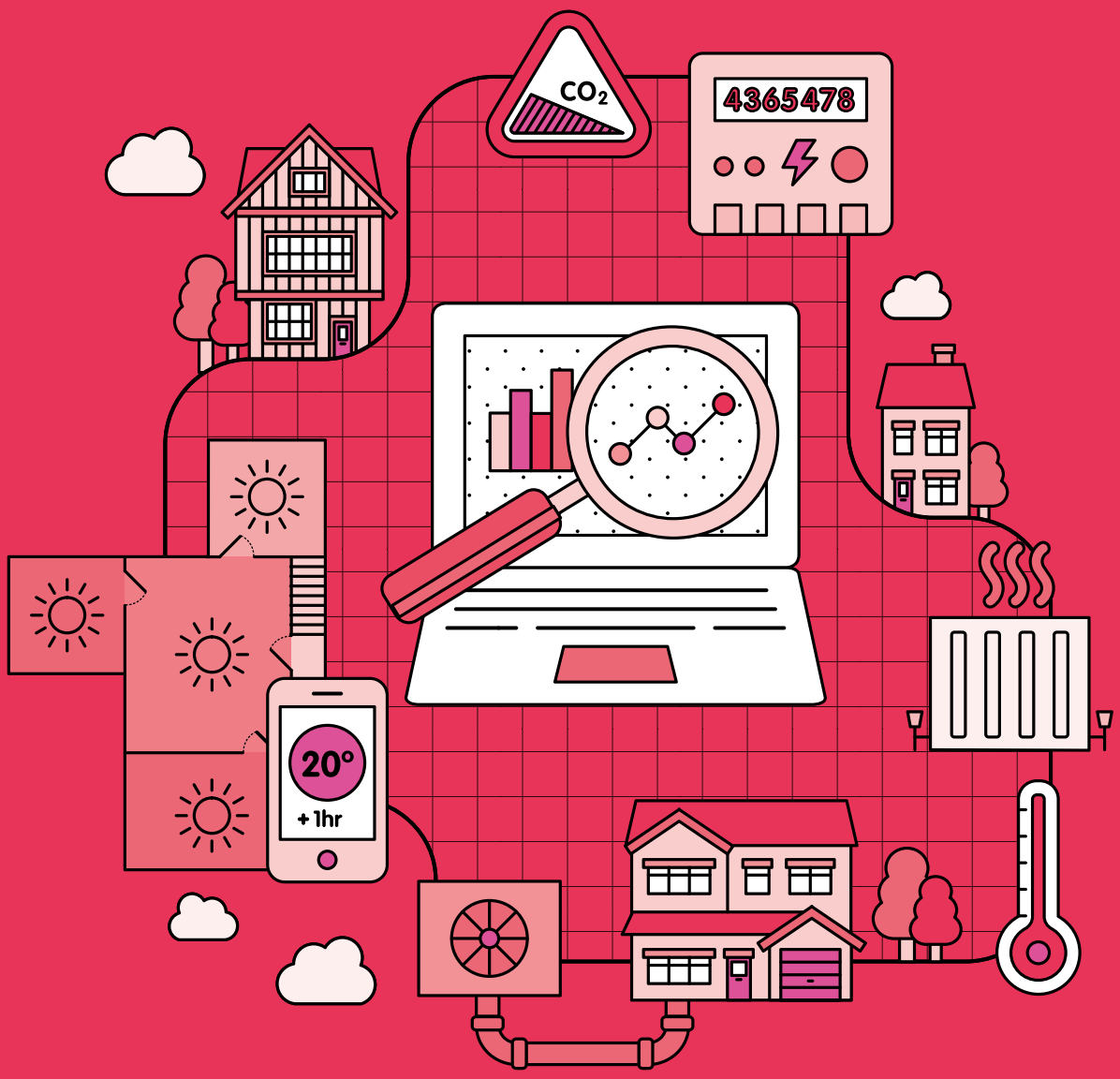
HOME ENERGY DYNAMICS

CATAPULT Energy Systems



Pathways to Low Carbon Heating: Dynamic Modelling of Five UK Homes

energy technologies institute

Contents

Acknowledgements

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- Our project delivery partners including EDF, CAR, Imperial College London and Claytex.

Glossary and Abbreviations

The following glossary defines terms as used in this report which may be unfamiliar to some readers or may be used in a specific way in this context.

Air changes per hour: a measure of the rate of ventilation air flow in terms of the air volume of the room.

Air gap: a space between two layers of a wall or glazing, which provides some thermal insulation.

Air source heat pump (ASHP): a heat source which extracts energy from the ambient outdoor air, even in cold weather, and raises it to a useful temperature. It delivers more energy (as heat) than it consumes (as electricity), the ratio known as **coefficient of performance (COP)**.

Ambient air: the air immediately surrounding the object of interest.

Average (mean) effective Coefficient of Performance (COP): the ratio of useful heat delivered to emitters and/or hot water outlets by a heat pump to the electrical energy it consumes over the time period of interest. This is smaller than the COP of the heat pump alone as it includes the delivery system heat losses (e.g. from the hot water tank).

Building fabric: the material and components from which a building is constructed, such as walls, floors, roofs, windows and doors.

CAPEX: capital expenditure; in this context, money spent on building fabric and heating system upgrades.

Cavity wall: a wall of a building featuring two layers of construction material separated by an air gap, usually up to 60 mm wide in UK construction before regulations required them to be insulated during construction.

Coefficient of Performance (COP): a ratio of useful heating or cooling provided to work required. COP is calculated by dividing the useful heat supplied (or removed) by a system by the work required by that system.

CWI: cavity wall insulation.

Domestic hot water (DHW): heated water supplied to taps, showers and baths for washing, etc.

District heat network: heat for multiple buildings is generated centrally then distributed by insulated pipework. An individual dwelling could connect to such a network with a **Heat Interface Unit** acting as the home's heat source, instead of a boiler, heat pump or other local heat source.

Dwelling: the building or part of a building in which people live.

Dynamic simulation: execution of a model (over a defined time period for a **dynamic** model) with boundary conditions and parameters set to represent a specific scenario, generating output ('results') which can improve understanding of the behaviour of the physical system.

EWI: external wall insulation.

Ground source heat pump (GSHP): a heat source similar to an ASHP but which extracts energy from the ground. The heat collector in the ground uses a circulating fluid either through a vertical bore hole or coils of tubing (known as a "**slinky**") buried in a horizontal trench.

Home Energy Services Gateway (HESG): connects energy service providers and device vendors with 'real-world' homes and consumers to trial new technologies, services and business models.

IWI: internal wall insulation.

MVHR: Mechanical Ventilation with Heat Recovery - provides filtered air into a building whilst retaining most of the energy that has already been used in heating the building.

OPEX: Operating Expenditure - in this context, energy costs for providing heating.

Party wall: a continuous wall shared by adjoining houses.

Peripheral floor insulation: insulation around the edges of the floor, from floor level to about 500 mm below ground (the main route for conductive heat loss from solid floors).

Refrigerant: a substance which is used by heat pumps to absorb heat at low temperature, then after compression release it at a higher temperature.

Solid wall: a wall of a building made from one or more layers of construction materials with no more than 10 mm gap between them.

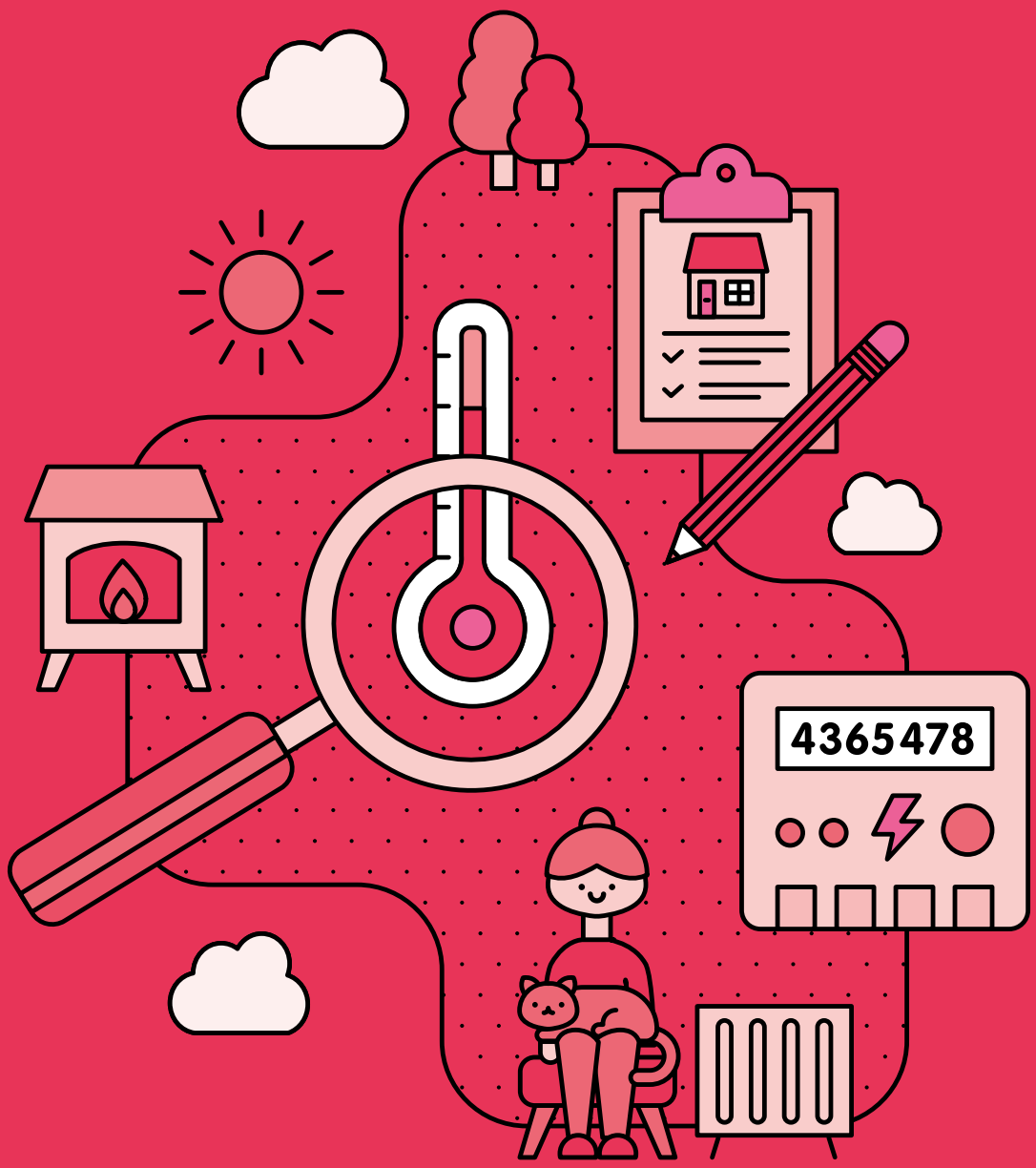
Space heating (SH): the provision of heat to the rooms of a building for the comfort of the occupants.

Thermal mass: the capacity of material (in this context, particularly the construction materials of a building) to store heat.

Thermostatic radiator valve (TRV): a valve fitted to standard domestic radiators which adjusts water flow through the radiator in proportion to the room temperature (near the TRV). They cannot achieve a precise room temperature, so are set by the occupants on a numerical scale (e.g. 1-5).

Wireless radiator valve (WRV): battery-operated valves, fitted to typical domestic radiators, which control the flow of hot water through the radiator according to signals sent wirelessly from the central control system.

