailed monitoring of 255 Scottish homes over 23 months, combined with provision of energy efficiency advice (Pullinger et al., 2021) in combination with surveys of residents. The aim was to evaluate energy savings that might arise from providing digital energy feedback to householders over and above the information provided by a standard smart meter In-Home Display. The detailed dataset from the study has been published and proved valuable for researchers (e.g. Crawley et al. (2022)). While survey evidence showed feedback increased awareness of ways to minimise energy use, the sample size proved too small to obtain statistically significant results on the impact on energy use of the feedback.
- DEFACTO investigated performance of zonal heating controllers in 68 owner-occupied homes (Lomas et al., 2022). Participants were split between control and intervention groups and the impact of controllers on heating energy demand was investigated.
- REFIT analysed heating behaviour and reaction to smart heating controllers in 20 homes (Kane et al., 2017)
- APTAtSCHE investigated older people’s attitudes to smart energy technology (Barnicoat and Danson, 2015).
- LEEDR (Low effort energy demand reduction) was a 4 year study of energy consumption and design interventions in 20 family homes (Buswell et al., 2017).

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The Green Homes Grant (GHG) Smart Meter Enabled Thermal Efficiency Rating (SMETER) project (DESNZ, 2025) collected smart meter data for homes which received interventions under the Green Homes Grant schemes. Meter data from before and after intervention for around 2000 homes in the GHG Voucher scheme was analysed using two SMETER energy signature methods and the change in ‘in-use HTC’ (see section 3.1) assessed for different interventions. Around 100 homes in the GHG-LAD scheme also had internal temperature measurements, but challenges with contractual arrangements meant that a full data set for before and after intervention was not available for most of these homes.

Other recent projects in the UK have been led by DNOs under Ofgem funding arrangements. These have involved more complex retrofits than those in Phase 1 of HfNZ. For example two projects investigated heat pumps: FREEDOM (WPD) installed hybrid heat pumps in range of social and private housing in Wales (Freedom Project, 2018) and CLNR (Northern Powergrid) included a social-science investigations of sets of heat pump installations in social housing in NE England (Judson et al., 2015).

The Energy Systems Catapult monitored 740 UK homes of a range of types following (but not before) the installation of heat pumps, aiming to assess performance of the heat pumps. The monitoring included multiple heat and electricity meters (Energy Systems Catapult, 2023).

## 2.2 What does this mean for HfNZ?

Large scale trials investigating the impact of energy efficiency interventions are infrequent, since the retrofit project opportunities and resources required to monitor and analyse them are seldom available to researchers. HfNZ offers an opportunity to trial retrofit measures in several hundred homes. The experience of IDEAL suggests that where interventions are expected to lead to relatively small changes in energy demand, it may be challenging to provide statistically significant evidence of the impact. Warm Front experience points to the importance of considering ‘comfort taking’ as interventions enable residents to heat their homes to higher temperatures (see section 4.3).

It is very important to be clear about the purpose of a trial. The wide variety of approaches taken by historical trials reflect the variety of research purposes as well as practical constraints in obtaining data. In the next section we discuss intervention study design.

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## 3. Study design and data analysis

This section discusses the design of studies to investigate energy use and temperature patterns in homes and to assess the impact of energy efficiency measures. The primary HfNZ research questions that require quantitative data analysis are:

- What are the energy savings of individual measures?
- What are the energy savings of different packages of measures?
- What is the current distribution of energy consumption in homes within the monitored sample?
- How does the energy consumption of the trial homes compare with a representative sample of homes?

### 3.1 Assessing changes in energy demand

"Field trials to identify the energy savings from interventions in homes are notoriously challenging, and especially when these relate to space heating."(Lomas et al., 2022). The challenges faced by researchers aiming to assess the impact of measures to reduce gas consumption for heating include:

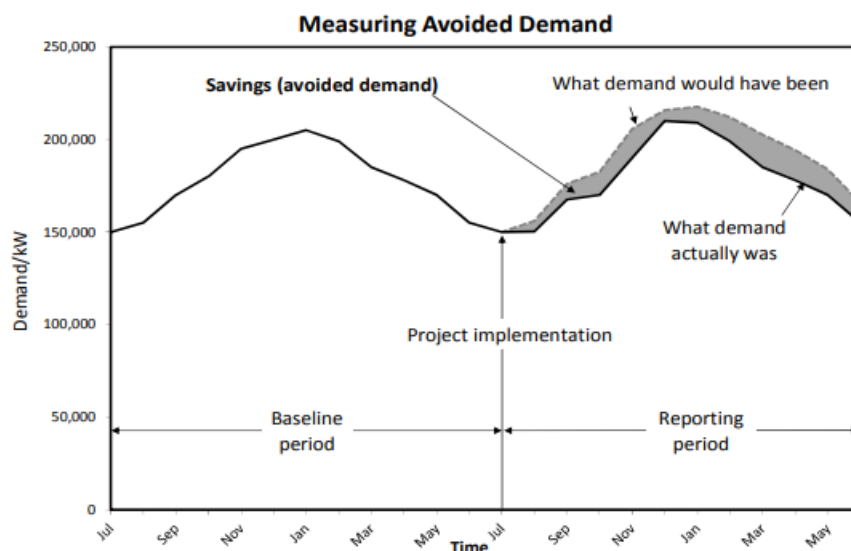
- Usually only a single gas meter for all gas used in the home is available. This means heating energy use has to be disaggregated from other gas uses (chiefly hot water and cooking).
- There are many possible behavioural and physical reasons for changes in energy use, leading to significant variation across groups of similar homes (and in the same house over time) (Fell and King, 2012). Occupancy patterns and temperature preferences of the household may change over time and lead to different heating requirements. Factors such as the presence of smokers and pets can lead to changes in window and door opening, which impacts heating demand.
- Individual measures may only lead to small savings in energy for heating, which may be difficult to detect amid the 'noise' of variation in daily energy use. The measures for Phase 1 of HfNZ are not anticipated to lead to large reductions in energy demand, so may not be detected if the sample size is small (see discussion of effect size below).

In order to assess the energy savings of a measure, a method to calculate the energy that would have been used if the intervention had not happened is required. The control group of HfNZ homes which do not receive interventions will provide a counterfactual which

allows the change in energy demand for homes receiving interventions to be compared with that for similar homes which do not receive energy efficiency measures. Taking a 'difference-in-difference' approach enables changes in energy demand which affect all homes (e.g. price rises) to be differentiated from changes in demand due to measures (Chindarkar and Goyal, 2023; Lomas et al., 2022).

An alternative approach to counterfactuals is to use a model to calculate the energy that would have been used if the intervention had not happened. The diagram below from EEVS (2014) illustrates this point. The dotted counterfactual line is the predicted demand if no intervention had happened, with the shaded area representing the cumulative energy savings over a year.

**Figure 1: Illustration of avoided energy (reproduced from Crown copyright report (EEVS, 2014))**



In this section, we introduce two alternative methods for counterfactual simulation which have been used in recent projects.

### 3.1.1 Energy signature techniques to provide counterfactual energy demand

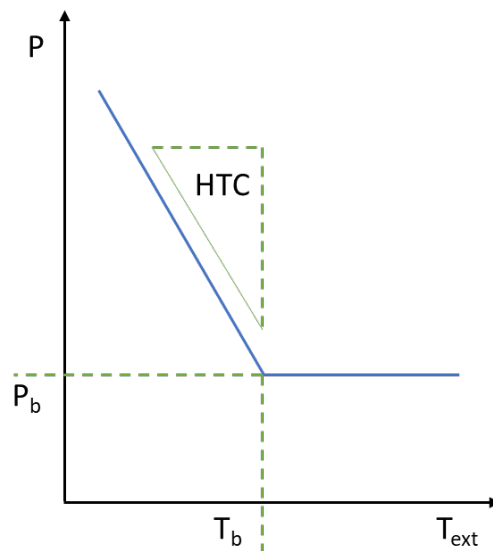
An energy signature is a plot of power to the home against external temperature. Energy signature techniques allow the energy used in the home to be predicted if the external temperature is known.

The Heating Degree Days (HDDs) technique is a simple signature method to adjust energy demand data for changes in external temperature. This involves calculation of how far the external ambient temperature is below a reference level (generally 15.5°C) for how many days (Day and others, 2006). The expected energy use based on data from before the intervention can be adjusted for recorded external temperature and compared with the actual (degree day adjusted) energy demand (Lomas et al., 2022).

