Programme Area: Smart Systems and Heat

Project: WP1 Integrated Electrical Heat

Title: Integrated Electric Heat – Upgrade Analysis Final Report

Abstract:

This deliverable is the final report of the Integrated Electric Heat project. It includes the methodology for developing the upgrade pathways, the upgrade pathways for five HEMS homes and an assessment of how thermal storage can flatten energy demand profiles for domestic heat. There are extensive appendices covering the modelling methodology, verification and output, as well as the home surveys and technology suitability. A landscape review of domestic heat storage, produced by NEF, is included as an annex to the main report.

Context:

The Integrated Electric Heating Project provided a modelling tool to evaluate the opportunities and challenges for electric heating to meet UK household requirements. The tool will be used to create and evaluate upgrade pathways for a small number of housing archetypes informed by detailed information gathered from dwelling participating in the recent Home Energy Management System trial.

Smart Systems and Heat Phase 1

Integrated Electric Heat Upgrade Analysis

Final Report

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Contents

1. Executive summary

Better control of domestic heating can enable low carbon solutions that are able to meet people's comfort needs. The application of detailed dynamic simulation can support the design and implementation of better integrated low carbon heating systems including electric and hybrid heating in existing homes and play an important role in delivering more sophisticated domestic energy services.

This report sets out the findings of the Integrated Electric Heat Project's Upgrade Analysis study, as part of the Energy Technology Institute's (ETI) Smart Systems and Heat (SSH) programme, to better understand the opportunities for and challenges to the practical implementation of low carbon heating upgrades for existing homes in the UK.

The study used data from real homes obtained from the trial of an advanced consumer-oriented Home Energy Management System (HEMS)[1]. This was combined to create five realistic homes, each with different characteristics in terms of size, type, age, context and occupant behaviour, intended to represent a broad sample of UK households. Different contexts were included to reflect likely availability of heat networks, external space constraints and access issues, all of which would be taken into consideration in real life decision making. The study used dynamic simulation to investigate potential upgrade pathways towards low carbon heating, combined with insight into consumers and buildings to develop a phased approach in which each step was able to maintain (or improve) the householders' experience of comfort and was also likely to be acceptable to them in terms of disruption, cost and providing co-benefits such as improved value, appearance and ease of maintenance of their home.

Consumer focus

The majority of households in the UK currently prefer gas central heating systems. Previous research as part of the SSH programme concluded that to accelerate mass market take-up of low carbon heating would require providing people with replacement options that are compellingly better than those available currently[2]. Investigating potential upgrade pathways for transitioning homes from gas to low carbon alternatives, thus led to the definition of simple, quantified, comfort indicators, recognising that consumers value comfort and convenience above straightforward financial return on investment or payback when making decisions about improving their homes. These comfort indicators, defined as 'fraction of time for which air temperature was below target in each heated room' and

[1] See report for ETI's Smart Systems and Heat Phase 1, "Trial of a consumer orientated advanced Home Energy Management System (HEMS), HEMS 2016/17 Winter Trial Analysis"
[2] https://www.eti.co.uk/insights/how-can-people-get-the-heat-they-want-without-the-carbon

'warm-up times' (time taken for each room to reach its desired temperature following an unheated period), were captured as outputs from the modelling, in addition to energy consumption, which was used to calculate running costs and carbon dioxide emissions.

Five representative households

The households, all of which currently use a gas combi-boiler to provide space and water heating, are described fully in the body of the report, but can be summarised as follows:

- 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.

The modelling was carried out using a sophisticated dynamic simulation modelling toolkit, considering the home as system, including building fabric, heating systems (including control), and patterns of occupant behaviour. Outputs from the model were used for quantitative comparisons of the impacts of potential upgrades[3]. To complete the analysis, consideration was also given to other factors affecting the choices a consumer might make such as convenience, disruption, the cost of a different measures and potential future cost savings.

Developing upgrade pathways to low carbon

A model was created for each of the five representative households, and simulations carried out to establish the 'base case' energy performance and occupants' comfort level. Further simulations were used to investigate the impacts of 'common sense' combinations of upgrades to building fabric, heating control and heating appliance technologies:

[3] 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

1. **Building Fabric improvements:** Most existing homes offer opportunities for improving thermal performance through enhancing insulation of the building envelope, increasing airtightness and eliminating draughts whilst making sure to provide adequate managed ventilation. Improvements to the building envelope can make homes more comfortable and enable smaller heating systems to provide satisfying heating and comfort. This is a benefit not available with gas combi-boilers which are sized based on hot water demand. Reducing the peak heating power needed to warm the home could also reduce demand on local energy networks.