Executive Summary



Nearly 20% of UK carbon emissions are produced from domestic heating. There is also uncertainty over the ability of low carbon heating solutions to match the household comfort currently provided by gas central heating for the majority of homes in the UK. Improving control of how we heat our homes could help to unlock low carbon solutions that can meet household comfort needs, save energy and reduce carbon emissions. It could also play an important role in delivering more sophisticated domestic energy services of the future. This report shows how better data and control combined with dynamic simulation of heating at home could help design and deliver a wide variety of more appealing and better performing low carbon heating solutions, including electric, hybrid and district heating.

Decarbonising domestic heating is an essential part of delivering a cost-effective transition to a low carbon energy system for the UK. This report summarises findings from analysis of upgrading five existing gas heated owner-occupied homes to low carbon heat. The aim was to explore upgrade pathways that were able to maintain or improve the heating experience of consumers whilst also reducing energy consumption and carbon emissions. To do this, every element of each home's heating system, including the heat source, radiators, pipes and pumps, as well as the fabric energy efficiency were considered. The operation of each home's heating system was modelled dynamically by simulating existing boiler operation together with radiator control and ventilation to realistically represent energy use and comfort. Heating energy use and household comfort was modelled for each room in relation to warm-up times and the duration different rooms achieved a target temperature range informed by detailed consumer research.

The analysis was undertaken using detailed data from real homes and consumers obtained as part of the first phase of the Smart Systems and Heat (SSH) programme, delivered by Energy Systems Catapult for the Energy Technologies Institute (ETI).

Key Findings

The key findings from the project were:

1. **Improved control of heating in individual rooms can improve comfort, energy efficiency and is an important element in the design, integration and operation of low carbon heating.** Recognising that payback and energy cost savings have not so far proved a sufficient driver to stimulate the domestic energy efficiency market, delivering improved comfort could provide a valuable mechanism for engaging householders and enabling industry to deliver better performing low carbon heating solutions.

2. **Electric heat pumps can provide good comfort in existing gas heated homes if sized and operated effectively in combination with targeted building fabric upgrades.** Operating heat pumps with a higher outlet temperature[1] can provide better thermal comfort with less costly and disruptive fabric and radiator upgrades.

3. **Hybrid heating systems could play an important role in transitioning to low carbon domestic heat.** Hybrids can deliver comfort and convenience and provide optionality to replace natural gas boilers with thermal storage, lower carbon gas or hydrogen boilers (from a repurposed gas network), or deeper energy efficiency improvements to the building fabric.

4. **The costs of low carbon heating upgrades cannot be met through energy savings alone.** Previous research has identified economic, political and technical barriers to the mass market uptake of low carbon heating [2]. This study has identified the potential for exploiting improved comfort, convenience and control to improve consumer engagement and potential for innovation to increase appeal and help reduce costs for consumers.

5. **Thermal storage in homes could help manage the demand placed on energy networks and reduce peaks by providing greater flexibility when energy is supplied and used in the home.** However, the thermal storage capacity required is typically larger than could be provided by the space available for hot water storage in most homes. Innovations in domestic thermal storage, such as use of phase change materials or delivering deeper levels of fabric retrofit, could contribute to managing peak heating demand.

6. **Improved data and simulation of domestic energy systems can help deliver low carbon heating solutions that deliver consumers the comfort they want and value.** The approach outlined in this report could be further developed and utilised by industry to better target retrofit and low carbon heating solutions and inform the design and delivery of domestic energy services[3].

1 e.g. up to 55°C in very cold weather, compared to the 35-45°C that is typical of current practice

2 Energy Technologies Institute (20185) Consumer challenges for low carbon heat https://www.eti.co.uk/insights/smart-systems-and-heat-consumer-challenges-for-low-carbon-heat

3 Energy Technologies Institute (2018) Domestic Energy Services https://www.eti.co.uk/insights/domestic-energy-services

Decarbonising domestic heating is an important part of delivering a cost-effective energy system transition for the UK

1. Introduction

Delivering low carbon heating to existing UK homes requires solutions that can be practically implemented and deliver standards of comfort equal to or better than those currently experienced. The UK's 28 million homes account for approximately 28% of total energy use[4] and 17% of all CO_2 emissions.[5] This is dominated by space heating, with contributions from hot water and cooking, produced by gas boilers in most UK homes (85% of dwellings in England in 2014[6]). Meeting the UK's commitment to reducing CO_2 emissions by 80% in 2050[7] depends on large number of homes switching to low carbon heating coupled with further decarbonisation of electricity.[8]

1.1 Electric Heating

Electric heating (including resistive and heat pumps), gas-electric hybrids and district heat networks are expected to play an important part in the UK's transition to a low carbon future.[9] They will need to be deployed in homes with diverse construction and thermal properties, different local environmental conditions and other constraints. These factors, and their ability to satisfy the needs and expectations of householders will determine their effectiveness in practice, and how widely and quickly they are adopted.

Although one of the potential solutions to decarbonised heating, a transition to electric heating will need to overcome persisting perceptions that electric heating is expensive, slow to respond, and lacks flexibility (hot water on demand) compared to gas combi-boilers. A large increase in electric heating, with peak power of 10-20 kW, will impact regional electricity networks, especially at times of peak demand. It will also require space for the installation of a hot water cylinder, often repurposed after the widespread switch to combi-boilers.

Large scale transition to heat pumps will increase peak demand for electricity, especially in peak periods. Until the electricity generation is substantially provided from low carbon sources, additional generation may be required at peak times from traditional high-carbon sources, making the marginal carbon intensity higher than using individual gas boilers. This supports the case for using hybrid heat pumps with gas boilers and thermal storage as a transition technology for space heating as part of the overall mix of heating solutions.

District heat networks are an alternative to heat pumps where technically feasible[10] but they depend on the development of local heat networks and households willingness to connect. Overcoming consumer inertia and establishing a positive reputation of alternatives to gas will be essential to persuade householders to install some form of heat pump to reach the uptake of around 50% that may be required by 2050.[10]

The transformation of domestic heat will not be achieved with a one-size-fits-all solution for every UK dwelling. Each home has a unique combination of building type, size and fabric, householders, neighbouring properties and space, location, and other factors which present different requirements and constraints and on the design of any changes necessary to reach satisfying, low carbon provision of heating.

A comprehensive evaluation of energy system changes requires a whole system approach which considers the impact of proposed changes on the broader energy supply system, including the energy network and other demand centres. For example, Energy Systems Modelling Environment (ESME)[11] and EnergyPath Networks[12] have been used to assess the impact of decarbonisation of heating on national and local energy systems.

4 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/729317/Energy_Consumption_in_the_UK__ECUK__2018.pdf
5 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/695930/2017_Provisional_Emissions_statistics_2.pdf
6 English housing survey, Energy Report, 2014: (UK Department for Communities & Local Government).
7 Climate Change Act.
8 https://www.theccc.org.uk/wp-content/uploads/2018/06/CCC-2018-Progress-Report-to-Parliament.pdf
9 Energy Technologies Institute - Options and Choices Update 2018.
10 ETI's Energy System Modelling Environment, v4.3.
11 https://www.eti.co.uk/programmes/strategy/esme
12 EnergyPath Networks modelling provides geographical analysis of local energy supply and consumption, see https://es.catapult.org.uk/projects/local-area-energy-planning/

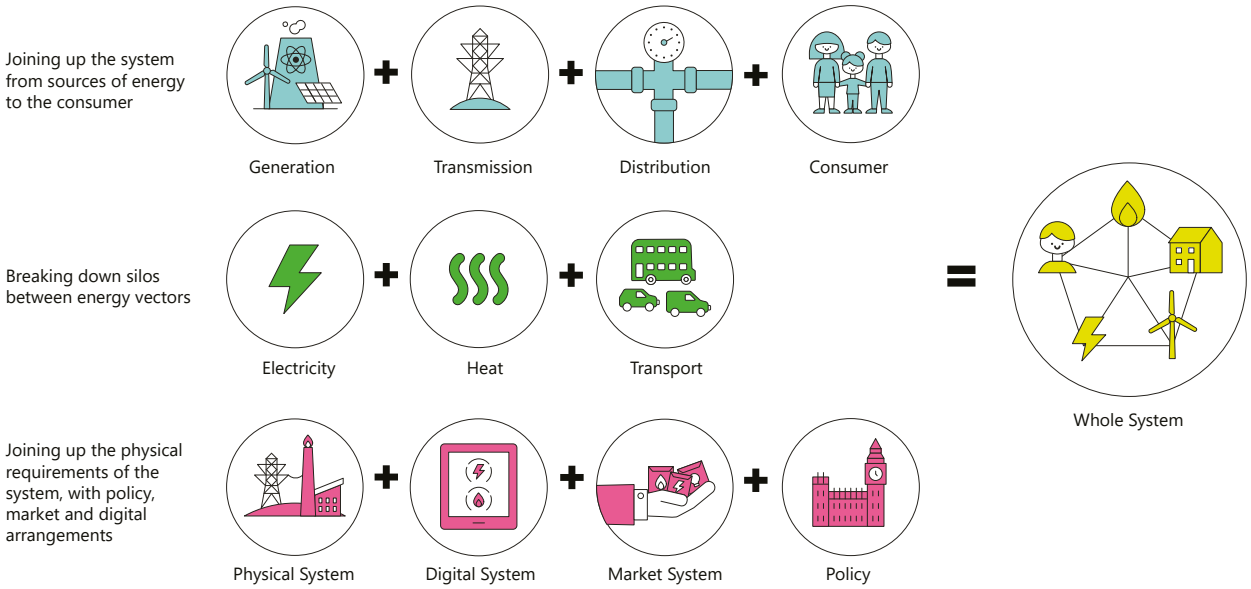
1.2 Purpose

This project examines the energy systems for individual homes using dynamic simulation modelling to understand the detailed interactions between the heating and control systems, building fabric, outside temperature and householder requirements. The results have been used to evaluate the impacts and benefits of implementing building fabric upgrades, low carbon heating systems, and thermal (hot water) storage to effectively reduce energy consumption and CO_2 emissions without compromising householder comfort. The model results have been combined with expertise on householder behaviour and a practical understanding of system design and installation to develop realistic and feasible pathways.

The modelling was underpinned by data from the Energy Systems Catapult's Home Energy Management System (HEMS) trial[13] as part of the Smart Systems and Heat Programme, which evaluated the impact of multi-zone heating control in 30 homes in winter 2016/17. This was combined with survey data on building type and construction, heating systems, and householder behaviour.

The outcome of this study is a set of potential upgrade pathways for five UK homes, all currently with gas central heating systems, and representative of over 30% of the UK's housing stock. The pathways present options for phased decarbonisation measures which can be scaled up to help meet regional and national targets for decarbonisation.

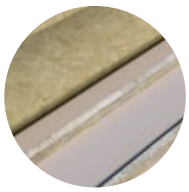
Figure 1: What is whole system thinking?



13 Smart Systems and Heat Phase 1, 'Trial of a consumer orientated advanced Home Energy Management System (HEMS), HEMS 2016/17 Winter Trial Analysis'.

1.3 Pathways to a comfortable, low carbon future

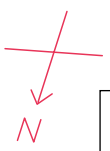
Detailed modelling toolkit for analysis of energy dynamics within UK homes, including consideration of the following:

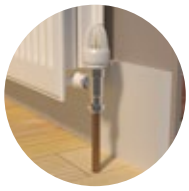


Roof build-up
including insulation, boards, air-gap, felting, tiles.

Meteorological data
Interpolated from data files containing hourly air temperature, insolation, wind speed & direction, humidity records.

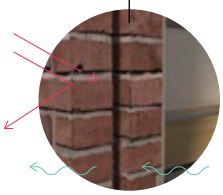
Room temperatures
Including influence of room contents (furniture, fittings etc).





Wet radiator network
Full thermal and hydraulic modelling of radiators, piping, valves and circulation pump.

Floors
Solid or suspended floors can be modelled, including floor coverings, structural elements, insulation, sub-floor vents and conduction through ground (including lateral losses).