The Power Temperature Gradient (PTG) is a plot of energy demand against external temperature (see fig 2). The balance temperature ( $T_b$  in the figure is the external temperature at which heating is no longer required by the residents – the demand  $P_b$  at temperatures above this level approximates a straight line). Models such as CalTRACK daily rely on establishing the PTG line for a building and using this to predict energy demand given external temperature (Rowe and Steinemann, 2023). SENSEI follows a similar technique but aims to incorporate a more granular consideration of occupancy timings than CalTRACK (EP Group, 2022; Rathmell et al., n.d.) .

The Heat Power Loss Coefficient (HPLC), represents the combined fabric heat transfer coefficient (HTC) and systems efficiency of a building in W/K. This is equivalent to the gradient of a PTG line assuming the internal temperature is constant. This gradient can then be used with actual temperature data to calculate a counterfactual energy demand. The concept has not been widely used in counterfactual analysis but potentially can be used in the generation of counterfactuals (i.e., GHG SMETER project, DESNZ, 2025). More sophisticated methods consider variation in internal as well as external temperature.

**Figure 2: Power temperature gradient (diagram provided by Frances Hollick)**



Various techniques have been developed to derive HTC and HPLC from smart meter data alone, or from smart meter data combined with internal temperature measurements. The UCL PTG technique (Gori et al., 2023; Hollick et al., 2020) derives in-use HTC without requiring internal temperature measurements. In this (and several other energy signature methods) the balance temperature for each individual home  $T_b$  is derived from smart meter and weather data.

The Deconstruct method (Chambers and Oreszczyn, 2019) uses weather and other data to apply a number of filters to smart meter data before calculating HTC without using internal temperature data. The SMETER Innovation programme included a range of other, proprietary techniques, several of which required internal temperature measurement (Loughborough University et al., 2020). PTG and other energy signature methods may be

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useful for HfNZ to calculate not only a counterfactual but also to measure changes in HPLC due to either heating system improvements or fabric improvements.

### 3.1.2 Data-driven (statistical and machine learning) models to provide counterfactual energy demand

An alternative approach is to derive statistical models from the available data. This generally includes selecting available physical data and socio-demographic data which is likely to relate to driving factors for both occupant behaviour and energy demand. Wei et al.'s (2014) review of 41 papers which investigated driving factors for occupant-controlled space heating in residential buildings concludes that eight factors “unambiguously influence space heating behaviour”: “outdoor climate, dwelling type, room type, house insulation, type of temperature control, occupant age, time of day and occupancy”.

Statistical regression investigates the relationship among different variables in a probabilistic framework (Wei et al., 2018). A common statistical technique is to derive a regression model from a large data set, for example McKenna et al. (2022) derived a regression model for total (gas + electricity) demand based on the SERL database of smart meter and survey data for nearly 13,000 homes. Regression models for energy demand are more common for electricity demand: Satre-Meloy (2019) describes regularization techniques to improve prediction of electricity demand. Anderson et al. (2017) report a linear mixed-effect model linking household characteristics to electricity demand.

Machine learning (ML) techniques are increasingly applied to develop models which can be used as counterfactuals. These differ from general statistical models which describe how the mean energy demand varies depending on identified variables because the ML models can be developed to predict energy demand in individual homes. The model is first trained on a subset of data from the home, then verified by checking how well it predicts the demand for another period when data is available. “all the parameters in a data-driven model will be carefully selected and modified through systematic comparisons between the model outputs and the historical data. This is the so-called learning process and only when the output errors fall within the required threshold, the corresponding data-driven models are deemed to be qualified for practical applications with fresh input data”(Wei et al., 2018). ASHRAE's Great Energy Predictor III competition received 415 reproducible online machine learning workflow examples (Miller et al., 2020). Machine learning ‘black box’ methods may be liable to over-fitting of data and inclusion of too many explanatory variables (McKenna et al., 2022).

A recent example of ML applied to energy demand data by UCL researchers is Zapata-Webb et al. (2023a). This analyses electricity and gas consumption in 5594 households from October 2022 – March 2023 using extreme gradient boosting counterfactual models trained on the same period in the previous winter to develop a predictive model for energy demand for each individual home.

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### 3.1.3 Physics based models

More detailed, physics-based, models of buildings can be used to provide counterfactuals but these are likely to require many more input parameters. EnergyPlus (<https://energyplus.net/>) is a commonly used example. The Standard Assessment Procedure (SAP) (DESNZ, 2022) and the related rdSAP model, which underpin the allocation of EPCs in the UK, require inputs including building size and configuration and details of building fabric and ventilation.

A publication from IEA EBC Annex 71 (Fitton & 20 contributing authors, 2021) provides an in-depth discussion of different methods of assessing thermal performance of buildings based on in-situ measurements. Many of these are very intrusive variants of co-heating testing in which the building is heated to a consistent, high temperature and measurements taken over multiple days or even weeks.

### 3.1.4 Evaluation of models

No detailed comparisons across different counter-factual model types for residential heating in the UK was identified in this study, with the exception of the evaluation of the SMETER competition methods (Loughborough University et al., 2020). Current research involving HfNZ partners - comparison of different ML methods and the RetroMeter project - is likely to be published in the timeframe of the HfNZ project and will inform the analysis work package.

### 3.1.5 Comparison with representative sample

The groups of homes involved in a study can be compared to the UK building stock more generally in order to examine how representative they are. For example Hamilton et al. (2013) compare the HEED (predecessor of NEED) sample with information from the English Housing Survey and the Valuation Office Agency and Webborn et al. (2021) compare the homes in the SERL Observatory with EHS data on demographics and building type. If recruitment for a trial is clustered in particular areas, this is more likely to lead to samples which are not representative of the whole population, for example if they are predominantly in lower income areas. Another challenge for trials is assessing potential response bias in which certain types of households are more likely to respond to invitations to participate in a trial (Battaglia et al., 2016; Trotta, 2018).

## 3.2 Intervention trial design

Most of the historical studies described simply gathered data from homes receiving energy efficiency interventions. Energy demand data before the intervention took place is essential for quantitative assessment of the impact of the intervention, but it was not always possible to gather this. The ability to recover up to 13 months of smart meter data

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once a household has given consent is a valuable route to assessing pre-intervention building performance.

Historically, few intervention studies have had a dedicated control group in part because good design required that the characteristics of the properties of a control group should be the type of properties that are eligible for that intervention and that sample should receive the intervention at a later date, which is often not acceptable or ethical. The only examples of including a control group in a UK energy demand research project that has been brought to light in this literature review are Warm Front and the DEFACTO trial (Lomas et al., 2022) in which no interventions were made in the first year of data collection. In the second year a group of half the homes (randomly assigned) received zonal heating controllers while the other half did not experience any changes to the heating system. This allowed the energy demand to be compared between the two groups of similar properties. A 'difference in difference' approach allowed general factors which changed the energy demand in both groups to be considered. Lomas et al. point out that this avoided a significant inaccuracy if savings had only been calculated based on weather corrections (incorrectly calculated saving of 5.97% as opposed to correctly calculated saving from zonal heating control of 3.50%). They outline the benefits of matching additional characteristics between the control and treatment groups if a large enough sample is available.

Analysis of NEED data also includes investigation of the impact of energy efficiency measures installed on gas consumption, comparing with similar properties which have not had interventions installed (DESNZ, 2023). The GHG SMETER project (DESNZ, 2025) is the first time SERL Observatory data has been used as a counterfactual in an analysis of interventions.

When analysing before- and after-intervention (or actual and counterfactual) data to examine whether the change in demand is significant, a range of statistical methods are applied, for example Hamilton et al. (2013) use a chi-squared test for comparing characteristics of two groups and Lomas et al. (2022) use the non-parametric Mann-Whitney-Wilcoxon test for comparison between non-normal distributions of gas demand data. It is usual to quote P values (the probability of the null hypothesis, generally that the intervention has not changed energy use) to indicate the level of significance. Anderson et al. (2020) argue that the commonly used threshold requiring  $P < 0.05$  may be unnecessarily restrictive in assessing evidence from intervention studies to inform energy policy.

Effect size is an important concept in statistical analysis, providing a method of quantifying the significance of a relationship between variables. The effect size calculation considers the mean and variability of the before and after intervention energy demands. The smaller the effect size, the larger the sample required to be sure the result is significant.