   All the homes modelled in the study offered the potential for some fabric improvements with House B offering the greatest potential for thermal efficiency improvement. Fabric upgrades identified across the homes included combinations of cavity, internal and external insulation in walls; loft insulation and insulation of flat roofs, replacement of a transparent conservatory roof with a solid, opaque, insulated roof; insulation of solid and suspended floors; better performing doors and windows; draught stripping. It was found that suitable upgrades achieved overall heat loss of less than 60 W/m^2 of floor area (in line with current new-build targets).

   Practical considerations mean that householders might be expected to choose to undertake first those improvements that can be carried out with minimal disruption such as the cavity wall insulation identified as an early fabric upgrade in House A. Conversely, internal wall insulation and loft insulation where lofts are already boarded or used for storage, are more likely to create 'inconvenience' barriers to households, perhaps negating even substantial benefits, until such time as more extensive refurbishment works are planned for other reasons. Occupants in a relatively sparsely occupied property such as in House B with two bedrooms, two reception rooms and only one occupant, are more willing to embark on undertaking extensive fabric upgrades all at once, as they can adjust their occupation pattern to work around rooms that are temporarily uninhabitable. Such practical considerations were factored in when developing the upgrade pathways, recognising that these are major factors in consumers' decision making. Hence in the case of House B, for example an extensive package of fabric upgrades including floor and internal wall insulation was suggested, whereas this might not have seemed a viable option if the house had been occupied by a family of four with pre-school children.

2. **Heating Control:** Most UK households still rely on single room thermostats located in the hall or living-room, and this level of control has been assumed as a starting condition for the all houses studied in the upgrade pathway analysis. In practice, positioning of the thermostat can confound control of temperatures throughout a home by turning heating on and off in response to the recorded temperature experienced at the thermostat, thus overriding any local control attempted by thermostatic radiator valves (TRVs). Modelling showed that such conditions can lead

to over or underheating in other rooms, a situation confirmed in practice in both the HEMS field trials and the Salford Energy House. More recently, the roll out of SMART meters, broader familiarity with communication and control technologies in other fields, and improvement in usability of interfaces is beginning to drive interest in more sophisticated control interfaces within the home - for entertainment, security, heating and appliances. Taking this into account alongside experience from the HEMS project[4], the use of multizone control (comprising a thermostat and on/off radiator control in each individual room) was therefore considered as an option that would be acceptable to householders, given minimal disruption, requiring only room thermostats, a new controller and swapping TRVs for wireless radiator valves. Modelling showed that this improved control would be universally beneficial for all homes in the study, shortening warm-up times, eradicating over-heating and increasing the proportion of heated time within the desired room temperature range, irrespective of other changes to the building fabric or heating system. However, providing improved control to individual rooms, introduced the potential for householders to demand (and achieve) higher room temperatures in previously cold rooms. Left unchecked and without also upgrading fabric efficiency, this could lead to increased energy consumption and House D and House E both showed small energy increases with the installation of multizone control, but improved comfort of their homes by increasing the temperatures of previously uncomfortable rooms.

3. **Heating Technologies:** To decarbonise domestic heat, previous research has identified three primary heating technologies (1) Electrifying heat in individual homes (2) Connecting homes and neighbourhoods to heat networks (3) Re-purposing the natural gas network to transport hydrogen or biogas. In this study a further option of hybrid solutions consisting of a heat pump and gas boiler combination was also considered as a potential transitional solution. In such cases a heat pump would provide base load space heating, with domestic hot water and space heating boost provided by a retained gas boiler. This hybrid option was found to be an attractive transitional step for House A and House C where no existing thermal storage existed (e.g. hot water cylinder) and the gas boilers are relatively new.

   In practice, over 85% of UK households currently use gas boilers for both space and hot water heating, and this is the basis for the five representative homes in this study. Over time, the default choice for most households would be to continue to use a gas fired heating system, replace their old boiler with a new gas boiler only when the old boiler fails, or when made aware of a financially attractive boiler scrappage incentive. A decision to move away from gas would be reinforced by ready access to alternative replacement devices through a stable and well-established supply chain, with no

[4] Smart Systems and Heat Phase 1, "Trial of a consumer orientated advanced Home Energy Management System (HEMS), HEMS 2016/17 Winter Trial Analysis"

perceived need to make changes to other parts of their heating or hot water system (hence minimal disruption) – although modelling shows that changes are often desirable and beneficial, especially to heating control, as explained below.