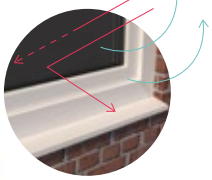
Some radiation is reflected and some is absorbed

Walls
Easily extended library of wall types typical of UK homes, including thermal conductivity and capacity of each layer of building material. Includes effect of built-in storage and chimney breasts.

Heating control
Range of standard and more sophisticated control systems can be included, enabling new variants to be quickly developed and tested.

Windows
Single/double glazed, typical range of UK window types and ages, with option of variable opening.

Some radiation enters room, some is reflected from window



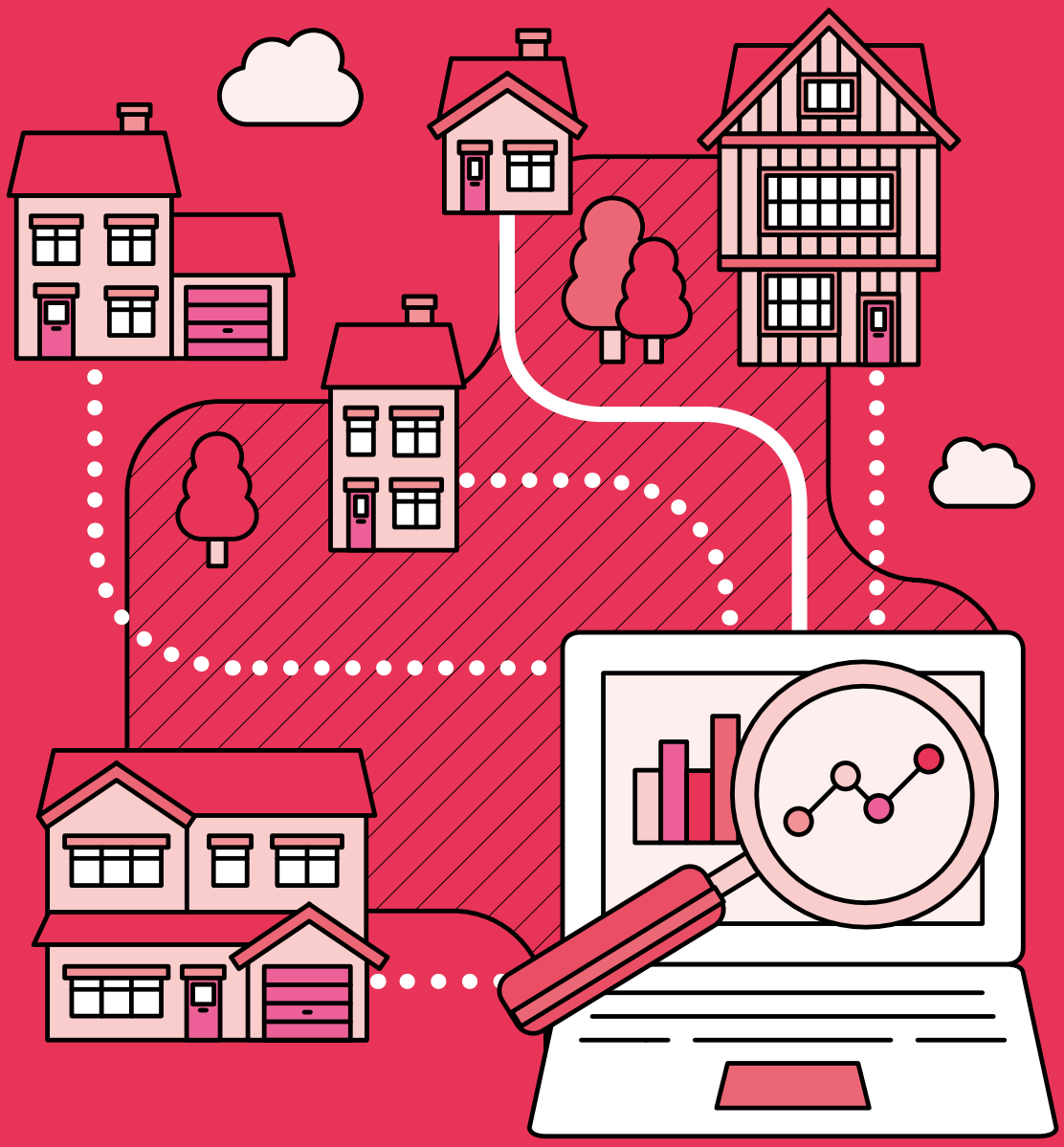
Heat escapes through window pane, frame and wall aperture.

Heat source
Can be easily switched to any other type of heat source (e.g. air-source or ground-source heat pump, hybrids, District Heat Interface Unit) and storage device (e.g. hot water cylinder, compact thermal storage).

Householder behaviour time profiles including

- desired temperature setting (per room if using multizone control)
- door and window opening
- occupancy and appliance usage
- DHW usage patterns.

2. Approach



This study used data from real homes obtained from an advanced consumer-oriented trial to create five representative UK homes, each with different characteristics in terms of size, type, age, context and occupant behaviour (an example is shown in Figure 2). Realistic contexts were included to reflect the likely availability of heat networks, external space constraints and access issues. Dynamic simulation modelling was then used to investigate potential low carbon upgrade pathways, combined with consumer and building insights. The outcome was a pathway showing progressive improvements to householder experience in terms of comfort, energy savings and reductions in CO_2 emissions. The study also considered the short and long-term costs, secondary benefits such as improved property values, and impacts such as building disruption.

Most households in the UK currently use gas central heating systems for hot water and central heating. The Smart Systems and Heat (SSH) programme has found that to accelerate the take-up of low carbon heating, the market must provide low carbon heating systems compellingly better than those currently available.[14] As well as energy saving and CO_2 emissions, comfort indicators have been developed to assess potential pathways, recognising that consumers value comfort and convenience in addition to financial return on investment when making decisions about improving their homes.

The two key comfort indicators considered were:

- the duration of when air temperature was below target in each heated room, and;
- the warm-up times taken for each room to reach target following an unheated period.

To accelerate the take-up of low carbon heating, the market must provide low carbon heating systems compellingly better than those currently available

14 https://www.eti.co.uk/insights/how-can-people-get-the-heat-they-want-without-the-carbon

2.1 The Homes

Figure 2: Example house design and floorplan

The five representative households all currently use a gas combi-boiler to provide space and water heating. Their other characteristics are summarised below:

- **House A** – 1950s, three-bedroom, semi-detached home occupied by a family with two school-age children with working parents. The house has partially insulated cavity walls and loft, with older double-glazed windows.
- **House B** – 1920s, two-bedroom, terraced home with a single occupant who works from home four days per week. The house has solid walls, some roof insulation and older double-glazed windows.
- **House C** – 1930s, three-bedroom, semi-detached home, occupied by a young family, meaning that the house is occupied most of the time. The house is solid brick with a conservatory and an extension constructed with insulated cavity walls. It has relatively new double-glazed windows.
- **House D** – 1970s, three-bedroom mid-terrace home occupied by an elderly couple. The house has uninsulated cavity walls, an insulated loft and older double-glazed windows.
- **House E** – 1980s, larger three/four-bedroom detached with later extensions and conservatory. The home is occupied by a working family with teenage children. It has insulated cavity walls and the loft of the original house is also insulated. It has modern doubled glazed windows upstairs, with older windows downstairs.

More detailed information on the five homes and households is provided in Table 2-1 (overleaf).

2.2 Household Assessment

2.2.1 The Households

Building survey data was combined with the results of householder interviews conducted during the HEMS field trial of 30 houses to create five representative households for analysis. The interviews characterised household heating requirements and attitudes towards changes in comfort offered by multi-zone control. Householder experience before and during the trial was captured from the interviews, for example domestic hot water usage, heating profiles, room occupancy, window and door opening, and use of secondary heating. The resulting set of composite homes used in the study is shown in Table 2-1 (overleaf).

Table 2-1: Summary of composite homes for upgrade analysis

Home	Household	House	Current state of building fabric	Proportion of stock[2]	Typical floor area[2]
A	Family with two children	1950s semi-detached house, 93 m^2 heated area[1]. Rural location	Inadequate insulation, old windows & doors	9.0%	70 m^2
B	Single man, working at home	1920s mid-terrace house, solid walls, 68 m^2. Urban location	No wall or floor insulation, old windows & doors	8.2%	60-85 m^2
C	Family with two young children	1930s semi-detached house, solid walls, 100 m^2 heated area[1]. Suburban location	No wall or floor insulation, new windows & doors	7.7%	90 m^2
D	Retired couple with visiting grandchildren	1970s mid-terrace, 76 m^2. Suburban location	No wall or floor insulation, old windows & doors	3.0%	75-90 m^2
E	Family with two teenage children	1980s detached, 130 m^2 heated area[1]. Suburban location	Loft insulation below modern standard, old windows & doors downstairs, heated conservatory	3.2%	90-150 $m^{2,}$

Note 1: excluding enclosed spaces without radiators, including hall/stairs/landing if heated.
Note 2: data taken from 'Cambridge Housing Energy Tool 2011' available at: 'https://www.gov.uk/government/statistics/cambridge-housing-energy-tool-guidance-note' and '2011 Cambridge Housing Model V3.02' available at: 'https://www.gov.uk/government/statistics/cambridge-housing-model-and-user-guide'.

2.2.2 Upgrades

A model was created for each of the five homes,and simulations carried out to establish the base case for energy performance and household comfort. Dynamic simulation modelling was used to investigate the impacts of technically feasible combinations of upgrades to building fabric, heating control and heating appliance technologies which were compared with the base case. Outputs from the model were used for quantitative comparisons of the impacts of potential upgrades.[15] The analysis included consideration of other factors affecting the choices a consumer might make such as costs, convenience and disruption.

15 The model was verified against the Salford Energy House, a fully instrumented pre-1919 end-terrace house in a controlled test environment. https://www.salford.ac.uk/built-environment/laboratories-and-studios/energy-house

Building Fabric Improvements

There is potential to improve the thermal performance of all of five homes through building fabric upgrades including enhanced insulation, double-glazing, increased airtightness and improved ventilation. These upgrades can provide satisfying levels heating and comfort from a lower power heating system, reducing the energy consumption, CO_2 emissions, and peak demand on local energy networks. This is not an option with gas combi-boilers which are sized for hot water demand.

The fabric upgrades considered in this study include wall insulation (cavity, internal and external) loft insulation and insulation of flat roofs, upgrade of conservatory roofs and glazing, insulation of solid and suspended floors, replacement doors and windows, and draught proofing. Together these upgrades can reduce overall heat loss to less than 60 W/m^2 of floor area compliant with current new-build targets. Householders can be expected to undertake less disruptive improvements first, such as cavity wall insulation, loft insulation and replacement windows and doors, and are likely to defer more disruptive upgrades to coincide with other refurbishment work.

Occupancy may significantly influence the preferred pathway. For example, in relatively sparsely occupied properties, e.g. House B, the single householder was willing to undertake extensive fabric upgrades in unison, which would be too disruptive for a family, or elderly householders.

Heating Control

Most UK homes currently rely on a single room thermostat located centrally, such as a hall or living room, to control temperature throughout a home by turning heating on and off in response to the temperature recorded at the thermostat, overriding local control by thermostatic radiator valves (TRVs). This arrangement was assumed as the base case for all the houses modelled. However, the central thermostat can conflict with the temperature settings at the TRVs causing overheating or underheating. Multi-zone control, by which temperature is controlled using a thermostat and managed radiator control in each individual room, promises greatly improved temperature management using digital wireless technology.