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## 3.3 Investigating occupant behaviour

The counterfactual models discussed above all assume that patterns of occupancy and behaviour (in particular, how residents operate their heating controls) do not change following intervention. How the residents schedule the timing and set temperatures for their heating has an important influence on heating energy demand. Wise et al. (2021) describe how residents of older, heritage buildings may have different energy behaviours (which diverge from standard energy modelling assumptions). It is important to distinguish model results (for both current demand and expected saving) and actual usage. The ‘prebound effect’ (Galvin, 2015; Sunikka-Blank and Galvin, 2012) describes homes which consume less heating energy than that calculated from physics-based models assuming standard occupancy patterns.

- Changes over time which could affect energy saving calculations can simplistically be divided between:
- Changes in circumstances (working patterns, new family members, pets etc) may lead to changes in occupancy patterns. Window and door opening patterns may change the airflows assumed in calculations, for example in the hypothetical example of a household where the single household member who smoked has now quit, leading to a change in window opening patterns
- ‘Comfort taking’: maintaining higher mean internal temperature following intervention. This can be deliberate (setting higher temperatures at the thermostat, either because this was impossible before, or costs less money now) or inadvertent (the same heating control settings with improved insulation led to shorter warm up times and longer cool downs, hence higher mean internal temperature).
- Households wishing to economise, perhaps as a result of increases in energy prices. Recent publications on trends in demand in winter 2022-23 during the ‘cost-of-living’ crisis describe how many of the participants in the SERL Observatory reduced energy demand and changed their behaviour (Huebner et al., 2023; Zapata-Webborn et al., 2023a).

### 3.3.1 Household surveys

Most intervention studies include surveys to gather data from the participants (or from surveyors who visit the participants) about:

- Physical characteristics of the building: age, type, size, wall construction, presence of insulation etc. This allows grouping of similar buildings and provides inputs for counterfactual models. For homes with EPCs much of this information is available from the public EPC register.

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- Sociodemographic characteristics of the household such as number and age of residents, employment status, income etc.
  - Residents' reactions to energy efficiency interventions: this may include their views on topics such as ease of use of controls, level of thermal comfort, disruption caused by installation, likelihood of recommending measures to friends and family etc.

Experience from previous surveys is valuable for new research and harmonising questions allows comparison across different samples. For example the questions in the SERL recruitment survey (Elam et al., 2023) draw on those from the English Housing Survey (DLUHC, 2023) and Understanding Society (Understanding Society, n.d.).

The Retrofit for the Future project drew on the experience of Post Occupancy Evaluation (chiefly used for non-domestic new build evaluation) as a systematic way to assess building performance and occupant satisfaction (Chiu et al., 2014; Spataru et al., 2010). Experience from this project provides a warning about interpreting occupant responses: for example, 60% of those surveyed had said they were 'comfortable' before the retrofit but when probed in more detail it turned out they were using electric blankets and other strategies that implied their heating system was inadequate.

The CARB-HES study, among others, included questions about where households could keep comfortably warm in their living room (Huebner et al., 2016). The Warm Front study specifically drew on the thermal comfort research tradition (see, for example de Dear et al. (1991) and Peeters et al. (2009)) to devise questions and measurements to assess resident satisfaction with their thermal environment (Hong et al., 2009).

The evaluation of the ECO scheme carried out for BEIS included analysis of characteristics of homes which received interventions and the residents' view of the benefits of measures, the temperature in their homes and the impact on their health (BEIS, 2021).

### 3.3.2 Combining survey and physical data

Survey data allows additional dimensions of interventions to be analysed. These additions to the insights from quantitative physical data may prove particularly valuable if the sample size is insufficient to provide evidence of the energy reduction impact of a particular intervention on a particular group of homes. The level of resident satisfaction and the changes they report in thermal comfort provide input for a more qualitative approach to assessing the success of measures.

The challenges of combining social and technical data should not be underestimated. Buswell et al. (2017) and Chiu et al. (2014) describe how research crossing disciplinary boundaries encounters practical difficulties such as differences in terminology and timing of data collection, alongside more fundamental philosophical differences between research methodologies.

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## 3.4 Timescales for data collection

To state the obvious, data for energy use both before and after intervention must be collected to enable analysis of the impact of the intervention on energy demand. The timescale to ensure sufficient data is available depends on a number of factors, including the level of variability (or noise) in the energy data. For PTG based measurements, collection in a shoulder period (spring or autumn) is more likely to establish quickly both the gradient of the PTG line during heating periods and the balance temperature and energy use when the heating is not in use. If the collection period starts in summer or winter, longer collection periods may be required. Some SMETER methods have recommended minimum data collection periods. The frequency of measurement is influenced by the research questions. For example Crawley et al. (2022) suggest 20 minute temperature data is collected to detect whether heating is running or not.

## 3.5 What does this mean for HfNZ?

A range of counterfactual approaches are available for consideration in developing the HfNZ analysis plan. A 'difference in difference' design is already built into the plans to compare energy use in a group of homes receiving interventions with a control group which do not. The SERL Observatory offers the possibility of comparing energy demand patterns with a wider control group.

The relatively small sample size and low expected demand reduction for each intervention investigated in Phase 1 of the project suggest that the effect size of the intervention is likely to be small, and the results may not be statistically significant. A range of regression and machine learning approaches are available to assess how much of the variation in energy demand can be attributed to measurable driving factors and hence minimise the uncertainty as far as possible. Anderson et al. (2017) argue that careful interpretation of results that conventional methods class as not statistically significant can still provide valuable evidence for energy policymakers.

There are many benefits of harmonising survey questions with those which have been tried and tested in previous research. Social data from surveys is valuable to investigate household reactions to interventions. It may also bring to light where actions by residents do not match the advice they have been given, or the expectations of designers. This behaviour in real life is a key factor in whether intended carbon reductions are achieved in practice.

## 4. Data and monitoring requirements

This section outlines approaches to monitoring and data collection in historical studies.

### 4.1 Energy monitoring

In the past studies used periodic manual meter readings or current clamp sensors and these methods are still used in homes without smart meters (BRE, 2021; Morton, 2016). The DEFACTO study made use of automated meter reading devices. The IDEAL project, which specifically recruited homes without smart meters, developed a customised data monitoring approach which included recording electricity apparent power (1 Hz) and gas usage (per fixed-volume pulse) at the meter. The design of fiscal gas meters to measure relative large fixed volume amounts gives little scope for recording at very high resolution however high resolution gas metering is available (Hollick, 2020).

The introduction of smart meters has led to a step change in the availability of half hourly energy data. The Smart Energy Research Lab (SERL) has been collecting half hourly meter data from nearly 13,000 homes recruited between 2019 and 2021. Once participants have been recruited, data is requested from the DCC via a DCC adaptor.

Practical experience is that 100% data availability cannot be expected from smart meters. Table 1, from the SERL smart meter data quality report for edition 5 of the SERL dataset, shows the percentages of possible readings where available (based on over 13,000 homes in total). NB cumulative meter readings are not provided to SERL, and an issue with changing timestamps for electricity data during British Summer Time (BST) underlies the low proportion for daily electricity.

**Table 1: Statistics for smart meter data availability, SERL edition 5**

| Reading                           | $\geq 95\%$ valid | $\geq 75\%$ valid |
|-----------------------------------|-------------------|-------------------|
| Daily gas                         | 65%               | 77%               |
| Half-hourly gas                   | 67%               | 67%               |
| Daily electricity (active import) | 44%               | 60%               |
| Half-hourly electricity           | 61%               | 89%               |

There is an extensive literature on dealing with missing values; see for instance the review by Lin and Tsai (2020). The approach taken in the SERL statistics report (Few et al., 2022) is that mean energy use per month for each fuel was calculated for total daily use as well as use in each half hour, if at least 50% of the data was available. For annual summaries, if the monthly energy use was available for all 12 months, then the mean of these (weighted by number of days in the month) was calculated and reported as the mean

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annual energy use. This ensures that any period of missing data should not unreasonably skew the annual result.

## 4.2 Weather

The weather is an uncontrolled variable that is known to impact a buildings energy consumption. Because the weather varies both over time and location, it is essential input into any study but particularly studies which are longitudinal in nature and not cross-sectional with a geographically co-located control group.