Electrifying heat in individual homes by using a heat pump, either ground source or air source, is seen as playing a potentially significant role in decarbonising heat in our homes and buildings[5]. Air Source Heat Pumps (ASHP) are easier to install and require less space, although may have slightly higher running costs than ground source heat pumps (GSPH) and tend to be noisier. As heat pumps operate with the highest coefficient of performance (ratio of electrical energy in to heat energy out) when delivering heating water at temperatures lower than gas boiler systems, larger radiators or heat emitters are usually required to deliver sufficient heat in cold weather periods. Installing high output radiators (or underfloor heating, where feasible) is therefore considered as part of the upgrade options. In all homes except for House D (which was found to have undersized downstairs radiators), the modelling indicated that use of high temperature heat pumps limited the need for radiator upgrades to bringing all radiators up to modern standards (double panel, double convector) without increasing their sizes - giving immediate comfort and convenience benefits.

Even with higher performance radiators, in colder weather and when heating up the house following a period of no heating, low temperature heat pumps may be unable to achieve or maintain desired room temperatures. On an individual home basis, this could be addressed by using a larger heat pump with faster circulation of heating water, but this increases capital cost and also creates additional 'spiky' demand on the local distribution network. This might not cause a problem in an isolated case, however, scaling up localised deployment of comparatively large capacity heat pumps could have serious impacts for the wider energy system. At the same time, heat pumps sized for space heating are not able to provide instantaneous domestic hot water to meet the needs of occupants. Using smaller heat pumps, with capped input power, operating at higher output temperatures than the current norm (accepting that this decreases the effective coefficient of performance to around 2.5-2.7), augmented by hot water storage, was shown to be capable of fulfilling both space heating and domestic hot water requirements for all five homes. Additional thermal storage allowed the heating energy demand to be spread throughout the day (avoiding peak times). Thermal storage capacity required was found to be strongly related to household heating patterns, reducing the space needed and capital costs for House A, House D and House E, where the occupants maintain warm temperatures throughout the day, despite the consequent increase in overall energy consumption relative to a home allowed to cool during the day.

[5] CCC Reducing Emissions Progress Report to Parliament June 2018

Work investigating potential network transitions in different local areas as part of the SSH programme found that heat networks could play an important role in the decarbonisation of heat in the UK. The likely ability of an existing home to connect to a heat network in future is location specific and was hence considered as an option for only one of the homes, House B. Heat supplied to existing homes at similar temperatures to gas boiler outlets can achieve familiar levels of comfort, with minimal additional upgrades. Simulations showed, however, that, in combination with targeted fabric upgrades, district heat could deliver good comfort at lower supply temperatures, thus enabling a wider range of low-carbon sources to provide heat to the networks.

Low carbon upgrade pathways for five homes

Upgrade pathways consisting of three or four successive steps were mapped for each of the five homes, to be carried out of a period of 10-15 years. The approximate time scales were primarily based on the expected life time of gas boilers, aiming to replace existing boilers with low carbon alternatives, rather than wait a further 15-20 years for a new boiler to need replacing.

House	Stage 1	Stage 2	Stage 3	Stage 4
House A 1950s semi-detached	Cavity wall insulation Multizone control (Y1-5)	New doors & windows Four new high output radiators (Y3-13)	6kW ASHP with EITHER existing boiler OR hot water cylinder (Y6-12)	
House B 1920s terraced	Insulate suspended floor Multizone control (Y1)	New doors & windows insulate walls One new high output radiator (Y3)	6kW ASHP with hot water cylinder OR interface to district heating network (Y6-10)	
House C 1930s semi-detached	More loft insulation Multizone control Four high output radiators (Y1)	8kW ASHP with existing boiler (Y2-5)	Internal wall insulation (Y5-10)	Remove boiler Add hot water cylinder Insulate conservatory and extension roofs (Y10-15)
House D 1970s terraced	Insulate walls More loft insulation Multizone control Two larger, high output, ground floor radiators (Y1)	New windows and doors (Y6)	6kW ASHP with addition of hot water cylinder (Y10)	

House E 1980s detached	Insulate extension loft Multizone control Limit conservatory set-point (Y1)	Opaque insulated roof and ultra-low U windows on conservatory (Y4)	New windows and doors downstairs Larger heated towel rail (Y7)	8kW ASHP OR 8kW GSHP, both with addition of 250l hot water cylinder (Y10)

In all cases, combinations of fabric and heating system upgrades with multizone control achieved better comfort and energy performance than pursuing a 'fabric only' or 'heating system only' approach. In some cases, installing an electric heat pump as well as keeping an existing gas boiler for peak heating demand provided an effective transitional route and retained flexibility in relation to planning and investment in local energy networks.