Technological development, for example the roll-out of smart meters, familiarity with telecommunication and control devices, and improved usability, are stimulating a market for more sophisticated control devices to control the home environment. The HEMS project demonstrated that multi-zone control, which requires a new controller, thermostat and wireless TRVs, is not particularly invasive and generally acceptable to the trial participants. Dynamic simulation modelling demonstrated that improved control benefits all homes in the study, shortening warm-up times, preventing overheating and increasing the duration when temperatures are within the target temperature range, irrespective of building fabric or heating system upgrades.

There is the risk of an unintended consequence that by providing improved control to individual rooms, householders can programme high room temperatures in previously cold rooms, which, without fabric upgrades, increases energy consumption in, for example, houses D and E.

Heating Technologies

85% of UK households currently use gas boilers for space and hot water heating. Therefore, this was selected as the base case for the five representative homes. Most households replace their gas boiler with another when it fails, or if offered an exchange or scrappage incentive. Moving away from gas requires access to an equivalent heat source with a mature supply chain, and minimal disruption to the household heating and hot water system. However, disruption may be more tolerable if the changes deliver benefits of improved control, reduced energy costs, and for some, reduced carbon emissions. Three primary heating technology options were considered to decarbonise domestic heating:

- **Heat Pumps** - air source and ground source

Electrifying heat in individual homes using a heat pump can make a very significant contribution to decarbonising heat in our homes and buildings.[16] Air source heat pumps (ASHPs) extract heat from the air using a heat exchanger. They are relatively easy to install and require less space but have slightly higher running costs than the ground source equivalent. Ground source heat pumps (GSHPs) extract heat from the ground using a horizontal or, more commonly, a vertical heat collector which adds to their cost. Both require a hot water tank to act as thermal storage and provide hot water on demand. Heat pumps have a relatively high coefficient of performance (the ratio of electrical energy consumed to the heat energy produced, compared with gas boilers).

Low-temperature heat pumps operate at lower water temperatures than gas boiler systems and require larger radiators to provide enough heat in cold periods, therefore radiator upgrades (or underfloor heating) is included with this option. Even with higher performance radiators, low temperature heat pumps may be unable to achieve or maintain target room temperatures in colder periods. A higher rated circulation pump might address this for a minor increase in cost and peak power demand.

High temperature heat pumps (55°C maximum temperature with a 60°C legionella cycle) reduce the need for radiator upgrades at the cost of greater power consumption. Modelling showed that in all homes except for House D whose downstairs radiators are undersized, simply upgrading radiators to modern standards (without increasing their size) was sufficient to meet comfort targets. However, increased power demand, whilst negligible for individual homes, in large numbers could impact the local distribution network.

Modelling showed that when combined with building fabric upgrades, lower power heat pumps (6-8kW) operating at higher output temperatures and with hot water storage, were capable of meeting space heating and domestic hot water requirements for all five homes, at the cost of a reduced Coefficient of Performance (COP) of 2.5-2.7.

Increasing hot water storage allows the heating energy demand to be spread throughout the day, avoiding times of peak demand. The required storage capacity is related to household heating patterns. A smaller storage tank, and less space to house it, is required when the house is heated throughout the day (for example Houses A, D and E), at the cost of increased energy consumption compared with a home allowed to cool.

16 CCC Reducing Emissions Progress Report to Parliament June 2018.

- **Heat Networks** - connecting homes and neighbourhoods

Heat networks are used to distribute hot water to a group of homes from a heat source through a network of insulated pipes. The heat source may be a gas boiler, a biomass boiler or a combined heat and power (CHP) plant. They provide an opportunity to decarbonise the heat source for a larger network of homes and are likely to play an important role in the decarbonisation of heat in areas where it is technically and economically feasible, for example in urban and suburban areas. Of the homes in this study, a connection was considered feasible only for House B where it was projected to deliver greater heat output and CO_2 emission reductions sooner than those for a heat pump.

Heat networks can match the levels of comfort provided by gas boilers with minimal additional upgrades. Dynamic simulation modelling shows that, in combination with fabric upgrades, they can deliver acceptable levels of comfort at lower supply temperatures, making a wider range of low carbon heat sources feasible.

- **Hybrid solution -** heat pump and gas boiler combination

A hybrid solution was included as a transitional solution in which a heat pump provides base load space heating boosted by the existing gas boiler which also heats the hot water. Hybrids guarantee current levels of comfort for modest reductions in energy costs and carbon emissions but have higher maintenance costs and defer the greater benefits of an all-electric solution. A hybrid was found to be an attractive transitional step for Houses A and C which have relatively recent combi-gas boilers.

Switching to low carbon gas such as hydrogen or biogas is a potential option for decarbonising large numbers of homes simply by converting their existing gas appliances. However, this option requires repurposing the natural gas network and significant infrastructure development and is beyond the scope of this study.

Wider UK energy context

In terms of the consequences of widespread adoption of such upgrade pathways on the national energy system and the impact of changes to energy networks on individual homes, the potential impact on peak grid demand can be reduced by using thermal (hot water) storage technologies. These enable the spreading of electrical power demand for heating over more hours in the day, with additional benefits to heating performance delivered to the householders.

A whole-system approach to local area energy planning is necessary to coordinate strategic decisions on the targeting of building improvements, future power, gas and heating networks and associated low carbon heating technologies in a local area.[17] Detailed consideration of individual homes will contribute to wider system decisions to prioritise the needs of consumers, and to ensure due consideration is given to the impact of large-scale deployment and the geographic concentration of upgrades in a given area. The focus on homes must also fit into the broader picture of energy transformation, including distributed supply, roll-out of electric vehicles, energy management and the establishment of alternative business models such as ones offering heat, power and mobility as services, all of which will influence how energy is supplied and used by households in the future.

17 Smart Systems and Heat Phase 1 WP2 Bidders Pack D11 Insight report 3: Local area energy planning implications for government.

2.3 Technology Assessment

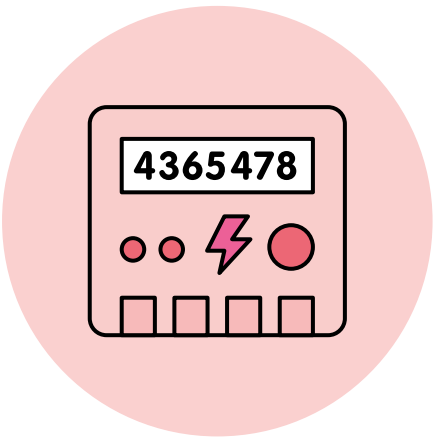
Identifying technologies suitable for installation in the home is essential to design practical pathways which meet the needs of householders and reduce carbon emissions. Initial assessments of physical suitability were based on real house surveys and local area energy planning analyses[18] adapted for the five homes archetypes. Informed by insights from SSH Phase 1, the technologies assessed in this study are listed below:

Building fabric:

- Wall insulation (external, internal, cavity);
- Floor insulation (for suspended and solid floors, peripheral external trench);
- Roof insulation (main roof, flat roofs, conservatories);
- Windows and doors.

Heating system components:

- Heat emitters (high power radiators, under floor heating);
- Heating control (multiple measurements, radiator valves, range of control strategies);
- Heating water circulation pumps (range of characteristics);
- Gas boilers (for modelling current situation, both combination and system variants);
- Air source heat pumps (ASHPs);
- Ground source heat pumps (GSHPs);
- Stratified hot water storage tanks (heated by hot water coil supplied by heat sources above, with optional resistive electric heating);
- Hybrid ASHP with gas combi-boiler;
- District heating using an indirect heat interface unit (HIU).



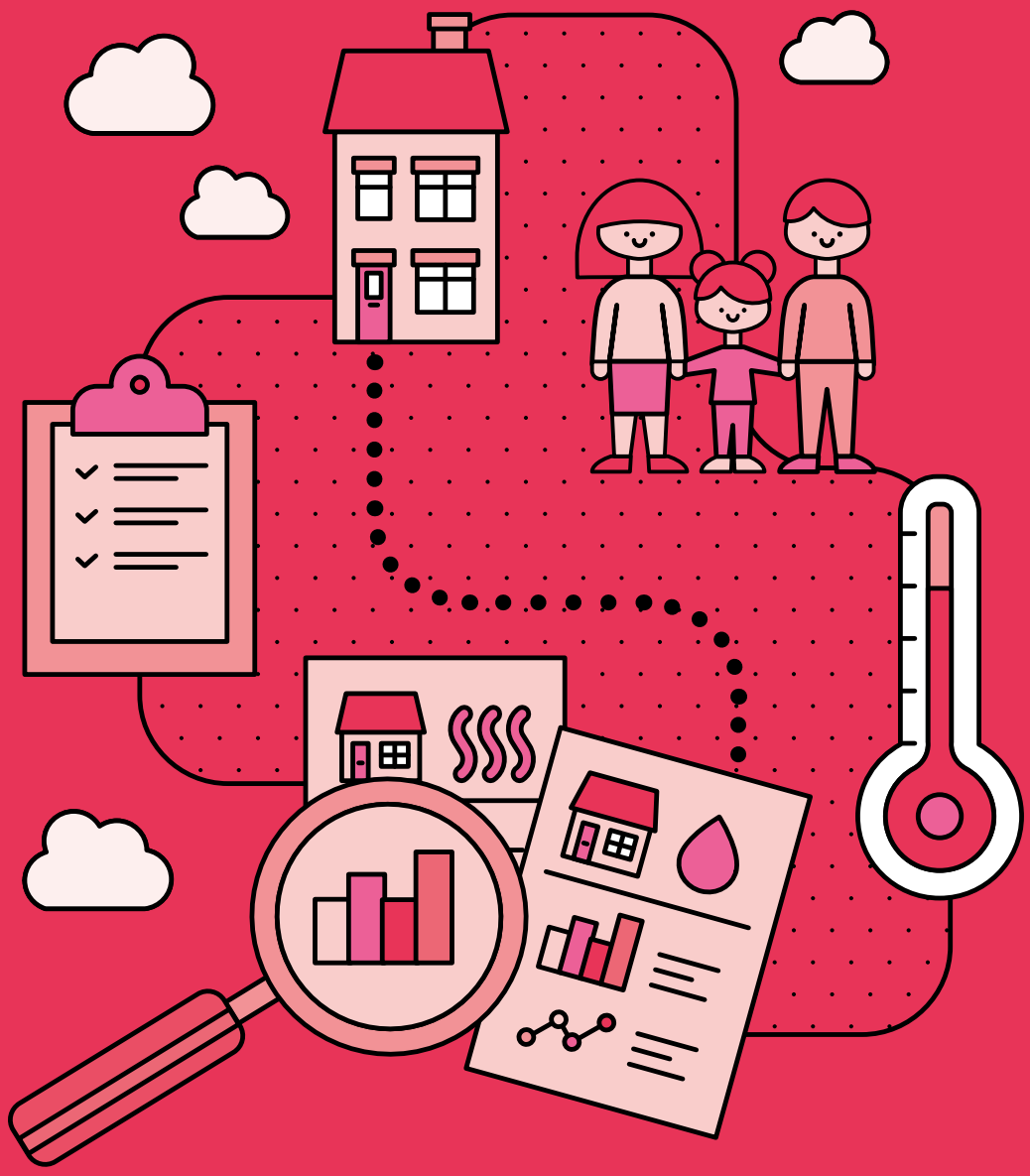
18 see https://es.catapult.org.uk/projects/local-area-energy-planning/

The following technologies have been partially included, excluded or deferred from the modelling at this stage:

- **Supplementary resistive heating for use with heat pumps:** this was modelled but found to be unnecessary to achieve good comfort in the scenarios simulated;
- **Resistive and electric storage heaters:** excluded because of high power demands on electricity supply and distribution infrastructure compared with heat pumps;
- **Secondary heating:** the aim was to provide comfortable room temperatures without recourse to secondary heating, which is often used to provide effects other than simple warmer air temperatures, such as ambience and visual impact;
- **Thermal storage** (other than hot water tanks): currently this has been analysed separately to the pathway development (see section 4);
- **Mechanical Ventilation with Heat Recovery (MVHR):** a key component of building fabric upgrades, along with improving air tightness. However, it is difficult to reliably quantify the effect on air changes per hour (ACH) of a particular upgrade (such as sealing all window frames and skirting boards) – this may be the subject of future sensitivity analyses;
- **Biomass heating:** whilst likely to play an important role in the future UK energy system,[19] its reliance on carbon capture and storage to reduce overall emissions, together with concerns over air quality, make it less suitable for wide scale deployment in individual homes for domestic heat, and it has therefore not been modelled. It has, however, been included in the technology suitability assessments for each home;
- **Solar thermal & solar PV:** these technologies and their role in carbon reduction have not yet been simulated. For future study, they have been included in the technology suitability assessments for each home;
- **Cooling:** this may play an increasing role in domestic thermal comfort in the UK, as it is already in apartment blocks. It has not been modelled in this study but is expected to be included in future studies;
- **Phase-change materials:** for houses with limited thermal storage, in the fabric or the hot water tank, phase-change materials can be used for heat storage. This option is not yet widely used and excluded from the study.