Three different approaches are generally used for monitoring the weather with radically different costs:

- Local monitoring of weather at the building location, this is very costly as it involves a full weather station ideally at each property to catch local variations in solar shading and wind obstructions.
- Use of the nearest metrological weather station, however not all-weather stations monitor all weather parameters that may impact a buildings energy use (e.g. diffuse and direct solar radiation) and so the nearest may be far away.
- Metrologically modelled local weather derived from all weather stations, for example SERL uses a dataset that comes from the Copernicus/ECMWF ERA5 hourly reanalysis). This is reanalysis (modelled) data based on readings from weather stations across GB at a horizontal resolution of  $0.25 \times 0.25$  degrees latitude and longitude (approximately 28 square km) for 22 weather variables. Because of the ability to obtain long term records from this model with some local variation and all variables normally needed for energy analysis, this method has become the method of choice for most energy analysis where detailed local solar and wind temperatures are not critically important variables.

External temperature is the most critical variable even to the simplest counterfactual modelling. Incorporating other weather data (especially solar irradiance) improves the accuracy of physical modelling (Chambers and Oreszczyn, 2019; Fitton and 20 contributing authors, 2021; Hollick et al., 2020). Which weather parameters are most important depend on the research questions and study design. Lighting energy use is dependent on day length and solar radiation, hot water energy demand in summer may be dependent on solar, air and ground temperature and ventilation is driven by external temperature and wind speed.

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## 4.3 Internal temperature

Internal temperature is a key variable and it's critically important to understand what research questions this variable is being monitored to answer. Here we outline three reasons for monitoring internal temperature:

- Measuring energy consumption and building efficiency. In this case the mean internal temperature of the building is the metric normally derived with monitoring in each room of the building, and this then converted into a mean internal temperature or zonal temperature weighting for floor area or volume. Physics-based counterfactuals require an estimate of mean internal temperature for the building. Establishing this is challenging. The temperature inside a typical UK home varies through day (Huebner et al., 2015). Different rooms in the dwelling may be at different temperatures and there may be considerable stratification within a room (especially in poorly insulated solid wall homes where there may be significant convective airflows), with temperature differences at different points in a room of 5°C or more (Wingfield personal communication). Work to establish the value of monitoring in multiple rooms concluded that using living room temperature can lead to an underestimation of HTC by 30%, while combining (volume-weighted) temperature for all the rooms reduced the deviation to 6% (Senave et al., 2020).
- Heating system control. The main form of control for many heating systems is the room thermostat, this determines when the heating system is turned on and is often set by the occupant, knowing the temperature at the thermostat helps to determine when the heating system is on and also the temperature its being controlled to. In addition, room radiator temperatures may be monitored if TRVs are installed. The IDEAL project also installed temperature probes on central heating and hot water pipes to indicate patterns of heating use.
- Monitoring occupant thermal comfort. This is critically important as often energy efficiency gains are taken as increased thermal comfort ('comfort-taking' or 'take-back'), not in reduced energy demand. When investigating thermal comfort, it is the internal temperature experienced by the occupants which is important, and additional variables such as radiant heat, humidity, clothing, and metabolic rate become relevant (Fanger, 1970). There is an extensive literature on monitoring and analysing occupant thermal comfort (generally in the context of non-domestic buildings) which can inform the framing of questions to assess whether residents are satisfied with their thermal conditions (Cao et al., 2011; de Dear et al., 1991; Kim et al., 2016; Peeters et al., 2009). See also the adaptive thermal comfort approach, which acknowledges residents will adapt their expectations depending on their experience of heating systems (Humphreys et al., 2015; Humphreys and Nicol, 1998; Nicol et al., 2012)

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In historical studies temperature and RH (see section 4.4 IAQ) have been recorded by loggers which have been collected or posted to the project team for analysis at the end of the project. Data-streaming options such as the tado° temperature sensors and API used by ESC's Living Lab can provide close to real-time data. In this case a 'smart thermostat' is used in monitoring mode only, but data is collected via a broadband connection to the manufacturer's cloud storage. PassivSystems smart heating controllers were used to gather temperature data for the FREEDOM study (Freedom Project, 2018) and also provided the residents access to temperature data via an app.

The data collection/streaming package developed for IDEAL had sensor boxes custom-built by the project, containing room temperature and relative humidity sensors, with radio-protocol communication to a Raspberry Pi base station with custom PCB receiver and software, and ethernet connection to the household's broadband router. It was found that significant project resource (including home visits) was required to develop this customised equipment to the point where it was robust enough to be installed and function reliably in a diverse range of real-world properties, and that the option for home visits was needed through the project to make repairs to maintain data quality. An excellent battery life was achieved.

The location of the sensor in a room is important, as is the design of the temperature sensor housing. This is particularly important in poorly insulated homes where there is a wide range of radiant and convective flows of heat within a room. It is therefore important to determine if the sensor is measuring the air temperature or some combination of air and radiant temperature and, given that the radiant temperature is critically dependent on location in room, this should be carefully considered in all monitoring experiments. Which is being measured may impact differently if measuring for the purpose of thermal comfort as opposed to energy use calculation.

## 4.4 Indoor Air Quality (IAQ)

The academic literature shows a variety of reasons for monitoring indoor air quality and different monitoring strategies as a result of different priorities (Abadie et al., 2019; Abadie and Wargocki, 2017). Frequently occupant health is the focus of the investigation, but IAQ measurements may also form part of studies on ventilation performance. McGill et al. (2016) provide an overview of IAQ in sustainable assessment rating systems.

Moisture levels are recorded alongside temperature normally with a relative humidity (RH) sensor. Gori et al. (2021) point out the importance of unintended consequences of retrofit of older buildings associates with excess moisture. To undertake this type of analysis to identify the unintended consequences on indoor air quality of energy efficiency measures not only does the RH need to be measured accurately but also the internal temperature and external temperature and RH. RH sensors have historically drifted from calibration particularly if they become dirty from cooking grease, etc.

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Carbon dioxide is frequently used as an indicator of IAQ in general (Chatzidiakou et al., 2015; Marques et al., 2019). It is less common to measure carbon monoxide levels. In CO measurements in flats in London, researchers found CO levels trending with external road traffic levels (Croxford et al., 2006; Stamp et al., 2022).

## 4.5 Heat metering

Metering of domestic heat flows (using measurements of flow rate and temperature of hot water to calculate the heat transferred) is rarely carried out in the UK. In countries where communal heating systems supply heat to a number of homes, the heat may be metered for billing by measuring the flow rate of hot water to each home (Siggelsten and Olander, 2010).

The main research area where heat meters have been used is in studies of the performance of heat pumps, when there is an aim to calculate coefficient of performance. The Energy Systems Catapult Electrification of Heat project used heat meter data to investigate heat pump performance (Energy Systems Catapult, 2023). The RHPP Assessment Report Appendix A3 (Lowe et al., 2017) summarised issues encountered with heat meters including poor installation of strap-on sensors or pocket sensors and poor calibration.

## 4.6 Occupancy and resident actions

A variety of methods have been used to infer occupancy, including detecting the presence of mobile phones and monitoring CO<sub>2</sub> concentration (Few and Elwell, 2021). Chen et al. (2018) provide a comprehensive review of different methods of occupancy detection. Researchers have frequently found that their chosen method did not deliver results as reliably as they had hoped. The experience of researchers working with switches to monitor window opening has also been mixed. Smart thermostatic radiator valves open up possibilities for monitoring residents' actions to set temperatures in individual rooms.

## 4.7 What does this mean for HfNZ?

There are clear advantages to using data streaming rather than data loggers to allow timely collection and analysis of data. Proven collection routes, for example via sensor manufacturer's cloud data repositories, introduce less reliability risk than customised solutions.

Care should be taken over specifying (and checking) the positioning of temperature probes given the variability of temperature within a typical home. Particular care should be taken with installation and calibration of heat meters to ensure collected data is meaningful.

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## 5. Providing energy efficiency advice

This section gives a brief overview of sources of, and good practice for, energy efficiency information to households in the UK. We touch on both encouraging low and no cost changes in behaviour and decisions about up-front investment (for example in insulation), but this short section is not intended to be a comprehensive coverage of the extensive literature on these topics. Some literature distinguishes between providing advice in person and more impersonal information provision, this section focuses on the latter. Information on residents' interactions with heating controllers is included, since this is particularly relevant for HfNZ Phase 1.