Overall, the study demonstrated that low carbon upgrade pathways can be practically implemented and deliver warm and comfortable homes. However, this is dependent on the effective integration of solutions, both within the home and across energy supply and distribution networks, for which better heating control is a critically important enabler. Furthermore, the financial savings achieved by the upgrades (based on current energy supply business models), do not outweigh the costs of the upgrades and so do not provide a sufficient driver of consumer choice.

Wider UK energy context

The report considers 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. Potential effects on peak grid demand can be reduced by using thermal storage technologies to allow 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 needed 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[6]. Detailed consideration of individual homes must contribute to wider system decisions to give priority to the needs of consumers, and to ensure correct allowances are made for the impacts of large scale deployment and geographic concentration of upgrades in a given area. The focus on homes must also fit into the broader picture, including distributed supply, roll-out of electric vehicles, energy management and the establishment of alternative business model such as ones offering heat, power and mobility as services, which will all influence how energy is supplied and used by households in the future.

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

Key findings

Decarbonising domestic heating is an important part of delivering a cost-effective energy system transition for the UK. Informed by previous research and insight into the what consumers value from their heating at home and by the drivers for domestic retrofit decisions, this study has developed consumer-focused upgrade pathways to low carbon heating.

The key findings from the project are:

1. **Multizone control can improve comfort, energy efficiency and householders' sense of agency and is an important element in the design, integration and operation of low carbon heating systems.** Recognising that payback and energy cost savings have not so far proved to be sufficient drivers in stimulating the domestic energy efficiency market, the potential for 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 homes if sized and operated effectively in combination with targeted building fabric upgrades.** Operating heat pumps with a higher outlet temperature (e.g. up to 55°C in very cold weather, compared to the 35-45°C that is typical of current practice) can provide good thermal comfort in line with current popular heating patterns, with less costly and disruptive fabric and radiator upgrades, albeit requiring slightly higher electricity consumption.

3. **Heat pump/gas boiler hybrid heating systems could provide a valuable transitional step towards low carbon domestic heat.** This could deliver satisfying comfort and convenience whilst also providing the option to replace the gas boilers with either (1) thermal storage or (2) lower carbon gas or hydrogen boilers should the gas network be repurposed, or potentially by deeper fabric energy efficiency improvements.

4. **The costs of low carbon heating upgrades cannot be justified purely on the savings in consumer energy costs.** Earlier studies have also identified many barriers. This current study provides insight into a possible role for exploiting improved comfort, convenience and controllability as drivers and routes to engagement, illustrates continuing scope for technology innovation to increase consumer choices and lower costs and could inform policymaking and incentives and well as advice and practical actions to evaluate and deliver upgrade options.

5. **Thermal storage in homes could help spread demand placed on energy networks and reduce overall peak demand, by providing greater flexibility in the time that energy is supplied and decoupling this from when energy is 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. **Dynamic simulation can provide insight into the impact of low carbon heating upgrades on people's comfort and help inform the design and integration of options whose benefits are less well understood, such as improved control.** The methodology and approach applied in this study could be extended in the future to support implementation of targeted domestic retrofit[7] and the design and delivery of domestic energy services[8]. It could also be used to inform policymaking.

[7] This could include application by retrofit assessors and designers under the soon to be adopted PAS2035 standard.
[8] Smart Systems and Heat Phase 1 - An ETI Insight Report: Domestic Energy Services

2. Introduction

Delivering low carbon heating to existing UK homes requires solutions that can be practically implemented and deliver standards of comfort equivalent to or better than those enjoyed in most of our homes today.

The UK's 28 million homes account for about 28% of the energy we use[9] with domestic fuel consumption producing 17% of all CO2 emissions[10]. This is dominated by space heating, with contributions from hot water and cooking. To meet the UK's 2050 Climate Change Act commitments, we will need to largely eliminate the emissions from heating at home, however, to date there has been slow levels of uptake of low carbon heating despite policy support[11] with insufficient incentive or appeal for the majority of consumers.