19 https://www.eti.co.uk/insights/delivering-greenhouse-gas-emission-savings-through-uk-bioenergy-value-chains

3. Low Carbon Heating Pathways

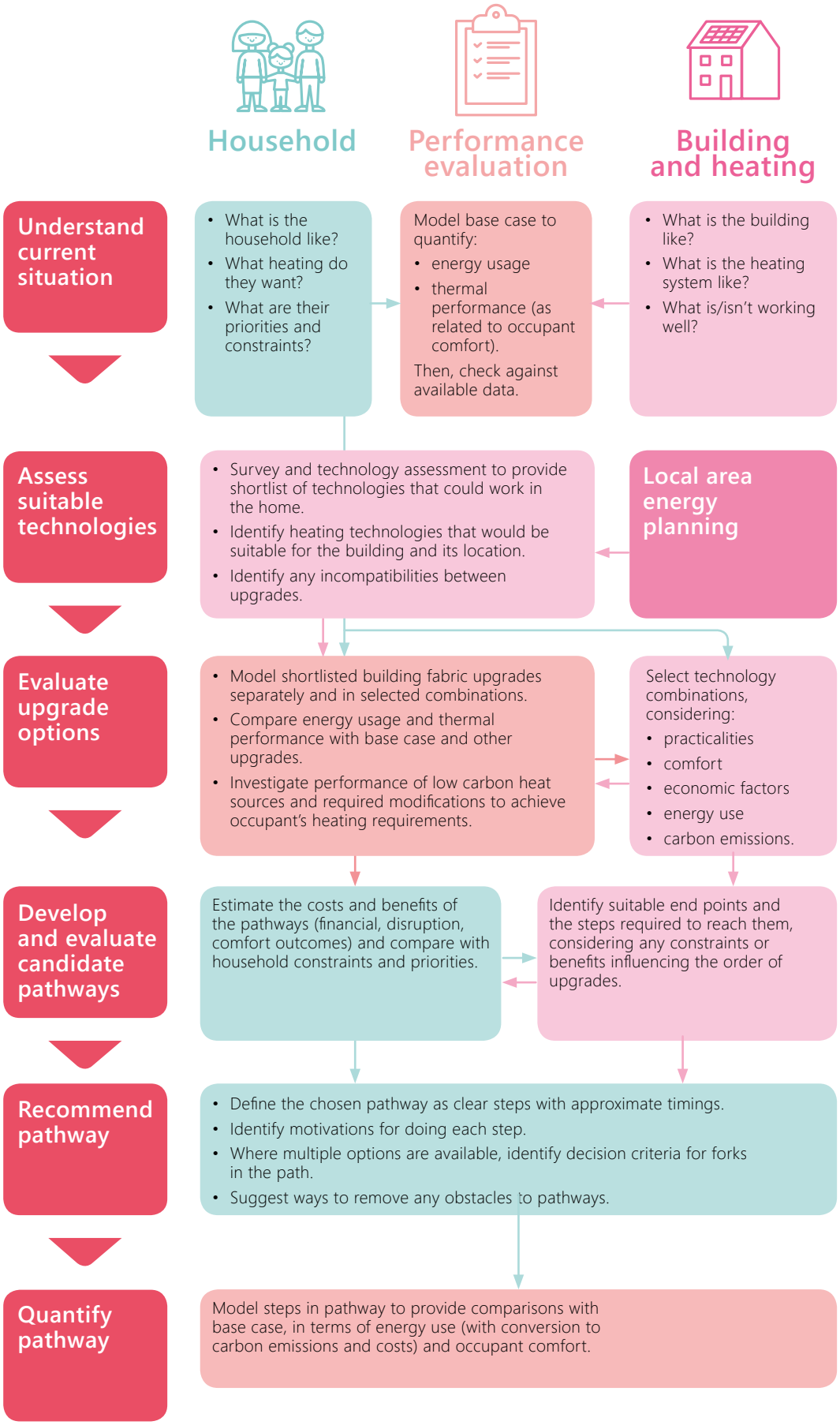


The methodology for developing the model upgrade pathways up to 2050 for the five homes illustrated in Figure 3. The pathway is defined up to and including the replacement of the heat source with fully electric or district heating which is expected to occur within 15 years, the approximate life span of existing gas boilers. Further upgrades can be expected in subsequent years based on updated projections of the carbon intensity of electricity and heat supply to 2050 (Table 3-1).

Pathways for each of the five houses are included in Appendices A-E. To produce each pathway, detailed survey data for each home was combined with information on household behaviour and home heating control to produce a base case model of the home. A detailed household questionnaire was used to collect information on attitudes towards comfort, costs and heating technologies reflecting household composition and priorities. The impact of various upgrade options, including building fabric, multi-zone control, conversion to electric heating and the addition of thermal and electric storage, was then simulated for a range of future scenarios and compared with the base case. Dynamic simulation modelling was used to optimise thermal comfort from various combinations of low carbon heat source and technically feasible fabric upgrades. The results could be used to inform decision making at household level and for regional energy planning.

Heating and domestic hot water system efficiency were compared in terms of the coefficient of performance, being the ratio of heat output and energy input which provide an indicator of the effective heating efficiency. Thermal comfort was assessed in terms of room mean air temperature, room warm-up times, and the percentage of time spent outside the target temperature range. Comfort is influenced by more factors than air temperature, for example the wall and floor surface temperatures and the thermal characteristics of furniture. The modelling therefore included building fabric upgrades (e.g. wall and floor insulation) which affect surface temperatures and affect householder comfort.

Figure 3: Pathway development process highlighting the necessary interactions between disciplines



To avoid over-optimistic predictions of comfort achievable from low carbon heat sources with relatively low output (compared with gas boilers), the homes were modelled for a winter period using mean temperature data for the north of England (Newcastle-upon-Tyne). Houses with shared walls (terraced and semi-detached) were assumed to have a similar heating profile, preventing heat transfer to the adjacent house. Conservative values of thermal efficiency were selected for materials, rather than manufacturers' best estimates, to better represent practical installation issues such as window and door frame design, air tightness, thermal bridging, and heat losses around apertures. For example, U-values of 2.0 $W/m^2/K$ were assumed for replacement double glazing, lower than the manufacturer specification for many new products.

The study included a financial analysis of the potential impact of upgrade pathways in terms of the capital cost of purchase and installation, and future household energy bills. A relatively high time resolution is required to assess the timing of peak demand in relation to the capacity of the local electricity network and the timing of electricity generation at different times.

3.1 National Energy System

For this analysis, future projections of energy prices and the carbon content of the grid are taken from the Energy System Modelling Environment (ESME) "Patchwork" future energy scenario.[20] Table 3-1 and Table 3-2 show projected national and annual average values for carbon intensity and energy costs respectively, differing from the prices paid by consumers due to the exclusion of VAT, supplier operating costs and any taxes and obligations on the energy industry. Table 3-1 shows the carbon intensity of electricity reducing from 0.36 to 0.002 $kgCO_2/kWh$ from 2020 to 2050 due to the decarbonisation of power supplied to the grid. This will impact directly on the benefit-cost ratio for low carbon domestic heating systems. Table 3-2 shows the cost of electricity increasing from 9.5 to 20.4 p/kWh and the cost of local heat increasing from 10.7 to 29.1 p/kWh over the same period.

Table 3-1: Carbon intensity, $kgCO_2/kWh$ annual national averages (ESME)

Year	Electricity	Natural Gas	Natural + Green Gas Mix	Local/District Heat
2020	0.3633	0.1836	0.1816	0.1607
2030	0.0926	0.1836	0.1748	0.1371
2040	0.0088	0.1836	0.1646	0.0045
2050	0.0018	0.1836	0.1454	0.0017

Carbon intensities vary over shorter timescales with the power generation mix, with weather, time of day, and regional and national peak demands. But even from 2050, when annual average carbon intensity of electricity is expected to have fallen to 1% of that of natural gas, marginal carbon intensities during peak demands may still be higher than those of domestic gas boilers (e.g. if open-cycle gas turbine power stations still provide generation during the peaks). This aspect is considered when evaluating thermal storage for reducing peak demands (section 4) and heat pump-boiler hybrids as a transitional technology.

20 For more information about the ESME future energy scenarios, see https://www.eti.co.uk/insights/options-choices-actions-uk-scenarios-for-a-low-carbon-energy-system

Note that the ratio of costs of gas to electricity shown in Table 3-2 gives an idea of the overall energy consumption reductions (at individual dwellings) required for electric heating to reduce energy bills for consumers (using the current prevalent business model of charging a fixed price per kWh). Achieving such reductions appears to be very challenging until sometime after 2040.

Table 3-2: Energy costs (excluding profit and tax) p/kWh annual national averages (ESME)

Year	Electricity	Natural Gas	Ratio of gas/elec cost	Local Heat
2020	9.54	2.88	30%	10.72
2030	15.17	3.45	23%	16.24
2040	27.26	6.54	24%	32.26
2050	20.43	9.00	44%	29.15

Note: the gross (higher) heating value of natural gas is used throughout when stating gas energy consumption values.

The pathways are based on current predictions of future energy prices and carbon emission targets. They include projections of the carbon intensity of the electricity supply but exclude external factors such as policy and regulation and market behaviour and are determined by many factors and cannot be predicted with confidence.

3.2 Energy Savings and CO_2 Emission Reductions

Table 3-3 shows a summary of the energy consumption results from the simulations, indicating the reduction in energy used and carbon emitted, relative to the original homes, necessary to achieve the target levels of thermal comfort. The differences in energy savings between full fabric upgrades and the ASHP cases include reduced losses from the gas boiler (typically 9-11% for a condensing boiler) and the increased efficiency of the heat pumps (typically producing about 2.5 times more useful heat than energy input). Greater savings might be achievable if the heat pump coefficient of performance (COP) is increased with lower outlet temperatures, but at the expense of comfort, longer warm-up times and greater costs of further fabric and radiator upgrades.

Table 3-3: Summary of energy consumption and carbon savings

House	Annual energy consumed for heating and DHW, MWh (% saving with respect to single zone base case)				Final carbon savings, %	
	Base case single zone	Base case multi-zone	Full fabric upgrades[1]	Heat source change[2]	2030	2040
A	14.7	13.8 (6%)	11.0 (25%)	4.0 (72%) [ASHP]	86%	99%
B	17.0	15.4 (9%)	9.8 (42%)	3.2 (81%) [ASHP], 7.9 (53%) [DH]	91% 82%	99% 99%
C	15.0	13.2 (12%)	9.8 (34%)	3.7 (75%) [ASHP]	88%	99%
D	14.0	14.9[3] (-6%)	11.3 (20%)	3.9 (72%) [ASHP]	86%	99%
E	16.3	16.8[3] (-3%)	15.0 (8%)	5.0 (69%) [ASHP]	85%	99%

Notes: 1 – includes multi-zone control and radiator upgrades (where recommended); 2 – not all the heat source options considered are shown; 3 - increases in desired or achieved room temperatures can increase energy consumption with multi-zone control, but also provide improved comfort.