### 5.1 Sources of energy efficiency information in Britain

The Energy Saving Trust is a key source of verified and trusted energy saving advice for households (<https://energysavingtrust.org.uk/energy-at-home/>), which is referred to by many other websites (including those of energy companies) and print media. Citizen's Advice also provide comprehensive energy saving advice (<https://www.citizensadvice.org.uk/consumer/energy/energy-supply/save-energy-at-home/>). Some charitable organisations (e.g. Age Concern, Macmillan Cancer Support) provide advice for particular sections of the population, and some third sector charitable organisations are specialist in providing energy advice to a range of households e.g. Centre for Sustainable Energy, Changeworks, Groundwork (Green Doctors). Many local authorities provide both general advice and guidance on retrofits. Central government also provides advice (gov.uk, 2024, n.d.) Apart from a small scale trial of two different framings (Casado et al., 2017), no academic literature quantifying the effectiveness of energy efficiency advice campaigns has been identified. The MEL (2015) report on the small scale behaviour trials evaluated (but did not quantify the impact of) a range of approaches

### 5.2 General principles for energy efficiency advice

The review for EST by UKERC (Warren and Foulds, 2020) provides a helpful summary of key points from energy advice literature, which include:

- Do not simply frame energy efficiency information in terms of saving money but provide multiple framings. (Wilson et al. (2018) point out that a primary emphasis on financial aspects was an issue with the Green Deal).
- Integrate ideas about 'the home' in communications about saving energy. Appealing messages include "altruistic drivers and non-monetary motivators such as environmental savings, comfort, and home improvement" .

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- Provide practical advice on how to achieve recommendations, including DIY instructions where appropriate.
  - There is a widespread suspicion of advice from energy companies since they are perceived as being motivated by commercial factors. Trusted organisations (for example community not-for-profits) have the advantage of operating outside the “business-side of energy saving”.

### 5.3 Barriers to action on energy efficiency

There is a large amount of academic literature from a plethora of different theoretical perspectives which is relevant for examining why households do not follow energy efficiency advice or action recommendations. Wilson and Dowlatabadi (2007) give an excellent overview of what these different ways of looking at the world imply for policy and interventions. Recent research has applied a ‘capability’ approach to understanding which householders can adopt which measures (Banks and Darby, 2021).

Galvin and Sunikka-Blank (2014) use a social-technical systems studies to investigate bottom up innovations in retrofit and how these diffuse to other households and through the supply chain. There are two points made in this paper which are particularly relevant for the HfNZ target homes:

- Clashes between standard retrofit solutions and heritage requirements. Many older homes of the solid-wall types targeted in HfNZ are in conservation areas and face planning constraints, particularly on measures such as external wall insulation and replacement glazing that affect the external appearance of the building. Wise et al. (2021) point out that typical retrofits may be unacceptable to residents’ heritage values.
- Local supply chain skills and knowledge are often insufficient for low carbon retrofit. Wade and Visscher’s (2021) introduction to a *Buildings and Cities* special issue focussed on domestic retrofit at scale highlight the need for support to develop supply chains (both existing workers and new entrants). Gillich et al. (2018) describe how retrofitting schemes are most effectively designed to take into account local market features.

Brocklehurst et al. (2021), in a review of international evidence on housing retrofit supply chains commissioned by BEIS, highlight conservatism in the retrofit industry and the importance of customer after-care, and suggest that local partnerships are needed to mobilise and organise the supply chain. They state, “the real finding was that no country or informant had found a way of achieving successful retrofit at any significant scale”. An alternative perspective is that some individual measures have established supply chains. For example, it can be argued that the UK has a highly successful window retrofit industry, which has needed practically no government support.

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## 5.4 Running heating systems efficiently

The main UK advice sources all include information about setting heating controllers using temperature setpoints and schedules to ensure comfort while minimising heating energy use. The academic literature on how residents use heating controls is relevant for understanding why households may not be following this best practice advice. Earlier studies investigated ‘mental models’ and interactions with conventional thermostats (Kempton, 1986; Meier et al., 2011; Pepper et al., 2011; Shipworth, 2011). More recent studies of user interactions with smart thermostats (Huchuk et al., 2018; Miu et al., 2019; Stopps & Touchie, 2021) show how the thermostats are not always used in the ways that their designers intended, and that residents can become frustrated when they are unable to achieve their desired heating pattern.

The opportunities for saving energy by reducing the flow temperature of condensing boilers (NESTA, 2022) only came to prominence in 2022, when it was one of the recommendations of a large scale public information campaign. About 40% of respondents to a January 2023 SERL survey reported lowering their boiler flow temperature (Huebner et al., 2023) and analysis of meter data suggests that this did lead to a lowering of heating energy consumption (Zapata-Webborn et al., 2023a).

## 5.5 Roadmaps

Roadmaps comprise outlines of steps or actions people need to take to get their home towards Net Zero. These may take a variety of forms and based on diverse sources of information, from generic online advice to very personalized advice based on a survey of the home alongside discussions with occupants. No academic assessments of effectiveness of roadmaps to net zero became known in the literature review. The HfNZ work on this topic will be developed in future project deliverables.

## 5.6 What does this mean for HfNZ?

The literature suggests that multiple framings of the energy efficiency message are more likely to lead to successful recruitment and implementation of measures. E.ON (the project partner responsible for recruitment of homes to the trial) is likely to face challenges in overcoming suspicions that advice and support from energy companies is commercially motivated.

It is important to pay attention to the barriers, both practical and psychological, faced by households contemplating retrofits. Residents should be consulted to establish which aspects of retrofits and new technology are important to them, and to assess whether the solutions offered meet their needs. HfNZ provides an opportunity to learn about resident perspectives from surveys.

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## 6. Conclusion

This literature review aims to set out learning from previous trials monitoring energy demand in the home to inform the HfNZ project. HfNZ represents a unique opportunity to carry out a relatively large-scale trial with data collection before and after intervention. A range of options are available to assess counter-factual energy demand but showing that small changes are statistically significant is likely to prove challenging. Nevertheless, a range of techniques including machine learning can be applied to the analysis, and the inclusion of qualitative survey data will also be valuable to assessing whether the interventions are successful from the residents' point of view.

### 6.1 HfNZ progress

At the outset of this literature review, key challenges faced by historical projects were identified as:

- Insufficient sample size to provide statistically significant evidence of energy saving
- Limited monitoring instrumentation due to cost
- Poor reliability of data. This includes lack of data about which interventions occurred at what times, and poor collection of contextual data
- Insufficient monitoring periods, in particular if there is no pre-intervention monitoring

At the time of writing, December 2025, Phase 2 of HfNZ is being delivered. The project has recruited well over 1,200 households, all of which are asked during recruitment to connect their smart meters to the project to provide half-hourly gas and electricity data. All households are provided with temperature and humidity monitoring equipment upon joining the project; some are also provided with additional equipment such as heat meters, submetering equipment, and indoor air quality monitoring equipment. Frequent checks are in place to ensure equipment continues to work and remains connected to the project and providing data, with incentives for householders linked to their continued provision of data. Many homes joined the trial in the spring/summer of 2024 and will remain in the trial until autumn 2026 and potentially longer.

## 7. References

- Abadie, M., Wargocki, P., Rode, C., Zhang, J., 2019. Proposed Metrics For IAQ in Low-Energy Residential Buildings. *ASHRAE J.* 61, 62–66.
- Abadie, M.O., Wargocki, P., 2017. CR 17: Indoor Air Quality Design and Control in Low-energy Residential Buildings- Annex 68 | Subtask 1: Defining the metrics | In the search of indices to evaluate the Indoor Air Quality of low-energy residential buildings.
- Anderson, B., Lin, S., Newing, A., Bahaj, A., James, P., 2017. Electricity consumption and household characteristics: Implications for census-taking in a smart metered future. *Comput. Environ. Urban Syst.*, Spatial analysis with census data: emerging issues and innovative approaches 63, 58–67. <https://doi.org/10.1016/j.compenvurbsys.2016.06.003>
- Anderson, B., Rushby, T., Bahaj, A., James, P., 2020. Ensuring statistics have power: Guidance for designing, reporting and acting on electricity demand reduction and behaviour change programs. *Energy Res. Soc. Sci.* 59, 101260. <https://doi.org/10.1016/j.erss.2019.101260>
- Banks, N.W., Darby, S., 2021. A capability approach to smart local energy systems: aiming for ‘smart and fair.’ European Council for an Energy Efficient Economy.
- Barnicoat, G., Danson, M., 2015. The ageing population and smart metering: A field study of householders’ attitudes and behaviours towards energy use in Scotland. *Energy Res. Soc. Sci.*, Special Issue on Smart Grids and the Social Sciences 9, 107–115. <https://doi.org/10.1016/j.erss.2015.08.020>
- Battaglia, M.P., Dillman, D.A., Frankel, M.R., Harter, R., Buskirk, T.D., McPhee, C.B., DeMatteis, J.M., Yancey, T., 2016. Sampling, Data Collection, and Weighting Procedures for Address-Based Sample Surveys. *J. Surv. Stat. Methodol.* 4, 476–500. <https://doi.org/10.1093/jssam/smw025>
- BEIS, 2021. Energy Company Obligation (ECO) Evaluation Wave 1.
- Beizaee, A., Lomas, K.J., Firth, S.K., 2013. National survey of summertime temperatures and overheating risk in English homes. *Build. Environ.* 65, 1–17. <https://doi.org/10.1016/j.buildenv.2013.03.011>
- BRE, 2021. Energy Follow Up Survey (EFUS) 2017 Methodology Report.
- Brocklehurst, F., Morgan, E., Greer, K., Wade, J., Killip, G., 2021. Domestic retrofit supply chain initiatives and business innovations: an international review 2, 533–549. <https://doi.org/10.5334/bc.95>