Electric heating (including resistive and heat-pumps), hybrid gas-electric and district heating in individual homes could all play an important part in the UK's transition to a low carbon future[12]. These solutions would need to be deployed in a wide range of homes with a diverse mix of construction, thermal properties and local environmental conditions and constraints. These factors combined with the very different needs and expectations of the people living in them will determine how effective these low carbon solutions are in practice, in terms of energy consumption and carbon emissions. The ability of these solutions to provide comfort and amenity to the satisfaction of consumers will be a critical factor in how widely and quickly they will be adopted.

To better understand how to deliver low carbon heating solutions in people's homes that are able to deliver good and if possible improved levels of comfort the Integrated Electric Heating project as part of the Smart Systems and Heat programme developed a methodology and modelling toolkit to gain insight into the detailed dynamic interactions between the heating system, control system, building fabric, consumer comfort and external factors such as weather on heating our homes. This modelling toolkit provides a means of better understanding the impact and benefit of implementing different upgrades to homes and their heating systems in order to decarbonise domestic heat and if these upgrades will deliver the comfort that people want and expect.

2.1. Analysis of low carbon upgrade pathways

This report sets out the findings from analysis of low carbon upgrade pathways for five UK homes heated with gas central heating, and representative of over 30% of the UK housing stock. This considered changes to the homes' heating systems and building fabric improvements, able to deliver the expected level of comfort for each household and

[9] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/729317/Energy_Consumption_in_the_UK__ECUK__2018.pdf
[10] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/695930/2017_Provisional_Emissions_statistics_2.pdf
[11] https://www.ofgem.gov.uk/environmental-programmes/domestic-rhi
[12] Energy Technologies Institute - Options and Choices Update 2018

considering the practical implementation of the upgrades recognising that households will be subject to many external influences on their decisions.

The modelling is based on combinations of data gathered during a trial of a consumer-focused Home Energy Management System (HEMS) involving 30 homes over the 2016/17 winter period. This was combined with data from surveys of building fabric and household behaviour of these homes to develop pathways that focus on practical and effective measures to reduce carbon emissions whilst also meeting the comfort and other needs of the occupants. The homes studied were realistic, being based on data and information collected from real homes in the HEMS field trial, whilst preserving the anonymity of the households in the trial, giving the study enough detailed data and information along with a broad range of real issues to consider during development of the pathways.

The upgrade pathways developed were used to inform discussion of what this might mean for the UK and the potential role and impact of heat storage in delivering low carbon heating.

3. Context and purpose

Currently the UK's households overwhelmingly favour gas boilers for providing their heating and hot water needs (e.g. in about 85% of dwellings in England in 2014[13]). Given the challenges of significantly reducing the carbon intensity of the gas they burn, a reduction in CO_2 emissions of 80% or more could be heavily dependent on a large number of homes switching to electric heating coupled with further decarbonization of electricity[14].

To achieve this transformation some of the obstacles to be overcome include:

1. Consumer inertia - people are familiar with the flexibility and comfort provided by gas combi-boilers and accept (or are unaware of) their shortcomings – such as the compromises between maximum and minimum power outputs (see summary in section **6**) and issues with supply of hot water discussed in section **5.1.4**.
2. Poor reputation of electric heating – perceived as expensive, unresponsive, inflexible.
3. Delivering a typical household's peak heating power demand of 10-20 kW, multiplied by millions of homes heating at similar times of day, would have substantial implications for the electricity supply and distribution infrastructure.
4. Many dwellings no longer have hot water cylinders – to replace a combi-boiler's 25-30 kW output for domestic hot water by resistive heating would be impractical.

High reliability, well managed, district heating systems can address most of these concerns, but are unlikely to be suitable for all locations across the UK[15] and are dependent on the development and extension of heat networks in local areas and the willingness of householders to connect with them.

The wide-scale adoption of heat pumps with thermal storage (at least for DHW) can potentially address points 3 and 4 in the above list. Overcoming the first two challenges will be essential to persuade enough householders to install some form of heat pump to reach the uptake of around 50% that may be required by 2050[15].

There is, therefore, a need to find ways to overcome the actual and perceived negative aspects, from a householder's perspective, of heat pump technologies compared to gas combi-boilers. These include: lower outlet temperatures requiring larger radiators and/or larger bore piping or underfloor heating with large distribution manifolds; the space required for thermal storage (with associated loss of amenity); noise (for air source heat pumps); disruptive ground works (for ground source heat pumps); high capital costs (although these may be offset by longer life spans); lack of widespread expertise to provide maintenance; and low credibility based on reports of poor performance and lower than expected uptake.