Comparing the cost ratios shown in Table 3-2 with the final energy savings in Table 3-3 indicates how soon these upgrades will reduce running costs below those of gas boilers (e.g. the 24% ratio in 2040 would require a 76% saving to break even). It is expected that heat pump performance will improve over the coming years as the market increases, and for the same outlet temperature (related to comfort) an increase in COP from 2.5 to 3 gives a 3-5% further energy saving, relative to the base case, which will assist slightly with the running cost comparison with gas boilers.

Installing a heat pump in series with an existing gas boiler was shown to perform as well as a hybrid heat source. This may be preferable to an "off the shelf" hybrid product since most of the houses had boilers with around 10 years of life remaining. The boiler continued to provide domestic hot water on demand, while the control of the two heat sources for space heating was very simple: the heat pump operated when there was demand for heating (provided the outside air temperature was higher than a threshold), then the boiler would boost the outlet temperature if the heat pump outlet was more than 2°C below their common outlet temperature. With an adequately sized heat pump (or sufficient fabric upgrades) this was very effective, allowing the boiler to warm up the rooms and then let the heat pump keep them warm.

More sophisticated approaches should be the subject of further study, but this method would be simple to implement in an add-on controller when integrating with an existing system (which would also require some bypass valves for single source operation). This form of hybrid also allows the household to remove the boiler and install hot water storage to rely solely on the heat pump at the end of boiler life.

Ground source heat pumps were found to give a smaller increase in average COP than the air source type. This was partly due to its high outlet temperature but was also found to relate to the modest difference in average air temperature and ground temperature around the heat collector when buried at a depth of 1-1.5m. Vertical bore holes and regions with greater extremes in both seasonal and diurnal air temperature variation can be expected to give a larger difference in performance. Further study to investigate these findings, and the impact of GSHPs on ground temperatures, is recommended.

Using a **heat interface unit (HIU)** to connect to a district heat (DH) network performed, as expected, similarly to a gas combi-boiler. Improving the thermal performance of the connected houses can significantly reduce peak loads and could allow lower network temperatures, with consequent benefits to DH system design and operation. To offset potential concerns about taking the heat source out of the householders' direct control, increasing the coverage of district heating requires careful management. For example, it would be prudent to announce firm plans to provide DH in a location well in advance to avoid householders installing new heating appliances which quickly become redundant, allowing for the expected life time of a gas boiler (around 15 years) – which leaves time for only two cycles of heating replacement before 2050. Also, managing or regulating heat suppliers should be considered to reduce the perceived risk of being tied to a single heat supplier, ensuring they deliver a satisfactory level of service, contain costs and maintain availability (minimising the impact of scheduled and unplanned maintenance).

Regarding building fabric upgrades, Table 3-4 indicates typical energy savings predicted by the simulations for those deemed feasible for each house. Note that not all these fabric upgrades were included in the final pathways, and further improvements were gained by heating system upgrades not included in this table.

The predicted impact of improvements to building fabric are mostly in line with expectations and vary with the original condition of the houses. Wall insulation, where there was none, predictably gives the largest savings. The benefit of increased loft insulation in contrast is small (all houses studied have at least 75 mm in their main roofs already). Insulating suspended floors saves significant energy but requires careful attention to ventilation. Solid floors were shown to lose heat primarily horizontally from the 500 mm immediately below floor level without peripheral insulation, making insulation of the entire floor area unnecessary and potentially detrimental to comfort if too much sub-floor thermal inertia is isolated from the room.

Table 3-4: Energy savings in mid-winter, relative to base case, from feasible building fabric upgrades

House	Wall Insulation	Floor insulation	Roof/loft insulation	New windows	New doors
A	9.7%	2.0%	1.2%	5.1%	4.3%
B	24.0%	5.6%	1.6%	4.3%	1.6%
C	17.9%	n/a	1.7%	n/a	n/a
D	12.0%	2.4%	1.6%	6.4%	0.4%
E	n/a	1.4%	0.8%	4.8%	0.5%

Unsurprisingly, the modelling confirmed that conservatories lose significant heat and have a negative impact on comfort in other rooms, especially if heated by a radiator in winter. This was the case in House E, where reducing its conservatory's target temperature to 15 °C when not in use saved 3% of the energy used for heating (in a large detached house). Insulating the roofs and upgrading the conservatory windows is expensive but makes a significant improvement to the utility of these spaces.

In the pathways developed above, the heat pump operations, although limited in power drawn from the grid, will still tend to demand peak power at about the same times for each house. If 15 million UK dwellings converted to electric heat this could impose a demand on the supply infrastructure of about 40GW, equivalent to about 40% of its current maximum capacity.[21] Reducing this peak load would require the demand from heat pumps to be spread more evenly over the day. Section 4 explores the use of thermal storage to achieve this, based on the heat demand profiles generated for the houses during the pathway development.

21 "In 2016, total installed capacity across all [distribution] networks in the UK was 98.5 GW" from Digest of UK Energy Statistics (DUKES) 2017, Chapter 5: electricity https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/633779/Chapter_5.pdf

3.3 Key Findings from Pathway Development

Pathways for each of the five houses are included in Appendices A-E, summarised in Table 3-5. They include floor plans for each house together with the proposed locations of their new heat sources (ASHP, HIU, or GSHP).

Table 3-5: Pathways for each of the five houses

House	Stage 1	Stage 2	Stage 3	Stage 4
House A 1950s semi-detached	Cavity wall insulation Multi-zone control (Yr1-5)	New doors & windows Four new high output radiators (Yr3-13)	6kW ASHP with EITHER existing boiler OR hot water cylinder (Yr6-12)	
House B 1920s terraced	Insulate suspended floor Multi-zone control (Yr1)	New doors & windows insulate walls One new high output radiator (Yr3)	6kW ASHP with hot water cylinder OR interface to district heating network (Yr6-10)	
House C 1930s semi-detached	More loft insulation Multi-zone control Four high output radiators (Yr1)	8kW ASHP with existing boiler (Yr2-5)	Internal wall insulation (Yr5-10)	Remove boiler Add hot water cylinder Insulate conservatory and extension roofs (Yr10-15)
House D 1970s terraced	Insulate walls More loft insulation Multi-zone control Two larger, high output, ground floor radiators (Yr1)	New windows and doors (Yr6)	6kW ASHP with addition of hot water cylinder (Yr10)	
House E 1980s detached	Insulate extension loft Multi-zone control Limit conservatory set-point (Yr1)	Opaque insulated roof and ultra-low U windows on conservatory (Yr4)	New windows and doors downstairs Larger heated towel rail (Yr7)	8kW ASHP OR 8kW GSHP, both with addition of 250l hot water cylinder (Yr10)

In all cases, combinations of fabric and heating system upgrades with multi-zone control improved comfort and energy performance compared with fabric-only or heating system upgrades on their own. In some cases, a hybrid heat pump provided an effective transitional option and retained flexibility in relation to planning and investment in local energy networks.

In each of the five case studies, air source heat pumps were selected as the replacement heat source. District heating was identified as a potential solution for House B, but running costs are projected to be far higher than those for a heat pump. A ground source heat pump was not selected for any of the five houses. A hybrid heat pump/gas boiler was selected as a transition technology for House C but eliminated in all cases by 2050.

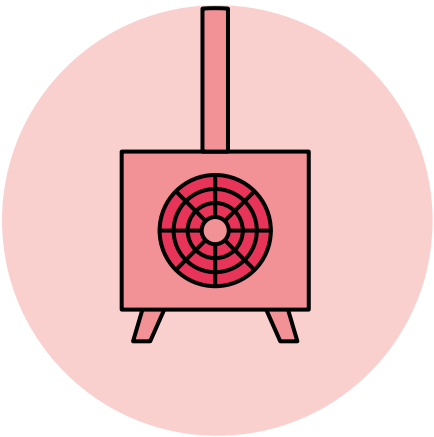
Heat pumps require the following conditions to produce acceptable levels of comfort:

- Use of high-temperature heat pumps (maximum 55°C outlet to radiators) achieving a COP of 2.5-2.7 or more during winter and a maximum one-hour warm-up time;
- Upgrade to high-output (double panel, double convector) radiators;
- Increase flow of hot water to the radiators by ensuring the water circulation pump is adequately sized and opening balancing valves (enabled by use of multi-zone control and replacement of microbore tubing);
- Improve the building fabric to reduce heat loss close to the standard of current UK building regulations (50-60 W/m^2 heat loss when the house is warm in winter).

A single thermostat and TRVs with independent control of each room's temperature (multi-zone control) were fundamental to achieving the required level of comfort and final energy savings, despite noticeable variation in the savings they provided without any other changes.

Some householders reported issues with single zone control, such as rooms not reaching desired temperatures quickly enough, some rooms overheating, and unnecessarily heating rooms when not in use. Other issues included not having enough flexibility or understanding of their heating control interfaces, such as the programmer, boiler temperature settings, TRVs and balancing valves. These issues can be addressed using multi-zone control and a modern, well designed, user-friendly control system interface.

The study demonstrated that heat pumps can successfully provide the heat and hot water needs of the homes with the addition of a hot water cylinder (or other thermal storage), building fabric upgrades (to reduce heat loss to 50-60 W/m2), upgrades to older radiators (bringing them up to double panel, double convector standard) and multi-zone control (which allowed increased water flow to the radiators).



Furthermore, these results were achieved with modestly sized heat pumps (6-8 kW nominal output) and the imposition of an input power limit (2.5-3 kW) to reduce the potential impact on the electricity supply infrastructure. This feature would be a useful (and simple) addition to the control systems supplied with heat pumps, preferably with the target setting accessible via a third-party interface. Successful scaling up depends on the effective integration of home solutions with the energy supply and distribution networks, for which improved heating control is a critical enabler.

Upscaling also depends on a positive business case for the adoption of low carbon heating. At current energy prices, the costs of the upgrades exceed the financial savings achieved so a purely financial case is insufficient on its own drive large-scale take up. A simple CAPEX/OPEX return-on-investment case would require a payback term of decades, beyond the lifespan of some of the upgrades. The running costs of electric heating are only predicted to become appreciably cheaper than gas heating after 2040 for four homes. House B is the oldest building with the worst original energy efficiency, and an air source heat pump has lower running costs as soon as sufficient building fabric improvements are implemented. However, the savings in running costs are still insufficient to justify potential capital expenditure of approximately £25k.