Buswell, R., Webb, L., Mitchell, V., Leder Mackley, K., 2017. Multidisciplinary research: should effort be the measure of success? *Build. Res. Inf.* 45, 539–555.  
<https://doi.org/10.1080/09613218.2016.1194601>

Cao, B., Zhu, Y., Ouyang, Q., Zhou, X., Huang, L., 2011. Field study of human thermal comfort and thermal adaptability during the summer and winter in Beijing. *Energy Build.*, Tackling building energy consumption challenges - Special Issue of ISHVAC 2009, Nanjing, China 43, 1051–1056. <https://doi.org/10.1016/j.enbuild.2010.09.025>

Casado, F., Hidalgo, M.C., García-Leiva, P., 2017. Energy efficiency in households: The effectiveness of different types of messages in advertising campaigns. *J. Environ. Psychol.* 53, 198–205. <https://doi.org/10.1016/j.jenvp.2017.08.003>

CEBM, 2023. Study designs [WWW Document]. URL  
<https://www.cebm.ox.ac.uk/resources/ebm-tools/study-designs> (accessed 12.4.23).

Chambers, J.D., Oreszczyn, T., 2019. Deconstruct: A scalable method of as-built heat power loss coefficient inference for UK dwellings using smart meter data. *Energy Build.* 183, 443–453. <https://doi.org/10.1016/j.enbuild.2018.11.016>

Chatzidiakou, L., Mumovic, D., Summerfield, A., 2015. Is CO<sub>2</sub> a good proxy for indoor air quality in classrooms? Part 1: The interrelationships between thermal conditions, CO<sub>2</sub> levels, ventilation rates and selected indoor pollutants. *Build. Serv. Eng. Res. Technol.* 36, 129–161. <https://doi.org/10.1177/0143624414566244>

Chen, Z., Jiang, C., Xie, L., 2018. Building occupancy estimation and detection: A review. *Energy Build.* 169, 260–270. <https://doi.org/10.1016/j.enbuild.2018.03.084>

Chindarkar, N., Goyal, N., 2023. Did it increase energy consumption? A difference-in-differences evaluation of a rural electrification policy in Gujarat, India using night-time lights data. *Energy Policy* 183, 113814. <https://doi.org/10.1016/j.enpol.2023.113814>

Chiu, L.F., Lowe, R., Raslan, R., Altamirano-Medina, H., Wingfield, J., 2014. A socio-technical approach to post-occupancy evaluation: interactive adaptability in domestic retrofit. *Build. Res. Inf.* 42, 574–590. <https://doi.org/10.1080/09613218.2014.912539>

Cooper, A., Shipworth, D., Humphry, A., 2014. UK Energy Lab: A feasibility study for a longitudinal, nationally representative sociotechnical survey of energy use.

Crawley, J., Manouseli, D., Mallaburn, P., Elwell, C., 2022. An Empirical Energy Demand Flexibility Metric for Residential Properties. *Energies* 15, 5304.  
<https://doi.org/10.3390/en15145304>

Croxford, B.J.F., Hutchinson, E., Leonardi, G.S., McKenna, L., Nicholson, L., Volans, G., Wilkinson, P., 2006. Real time carbon monoxide measurements from 270 UK homes [WWW Document]. Jetter J Ed Proc. Indoor Environ. Qual. Probl. Res. Solut. Conf. 2006 Air Waste Manag. Assoc. AWMA US EPAs Off. Res. Dev. Raleigh N. C. USA 2006. URL  
<https://discovery.ucl.ac.uk/id/eprint/5017/> (accessed 10.3.23).

- Csoknyai, T., Legardeur, J., Akle, A.A., Horváth, M., 2019. Analysis of energy consumption profiles in residential buildings and impact assessment of a serious game on occupants' behavior. *Energy Build.* 196, 1–20. <https://doi.org/10.1016/j.enbuild.2019.05.009>
- Day, T., others, 2006. Degree-days: theory and application. *Chart. Inst. Build. Serv. Eng. Lond.* 106.
- de Dear, R., Leow, K.G., Foo, S.C., 1991. Thermal comfort in the humid tropics: Field experiments in air conditioned and naturally ventilated buildings in Singapore. *Int. J. Biometeorol.* 34, 259–265. <https://doi.org/10.1007/BF01041840>
- DESNZ, 2025. Green Homes Grant (GHG) SMETER project evaluation [WWW Document]. GOV.UK. URL <https://www.gov.uk/government/publications/green-homes-grant-ghg-smeter-project-evaluation> (accessed 23.12.25).
- DESNZ, 2023. National Energy Efficiency Data-Framework (NEED) [WWW Document]. GOV.UK. URL <https://www.gov.uk/government/collections/national-energy-efficiency-data-need-framework> (accessed 11.13.23).
- DESNZ, 2022. Standard Assessment Procedure [WWW Document]. GOV.UK. URL <https://www.gov.uk/guidance/standard-assessment-procedure> (accessed 11.16.23).
- DLUHC, 2023. English Housing Survey 2021 to 2022: technical report.
- DLUHC, 2022. English Housing Survey 2021 to 2022: headline report [WWW Document]. URL <https://www.gov.uk/government/statistics/english-housing-survey-2021-to-2022-headline-report/english-housing-survey-2021-to-2022-headline-report> (accessed 9.13.23).
- EEVS, 2014. Electricity Demand Reduction Pilot: Measurement and Verification Manual.
- Elam, S., Webborn, E., Few, J., McKenna, E., Pullinger, M., Oreszczyn, T., Anderson, B., Ministry of Housing Communities & Local Government, European Centre for Medium-Range Weather Forecasts, Limited, R.M.G., 2023. Smart Energy Research Lab Observatory Data, 2019-2022: Secure Access. 6th Edition. UK Data Serv. <https://doi.org/10.5255/UKDA-SN-8666-6>
- Energy Systems Catapult, 2023. Electrification of heat demonstration project: Interim heat pump performance data analysis report.
- EP Group, 2022. Metered Energy Savings: Final Report.
- Fanger, 1970. Thermal comfort: analysis and applications in environmental engineering. McGraw-Hill, New York.
- Fell, D., King, G., 2012. Domestic energy use study: to understand why comparable households use different amounts of energy. DECC.

Few, J., Elwell, C.A., 2021. Applying the CO<sub>2</sub> concentration decay tracer gas method in long-term monitoring campaigns in occupied homes: identifying appropriate unoccupied periods and decay periods. *Int. J. Build. Pathol. Adapt.* 41, 96–108. <https://doi.org/10.1108/IJBPA-05-2021-0077>

Few, J., Pullinger, M., McKenna, E., Elam, S., Webborn, E., Oreszczyn, T., 2022. Smart Energy Research Lab: Energy use in GB domestic buildings 2021. Smart Energy Research Lab (SERL) Statistical Reports Volume 1. UCL, London, UK.

Fitton, R., 20 contributing authors, 2021. Building energy performance assessment based on in-situ measurements.

Foulds, C., Powell, J., Seyfang, G., 2013. Investigating the performance of everyday domestic practices using building monitoring. *Build. Res. Inf.* 41, 622–636. <https://doi.org/10.1080/09613218.2013.823537>

Freedom Project, 2018. Freedom Project Final Report October 2018. Freedom Project.

Galvin, R., 2013. Targeting ‘behavers’ rather than behaviours: A ‘subject-oriented’ approach for reducing space heating rebound effects in low energy dwellings. *Energy Build.* 67, 596–607. <https://doi.org/10.1016/j.enbuild.2013.08.065>

Galvin, R., Sunikka-Blank, M., 2014. The UK homeowner-retrofit as an innovator in a socio-technical system. *Energy Policy* 74, 655–662. <https://doi.org/10.1016/j.enpol.2014.08.013>

Gillich, A., Sunikka-Blank, M., Ford, A., 2018. Designing an ‘optimal’ domestic retrofit programme. *Build. Res. Inf.* 46, 767–778. <https://doi.org/10.1080/09613218.2017.1368235>

Gori, V., Johnston, D., Bouchié, R., Stamp, S., 2023. Characterisation and analysis of uncertainties in building heat transfer estimates from co-heating tests. *Energy Build.* 295, 113265. <https://doi.org/10.1016/j.enbuild.2023.113265>

Gori, V., Marincioni, V., Altamirano-Medina, H., 2021. Retrofitting traditional buildings: a risk-management framework integrating energy and moisture 2, 411–424. <https://doi.org/10.5334/bc.107>

gov.uk, 2024. How to save energy and lower your bills this winter [WWW Document]. Help Househ. URL <https://helpforhouseholds.campaign.gov.uk/energy-saving-advice/> (accessed 2.6.24).

gov.uk, n.d. Find ways to save energy in your home [WWW Document]. URL <https://www.gov.uk/improve-energy-efficiency> (accessed 2.6.24).

Gupta, R., Gregg, M., Passmore, S., Stevens, G., 2015. Intent and outcomes from the Retrofit for the Future programme: key lessons. *Build. Res. Inf.* 43, 435–451. <https://doi.org/10.1080/09613218.2015.1024042>

- Hamilton, I.G., Steadman, P.J., Bruhns, H., Summerfield, A.J., Lowe, R., 2013. Energy efficiency in the British housing stock: Energy demand and the Homes Energy Efficiency Database. *Energy Policy* 60, 462–480. <https://doi.org/10.1016/j.enpol.2013.04.004>
- Hollick, F.P., 2020. Developing a dynamic method to assess the thermal performance of occupied dwellings (Doctoral). Dr. Thesis UCL Univ. Coll. Lond. Presented at the UCL (University College London), UCL (University College London).
- Hollick, F.P., Gori, V., Elwell, C.A., 2020. Thermal performance of occupied homes: A dynamic grey-box method accounting for solar gains. *Energy Build.* 208, 109669. <https://doi.org/10.1016/j.enbuild.2019.109669>
- Hong, S.H., Gilbertson, J., Oreszczyn, T., Green, G., Ridley, I., 2009. A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment. *Build. Environ.* 44, 1228–1236. <https://doi.org/10.1016/j.buildenv.2008.09.003>
- Hong, S.H., Oreszczyn, T., Ridley, I., 2006. The impact of energy efficient refurbishment on the space heating fuel consumption in English dwellings. *Energy Build.* 38, 1171–1181. <https://doi.org/10.1016/j.enbuild.2006.01.007>
- Huebner, G., Hanmer, C., Zapata-Webborn, E., Pullinger, M., McKenna, E.J., Few, J., Elam, S., Oreszczyn, T., 2023. Self-reported energy use behaviour changed significantly during the cost-of-living crisis in winter 2022/23: Insights from cross-sectional and longitudinal surveys in Great Britain. <https://doi.org/10.31235/osf.io/984yh>
- Huebner, G.M., McMichael, M., Shipworth, D., Shipworth, M., Durand-Daubin, M., Summerfield, A., 2013. Heating patterns in English homes: Comparing results from a national survey against common model assumptions. *Build. Environ.* 70, 298–305. <https://doi.org/10.1016/j.buildenv.2013.08.028>
- Huebner, G.M., McMichael, M., Shipworth, D., Shipworth, M., Durand-Daubin, M., Summerfield, A.J., 2015. The shape of warmth: temperature profiles in living rooms. *Build. Res. Inf.* 43, 185–196. <https://doi.org/10.1080/09613218.2014.922339>
- Huebner, G.M., Shipworth, D., Hamilton, I.G., Oreszczyn, T., 2016. Too hot, too cold? An analysis of factors associated with thermal comfort in English homes. Presented at the Proceedings of 9th Windsor Conference: Making Comfort Relevant.
- Humphreys, M., Nicol, F., Roaf, S., 2015. *Adaptive Thermal Comfort: Foundations and Analysis*. Routledge, London ; New York.
- Humphreys, M.A., Nicol, J.F., 1998. Understanding the adaptive approach to thermal comfort. *ASHRAE Trans.* Atlanta 104, 991.
- Judson, E.P., Bell, S., Bulkeley, H., Powells, G., Lyon, S., 2015. The Co-Construction of Energy Provision and Everyday Practice: Integrating Heat Pumps in Social Housing in England. *Sci. Technol. Stud.*

- Kane, T., Firth, S.K., Hassan, T.M., Dimitriou, V., 2017. Heating behaviour in English homes: An assessment of indirect calculation methods. *Energy Build.* 148, 89–105. <https://doi.org/10.1016/j.enbuild.2017.04.059>
- Kane, T., Firth, S.K., Lomas, K.J., 2015. How are UK homes heated? A city-wide, socio-technical survey and implications for energy modelling. *Energy Build.* 86, 817–832. <https://doi.org/10.1016/j.enbuild.2014.10.011>
- Kempton, W., 1986. Two Theories of Home Heat Control. *Cogn. Sci.* 10, 75–90.
- Kim, J., de Dear, R., Parkinson, T., Candido, C., Cooper, P., Ma, Z., Saman, W., 2016. Field study of air conditioning and thermal comfort in residential buildings, in: *Proceedings of 9th Windsor Conference :Conference: Making Comfort Relevant*, 7-10 April 2016, , Cumberland Lodge, Windsor. Network for comfort and energy use in buildings, London.
- Lin, W.-C., Tsai, C.-F., 2020. Missing value imputation: a review and analysis of the literature (2006–2017). *Artif. Intell. Rev.* 53, 1487–1509. <https://doi.org/10.1007/s10462-019-09709-4>
- Lomas, K.J., Allinson, D., Watson, S., Beizaee, A., Haines, V.J., Li, M., 2022. Energy savings from domestic zonal heating controls: Robust evidence from a controlled field trial. *Energy Build.* 254, 111572. <https://doi.org/10.1016/j.enbuild.2021.111572>
- Lomas, K.J., Kane, T., 2013. Summertime temperatures and thermal comfort in UK homes. *Build. Res. Inf.* 41, 259–280. <https://doi.org/10.1080/09613218.2013.757886>
- Loughborough University, Halton Housing, Leeds Beckett University, UCL, 2020. Technical evaluation of SMETER Technologies (TEST) Project.
- Lowe, R., Summerfield, A., Oikonomou, E., Love, J., Biddulph, P., Gleeson, C., Chiu, L.F., Wingfield, J., 2017. Final report on analysis of heat pump data from the Renewable Heat Premium Payment (RHPP) scheme. BEIS, London.
- Marques, G., Ferreira, C.R., Pitarma, R., 2019. Indoor Air Quality Assessment Using a CO2 Monitoring System Based on Internet of Things. *J. Med. Syst.* 43, 67. <https://doi.org/10.1007/s10916-019-1184-x>
- McGill, G., Oyedele, L.O., McAllister, K., Qin, M., 2016. Effective indoor air quality for energy-efficient homes: a comparison of UK rating systems. *Archit. Sci. Rev.* 59, 159–173. <https://doi.org/10.1080/00038628.2015.1078222>
- McKenna, E., Few, J., Webborn, E., Anderson, B., Elam, S., Shipworth, D., Cooper, A., Pullinger, M., Oreszczyn, T., 2022. Explaining daily energy demand in British housing using linked smart meter and socio-technical data in a bottom-up statistical model. *Energy Build.* 258, 111845. <https://doi.org/10.1016/j.enbuild.2022.111845>
- Meier, A., Aragon, C., Pepper, T., Perry, D., Pritoni, M., 2011. Usability of residential thermostats: Preliminary investigations. *Build. Environ.* 46, 1891–1898. <https://doi.org/10.1016/j.buildenv.2011.03.009>

MEL, 2015. DECC Smart Meter Small-scale Behaviour Trials - Synthesis Report 6.0.