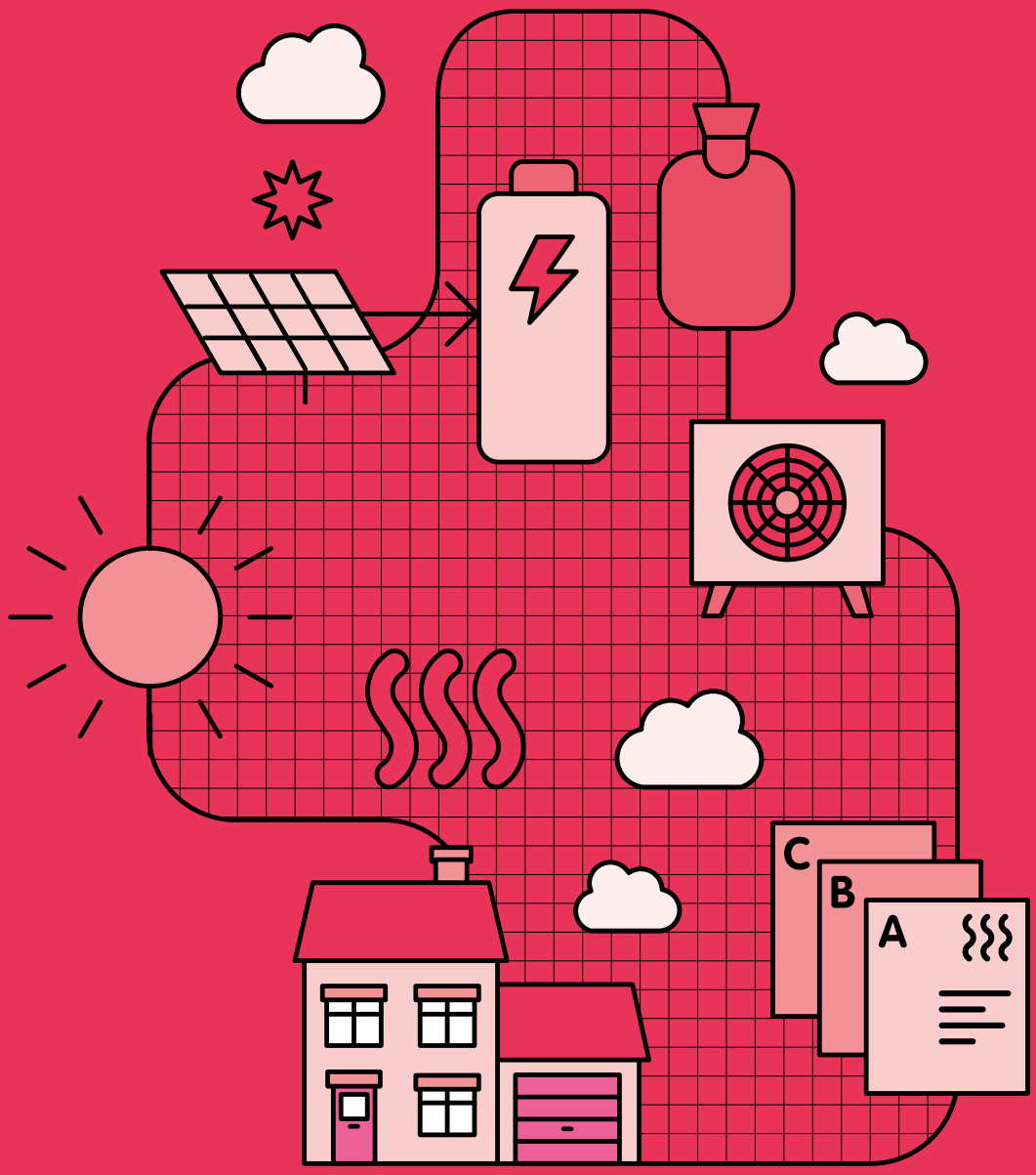
Market and government financial incentives are currently insufficient to persuade consumers to adopt electric heating, even when directed at the most effective upgrades. Improvements in comfort and increased property values provided by fabric upgrades may motivate some but is unlikely to be sufficient to induce a large scale change to electric heating. Carbon pricing, or subsidies for low carbon heating will almost certainly be required to drive the necessary transition.

Estimates of capital costs for upgrades are based on a publication for the UK government's Department for Business, Energy and Industrial Strategy[22], with additional estimates based on in-house experience.

The study demonstrated that heat pumps can successfully provide the heat and hot water needs of the houses without necessarily upgrading the radiators or circulation system

22 What does it cost to retrofit homes? Updating the Cost Assumptions for BEIS's Energy Efficiency Modelling, J Palmer et al (2017).

4. Thermal Storage



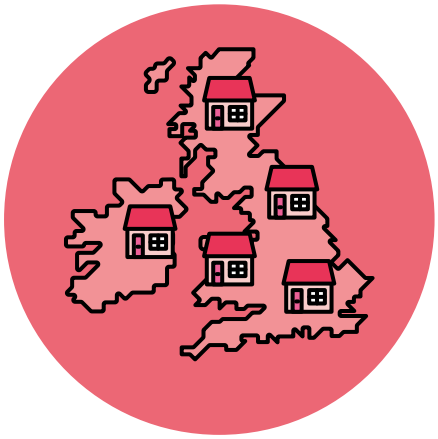
The prospect of large-scale uptake of heat pumps for domestic heating will significantly increase demand on the electricity grid, particularly when peak demand occurs at the same time for many households, during cold weather spells, and when it coincides with other peaks in electricity demand. Furthermore, as an increasing proportion of electricity generation comes from renewable sources which are intermittent, demand management measures will be required to use electricity when the renewable resource is abundant and during periods of reduced demand elsewhere.

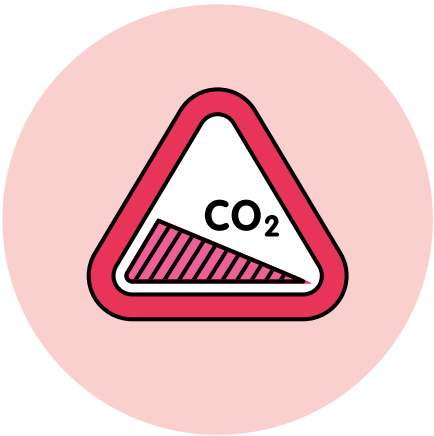
Demand management at the domestic level could help meet these new supply and demand requirements by managing the operation of heat pumps according to the availability of grid electricity, using energy storage to maintain target levels of comfort. Without demand management, large-scale adoption of electric heating would require reinforcement of the electricity distribution network, as well as the costs and carbon emissions of maintaining greater peak-load generation capacity. It would also require curtailment of renewable generation at times of over-supply or increased large-scale storage capacity within the generation and distribution system. Space for domestic storage is often limited, so there is a trade-off between minimising costs in the system beyond the dwelling and meeting the needs of households.

A high-level estimate of thermal storage requirements has been produced which would allow the heat pump to provide space heating while placing a reduced load on the grid during hours of peak demand. If the objective is simply to avoid exacerbating the daily peak of electricity demand, the optimal strategy may be to run the heat pump steadily, at a fixed power level throughout the day, with a period of low or no power consumption coinciding with the evening demand peak. This would spread the load out as evenly as possible over a 24-hour period.

If the strategy were to avoid running during the evening peak, but run unrestricted the rest of the time, or perhaps taking advantage of electricity price variations, periods of peak demand would be created due to the cumulative effect of many heat pumps following the same rules. Heat pumps operate more efficiently over sustained periods, rather than frequent on/off cycles and power modulation, particularly if a continuous low base-load strategy encourages installation of smaller capacity heat pumps. Hence it is recommended that the heat pump is operated at fixed output as much as possible, switching off or reducing power during peak times, and using thermal storage to buffer the output and match it to household heat demand.

As the electrification of heat and renewable energy generation increase substantially in the future, the management of heat pump energy demand using thermal storage will become critical. Reducing or entirely eliminating power draw from the heat pump during the evening peak demand period is possible with technically feasible quantities of storage of approximately 20 kWh. This will require a hot water cylinder of around 9 kWh, 2-3 times larger than the one familiar to householders if sized for the coldest days in winter. This is supported by the Newcastle Local Area Energy Strategy[23] which recommends that 500 litre tanks are optimal for buildings with air source heat pumps to minimise whole system costs, although smaller than would be required to completely avoid electricity demand during peak times.





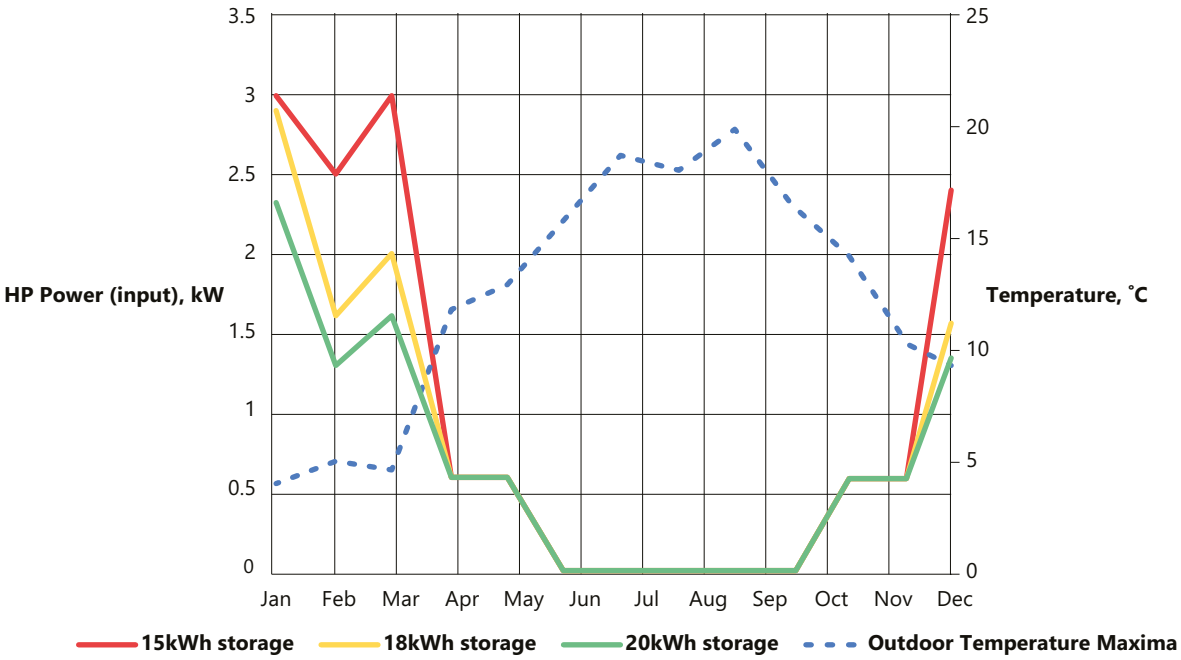
23 https://es.catapult.org.uk/projects/local-area-energy-planning/

4.1 Integrating Thermal Storage

Heating system demand on individual very cold days is significantly greater than the average daily demand for the rest of the year. Designing the system for peak load produces excessive storage requirements in the region of 20 kWh for a heat pump with storage in a typical northern UK home, even with comprehensive fabric retrofit. Most households are familiar with domestic hot water (DHW) cylinders, which typically store around 10 kWh of heat and are approximately 0.6m in diameter and 1.5m in height. However, a larger water tank is required to store water at the lower temperatures produced by heat pumps and for effective demand management, requiring greater space per kWh stored.

A less conservative approach is to design the system to meet the majority of operating conditions, with a reduced storage capacity and lower cost, which is more likely to be acceptable to householders. However, using heat pumps to make up energy shortfalls on occasions when storage is depleted would cause large spikes in demand during cold periods, meaning network reinforcement would be required. Gas-fired heating could be deployed as a back-up at these times but would require a regional gas grid to be maintained and financed for relatively infrequent usage. Figure 4 shows the electricity demand and water temperature requirements for three storage capacity options. Note that peak grid demand is effectively doubled in winter when storage is reduced from 20 to 15 kWh.

Figure 4: Plots showing heat pump electrical power setting required with three different storage capacities, thoughout the year. Plots produced using data from House C with full upgrades applied and standalone air source heat pump.



Another option is to relax comfort targets during very cold periods which may offer an acceptable compromise between cost and performance. Further analysis would be valuable to evaluate how this could be delivered in a way which is attractive to customers while maintaining their sense of control and comfort. Increasing permissible heating-up times for selected rooms, effectively using the materials of the building as additional storage during onerous weather conditions, may also allow storage capacities to be kept within manageable limits.