Miller, C., Arjunan, P., Kathirgamanathan, A., Fu, C., Roth, J., Park, J.Y., Balbach, C., Gowri, K., Nagy, Z., Fontanini, A.D., Haberl, J., 2020. The ASHRAE Great Energy Predictor III competition: Overview and results. *Sci. Technol. Built Environ.* 26, 1427–1447. <https://doi.org/10.1080/23744731.2020.1795514>

Morgan, C., Foster, J.A., Poston, A., Sharpe, T.R., 2017. Overheating in Scotland: contributing factors in occupied homes. *Build. Res. Inf.* 45, 143–156. <https://doi.org/10.1080/09613218.2017.1241472>

Morton, A., 2016. Heating use in UK homes. PhD thesis. Loughborough University.

NESTA, 2022. Money saving boiler challenge: supporting evidence.

Nicol, F., Humphreys, M., Roaf, S., 2012. Adaptive thermal comfort : principles and practice. Routledge, London.

ONS, 2023. Energy efficiency of housing in England and Wales.

Oreszczyn, T., Hong, S.H., Ridley, I., Wilkinson, P., 2006. Determinants of winter indoor temperatures in low-income households in England. *Energy Build.* 38, 245–252. <https://doi.org/10.1016/j.enbuild.2005.06.006>

Pallonetto, F., De Rosa, M., Finn, D.P., 2022. Environmental and economic benefits of building retrofit measures for the residential sector by utilizing sensor data and advanced calibrated models. *Adv. Build. Energy Res.* 16, 89–117. <https://doi.org/10.1080/17512549.2020.1801504>

Peeters, L., Dear, R. de, Hensen, J., D’haeseleer, W., 2009. Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. *Appl. Energy* 86, 772–780. <https://doi.org/10.1016/j.apenergy.2008.07.011>

Peffer, T., Pritoni, M., Meier, A., Aragon, C., Perry, D., 2011. How people use thermostats in homes: A review. *Build. Environ.* 46, 2529–2541. <https://doi.org/10.1016/j.buildenv.2011.06.002>

Petrov, I., Ryan, L., 2021. The landlord-tenant problem and energy efficiency in the residential rental market. *Energy Policy* 157, 112458. <https://doi.org/10.1016/j.enpol.2021.112458>

Pullinger, M., Kilgour, J., Goddard, N., Berliner, N., Webb, L., Dzikovska, M., Lovell, H., Mann, J., Sutton, C., Webb, J., Zhong, M., 2021. The IDEAL household energy dataset, electricity, gas, contextual sensor data and survey data for 255 UK homes. *Sci. Data* 8, 146. <https://doi.org/10.1038/s41597-021-00921-y>

Rathmell, A., Oreszczyn, T., Phillips, J., Thomas, S., Jofeh, C., n.d. Towards a protocol for metered energy savings in UK buildings.

- Rowe, W., Steinemann, J., 2023. RetroMeter WP2 - Methods Development. Energy Systems Catapult.
- Satre-Meloy, A., 2019. Investigating structural and occupant drivers of annual residential electricity consumption using regularization in regression models. *Energy* 174, 148–168. <https://doi.org/10.1016/j.energy.2019.01.157>
- Shipworth, M., 2011. Thermostat settings in English houses: No evidence of change between 1984 and 2007. *Build. Environ.* 46, 635–642. <https://doi.org/10.1016/j.buildenv.2010.09.009>
- Siggelsten, S., Olander, S., 2010. Individual heat metering and charging of multi-dwelling residential housing. *Struct. Surv.* 28, 207–214. <https://doi.org/10.1108/02630801011058933>
- Spataru, C., Gillott, M., Hall, M.R., 2010. Domestic energy and occupancy: a novel post-occupancy evaluation study. *Int. J. Low-Carbon Technol.* ctq020. <https://doi.org/10.1093/ijlct/ctq020>
- Stamp, S., Burman, E., Shrubsole, C., Chatzidiakou, L., Mumovic, D., Davies, M., 2022. Seasonal variations and the influence of ventilation rates on IAQ: A case study of five low-energy London apartments. *Indoor Built Environ.* 31, 607–623. <https://doi.org/10.1177/1420326X211017175>
- Stewart, I., 2023. Constituency data: Central heating, 2021 census.
- Summerfield, A.J., Lowe, R.J., Bruhns, H.R., Caeiro, J.A., Steadman, J.P., Oreszczyn, T., 2007. Milton Keynes Energy Park revisited: Changes in internal temperatures and energy usage. *Energy Build., Comfort and Energy Use in Buildings - Getting Them Right* 39, 783–791. <https://doi.org/10.1016/j.enbuild.2007.02.012>
- Technology Strategy Board, 2013. Retrofit Revealed: The Retrofit for the Future projects - data analysis report.
- Topouzi, M., 2016. Occupants' interaction with low-carbon retrofitted homes and its impact on energy use (PhD Thesis). University of Oxford.
- Trotta, G., 2018. Factors affecting energy-saving behaviours and energy efficiency investments in British households. *Energy Policy* 114, 529–539. <https://doi.org/10.1016/j.enpol.2017.12.042>
- Tweed, C., Dixon, D., Hinton, E., Bickerstaff, K., 2014. Thermal comfort practices in the home and their impact on energy consumption. *Archit. Eng. Des. Manag.* 10, 1–24. <https://doi.org/10.1080/17452007.2013.837243>
- Understanding Society, n.d. Understanding Society Main survey.
- Vellei, M., Ramallo-González, A.P., Coley, D., Lee, J., Gabe-Thomas, E., Lovett, T., Natarajan, S., 2017. Overheating in vulnerable and non-vulnerable households. *Build. Res. Inf.* 45, 102–118. <https://doi.org/10.1080/09613218.2016.1222190>

- Wade, F., Visscher, H., 2021. Retrofit at scale: accelerating capabilities for domestic building stocks 2, 800–811. <https://doi.org/10.5334/bc.158>
- Warren, G., Foulds, C., 2020. 'Better' domestic energy advice in England? A narrative literature review.
- Webborn, E., Few, J., McKenna, E., Elam, S., Pullinger, M., Anderson, B., Shipworth, D., Oreszczyn, T., 2021. The SERL Observatory Dataset: Longitudinal Smart Meter Electricity and Gas Data, Survey, EPC and Climate Data for over 13,000 Households in Great Britain. *Energies* 14, 6934. <https://doi.org/10.3390/en14216934>
- Wei, S., Jones, R., de Wilde, P., 2014. Driving factors for occupant-controlled space heating in residential buildings. *Energy Build.* 70, 36–44. <https://doi.org/10.1016/j.enbuild.2013.11.001>
- Wei, Y., Zhang, X., Shi, Y., Xia, L., Pan, S., Wu, J., Han, M., Zhao, X., 2018. A review of data-driven approaches for prediction and classification of building energy consumption. *Renew. Sustain. Energy Rev.* 82, 1027–1047. <https://doi.org/10.1016/j.rser.2017.09.108>
- Wilson, C., Dowlatabadi, H., 2007. Models of Decision Making and Residential Energy Use [WWW Document]. <http://dx.doi.org/10.1146/annurev.energy.32.053006.141137>. URL <http://www.annualreviews.org/eprint/mbkndFDcke3he4RxYDHx/full/10.1146/annurev.energy.32.053006.141137> (accessed 12.14.16).
- Wilson, C., Pettifor, H., Chryssochoidis, G., 2018. Quantitative modelling of why and how homeowners decide to renovate energy efficiently. *Appl. Energy* 212, 1333–1344. <https://doi.org/10.1016/j.apenergy.2017.11.099>
- Wingfield, D.J., Bell, M., Miles-Shenton, D., Lowe, R., South, T., 2008. Lessons from Stamford Brook.
- Wise, F., Moncaster, A., Jones, D., 2021. Rethinking retrofit of residential heritage buildings 2, 495–517. <https://doi.org/10.5334/bc.94>
- Zapata-Webborn, E., Hanmer, C., Oreszczyn, T., Huebner, G., McKenna, E.J., Few, J., Elam, S., Pullinger, M., Cheshire, C., Friel, D., Masters, H., Whittaker, A., 2023a. Winter demand falls as fuel bills rise: Understanding the energy impacts of the cost-of-living crisis on British households. <https://doi.org/10.31219/osf.io/83a4t>
- Zapata-Webborn, E., McKenna, E., Pullinger, M., Cheshire, C., Masters, H., Whittaker, A., Few, J., Elam, S., Oreszczyn, T., 2023b. The impact of COVID-19 on household energy consumption in England and Wales from April 2020 to March 2022. *Energy Build.* 297, 113428. <https://doi.org/10.1016/j.enbuild.2023.113428>

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