4.2 Storage Technologies

4.2.1 Heat Storage

Heating water in a tank is an example of sensible heat storage which changes the temperature of the water without changing its state to a gas. Where a storage tank is not feasible, latent heat storage is an alternative which uses electric power to change the phase of a material between solid, liquid and/or gas. Latent heat storage has a volumetric heat capacity two to three times less than that of hot water storage so is well suited where storage space is limited. Latent heat storage products deliver most of their stored heat at a constant temperature and have longer operating lives than currently available electrochemical batteries (for example Sunamp Heat Batteries[24]). However, they are currently more expensive than sensible heat equivalents.

Hybrid storage solutions are available where phase change material is added to the water in a tank to boost the heat capacity. This is a cost-effective approach in some cases, particularly if it permits the use of readily available tank equipment, or adaptation of tanks already installed. This concept has been demonstrated by the manufacturer PCM Products through several applications of such materials.[25]

Looking further ahead, thermochemical heat storage systems are being developed, although are not currently market-ready. These use a reversible chemical reaction to absorb and release heat. Energy can be stored by changing the chemical state of a material, then extracted with a subsequent reaction. The technology promises significantly higher energy storage per unit volume compared to sensible heat storage (more than ten times that of water), and the material stays cool while storing energy eliminating heat loss from the tank. If brought to mass market at acceptable cost, thermochemical storage could make the prospect of demand management completely attainable without significant space implications for the household.

24 https://www.sunamp.com/
25 http://www.pcmproducts.net/Solar_Heat_Storage_Recovery.htm

4.2.2 Electrical Storage

Electrochemical batteries are widely expected to provide energy storage in future energy systems transferring the storage from the output side to the input side of the heat pump. This can reduce the quantity of energy storage required by a factor equal to the heat pump's COP. For instance, a requirement for 20 kWh of thermal storage would translate to 8 kWh of electricity storage with a COP of 2.5. At the time of writing, the Tesla Powerwall[26] – an electrochemical battery aimed at the domestic market – is available at a roughly similar cost per kWh to the Sunamp Heat Battery – a phase-change thermal storage device for home use (not including installation costs). The Powerwall's energy density (approximately three times that of the heat battery) and smaller footprint makes electric storage more compact than thermal storage for equal performance.

Electrical storage enables the heat pump to be operated more efficiently than providing heat directly. When augmented by electric storage, a heat pump can be run mainly in the daytime at higher efficiency (due to higher outside temperatures) and avoiding night time noise than if run continuously to charge a thermal store. However, thermal storage requires the heat pump to operate at a higher temperature than when space heating directly (due to heat loss in storage) with the penalty of a reduced COP. Electric storage also enables stored power to be used in place of grid power, or locally generated power (e.g. solar PV), for other household demand at peak times reducing electricity costs.

By delivering stored heat at high output, thermal storage can enable fast, responsive warm-up on demand (even exceeding the performance of a gas heating system) as well as the use of a smaller capacity heat pump, benefits which electric storage does not offer. Furthermore, electrochemical batteries will degrade with partial charge/discharge cycles, rapid cycles (especially if not allowed to cool between cycles) and will decline significantly after an order of magnitude fewer charge/discharge cycles than phase change heat batteries, implying higher maintenance costs.[27] Thermal and electric storage could be analysed further to define optimal operating conditions for electric and heat storage technologies.

A disadvantage of using electrical storage is that the maximum heat output of the system is limited by the heat pump capacity. By delivering stored heat at high output, thermal storage can enable fast, responsive warm-up on demand (even exceeding the performance of a gas heating system) and the use of a smaller heat pump – benefits which electric storage does not offer. Furthermore, electrochemical batteries will degrade with partial charge/discharger cycles, rapid cycles (especially if not allowed to cool between cycles) and will decline significantly after an order of magnitude fewer charge/discharge cycles than phase change heat batteries, implying higher maintenance costs. These relative merits and drawbacks of thermal and electrical storage could be the subject of further modelling and analysis work, to identify which circumstances favour which technology.

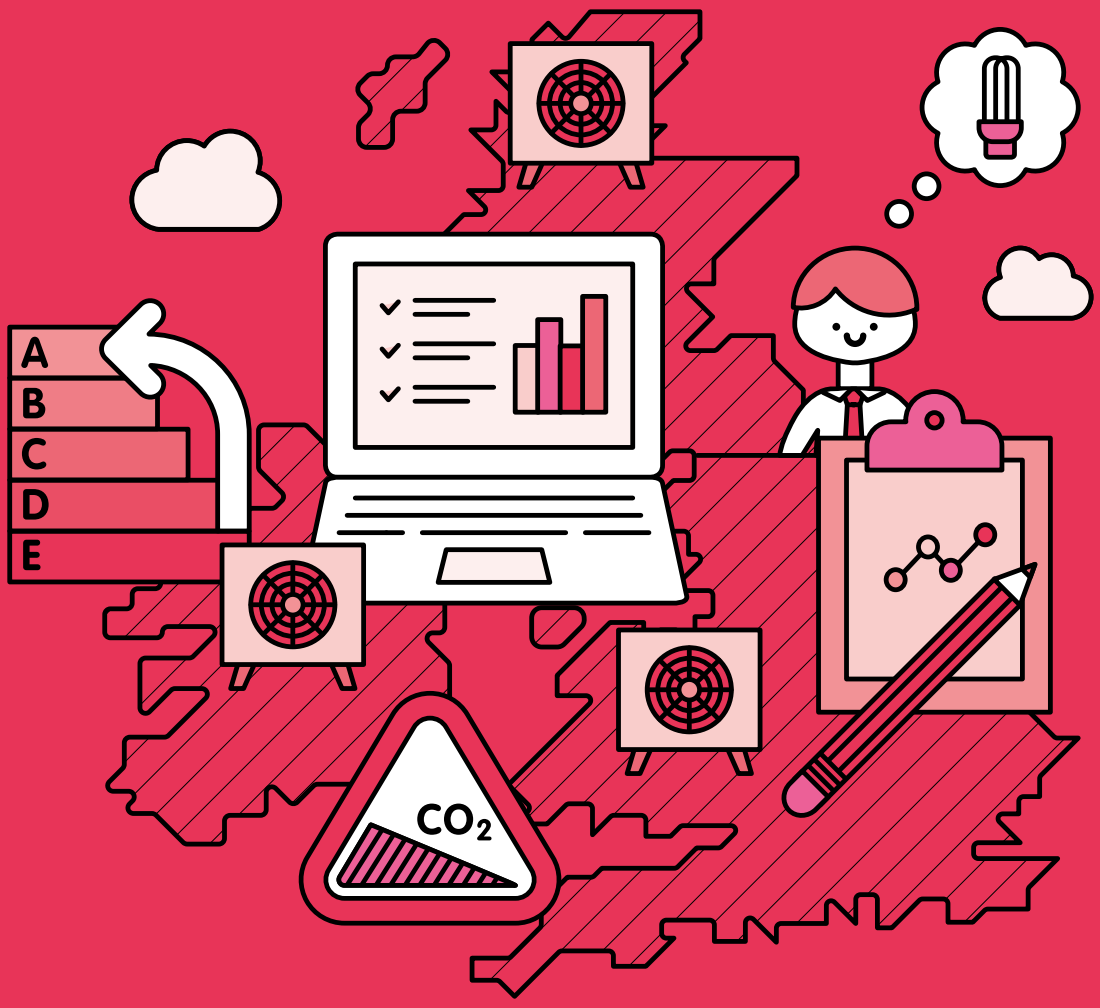
26 https://www.tesla.com/en_GB/powerwall
27 https://www.sunamp.com/residential/

4.3 Timing of Peak Grid Demand Periods

The influence on storage requirements of responding to varying availability or price of grid electricity was studied for more complex patterns than a single evening peak. For instance, if short-term fluctuations in wind and solar output caused changes in electricity price, storage could be sized to allow the heat pump to reduce power in response to this price signal without adverse effect on comfort. Unsurprisingly, a general rule emerges that longer powered-down periods and higher coincidence of these periods with heating demand require higher heat pump output the rest of the time, and larger storage capacities. These results suggest that heat pump operating profiles which deviate from a near continuous load will increase the rate of charging thermal storage required and therefore increase national peak electrical loads with implications to the generation and distribution systems.

Electrical storage enables the heat pump to be operated more efficiently than providing heat directly. When augmented by electrical storage, a heat pump can be run mainly in the daytime at higher efficiency

5. Conclusions



This study has demonstrated the potential feasibility of providing satisfying electric heat to a range of typical UK dwellings, arrived at through a series of manageable steps over at least a decade. In each of five houses studied, comfortable, low carbon heating was provided by a combination of targeted building fabric upgrades, radiator and system upgrades, adoption of multi-zone heating control and installation of high temperature heat pumps (with an option of district heating in one case). A quantified methodology for producing upgrade pathways has been developed, focusing on the high impact upgrades which if applied to enough homes of various types could be used as guidance for larger numbers of dwellings with similar features.

The study shows that while capital costs for the pathways range from about £18,000 to over £35,000, the operating cost savings of electric heat may not be apparent on all but the most inefficient houses until after 2040, making the financial motivation to transition to electric heating very weak for most householders. Changes to the energy market and government incentives, such as carbon pricing or low carbon subsidies, are likely to be required to drive the transition to comfortable low carbon heat. For example, current incentives, such as the Domestic Renewable Heat Incentive (RHI), have encouraged suppliers to promote the use of low temperature heat pumps to maximize seasonal COP, necessitating more expensive radiator and insulation upgrades to provide comfortable daytime temperatures without imposing higher night time temperatures.

A multidisciplinary analysis has been used to generate upgrade pathways which combine detailed modelling for five archetypal homes with practical knowledge of building fabric and heating systems, together with the needs and behaviour of householders. The study has shown how relatively simple metrics for heating performance, relating to occupant comfort and energy use, provide important information for comparing upgrade options. Further development of comfort metrics which can be modelled and measured in real houses will help identify heating transition pathways that are attractive to consumers. They may also help stimulate the market for home improvements that improve comfort and reduce cost and carbon.

Improved modelling and simulation of upgrades can provide a fresh perspective on issues which may not have been widely appreciated. This approach can identify root causes and innovative solutions to problems that right now are not being addressed effectively and suggest new ways to improve domestic heating performance and control.

Improved modelling and simulation of upgrades can provide a fresh perspective on issues which may not have been widely appreciated

To meet national carbon targets, a million heat pumps would have to be installed per year over the next 10 years. Achieving the necessary level of uptake of heat pumps will require both government encouragement combined with rapid capacity development to supply building fabric and low carbon heating system upgrades. For this to happen, installed heat pumps need to be proven to be viable heat sources for UK homes, providing satisfying comfort and value for money. Prices can be expected to fall with economies of scale as the market for technologies, equipment and services matures, with increased availability of trained installers and service technicians, and increased investment to develop more efficient and consumer friendly heat pumps.

The study is innovative in the targeted use of detailed dynamic simulation of domestic heating systems. It demonstrated that three temperature measurements per room and knowledge of radiator size and type could form the basis of a continuous algorithm to calculate room heating up times. It is recommended that the approach is developed and tested further in real houses, perhaps as part of the HESG field trials. Such an algorithm could then be used to identify the greatest gains from fabric and other upgrades, for example rooms with excessive heat loss or radiators which are undersized.

It would be beneficial to analyse a wider range of dwellings, including apartments, to further develop the approach to pathway development. A wider study of heat pump performance would also be valuable, including further comparison of air and ground source heat pumps for various types and locations of homes, establishing criteria for the retrofit of under floor heating, and development of more sophisticated controls for heat pumps and hybrids (with gas boilers and thermal storage) and to improve (wireless/thermostatic radiator valve) control of room temperatures.

Disclaimer

Energy Systems Catapult supports innovators in unleashing opportunities from the transition to a clean, intelligent energy system.

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