From the broader perspective of minimizing carbon emissions nationally, mass use of heat pumps also runs the risk of subjecting the grid to peak demands large enough to require

[13] English housing survey, Energy Report, 2014: (UK Department for Communities & Local Government)
[14] https://www.theccc.org.uk/wp-content/uploads/2018/06/CCC-2018-Progress-Report-to-Parliament.pdf
[15] ETI's Energy System Modelling Environment, v4.3

additional generation from high carbon sources, making the marginal carbon intensity higher than using individual gas boilers to cover the peak demand. This is part of the rationale for considering hybrids of heat pumps with gas boilers and thermal storage for space heating as part of the overall mix of heating solutions.

The envisaged transformation of domestic heat will not be achieved with a universal solution for every one of the tens of millions of varied UK dwellings. Each home has a unique combination of building type, size and fabric, householders, neighbouring properties and space, location etc., all of which impose different constraints and requirements on the design of any changes necessary to reach satisfying, low carbon provision of heating.

Energy and carbon efficient solutions that are attractive to householders, and attempt to limit costs, requires a whole system approach – considering all the components and interactions within dwellings, in the context of the broader energy supply system. National and local energy systems perspectives have been provided by analysis undertaken using ESME and EnergyPath Networks[16], while this project considers the energy systems within individual homes. The detailed, comprehensive, domestic heating dynamic modelling tool-kit developed during this project ("IEHeat") is designed to investigate performance and develop solutions at the dwelling level. The intent is not to use the tool in isolation, however, but to benefit from close cooperation with those who understand householder behaviour, priorities and motivations, and those with a deep knowledge of the mechanics and practicalities of installing effective upgrades to dwellings.

Given the context outlined above, this study aimed to create and evaluate upgrade pathways for a defined number of housing archetypes using currently available technologies combined and controlled to deliver satisfying space and water heating performance. This was intended to deepen understanding of the interactions between domestic heating systems, control systems, building fabric, weather and consumer requirements, leading eventually to solutions enabling electric heat to play a significant role in decarbonising domestic heat in the UK.

This report details the methodology developed to produce coherent and quantified pathways – tailored to the occupants' needs, priorities and motivations – leading to low carbon domestic heat delivering comfort and household satisfaction, at least as good as that currently provided by gas central heating. The magnitude of the task facing the UK domestic energy sector makes the methodology and tools to assist in this undertaking as important as the outcomes of the pathways themselves.

In producing pathways, the extent to which detailed dynamic simulation enables or improves the outcomes of the process will be demonstrated. Ascertaining the required level of detail in the modelling and input data, uses for the simulation output and the value of combining this with non-simulation data, are also aims of the study. Finally, when developing detailed models, it is common to find issues or solutions to problems that have not been anticipated.

[16] EnergyPath Networks modelling provides geographical analysis of local energy supply and consumption, see https://es.catapult.org.uk/projects/local-area-energy-planning/

4. Methodology

To illustrate the process and potential outcomes of developing upgrade pathways to achieve low carbon, comfortable domestic heat, five realistic dwellings were analysed. The study was presented with a wide range of "real world" issues to address by combining building survey data and responses to householder interviews conducted during the HEMS field trial of 30 houses. This approach also aimed to avoid revealing the identity of the householders involved. Full details of the data defining each of the resulting composite, fictional homes are presented in **Appendix 3**.

Discussion of the households' behaviour, needs and priorities are included in the simulation results summaries (**Appendix 5**) and descriptions of pathway development for each home (section **5**). The interviews held with the HEMS trial householders aimed to ascertain their current (pre-trial) behaviour and heating requirements and how they reacted to the changes to comfort offered by multizone control during the trial. Any difficulties they had before or during the trial were also recorded from the interviews, as were domestic hot water usage, heating profiles and room occupancy, window and door opening habits and any use of secondary heating. Selected, consistent, responses from all 30 trial households were distributed amongst the five study homes to provide the study with a variety of realistic household characteristics, relating directly to over 30% of the UK housing stock.

The resulting set of composite homes used in the study is shown in Table 4-1.

Table 4-1 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'.

The survey requirements for this study and the process used for pathway development are described in the following sections.

4.1. Technology suitability assessment

Identifying technologies that would be suitable for installation in a home is key to developing a practical pathway that satisfies both the aim to dramatically reduce carbon emissions and the needs and priorities of the householders. Initial assessments of physical suitability were made on the basis of surveys of real houses and local area energy planning analyses[17], adapted to match the five homes created for this study.

The range of technologies considered for home heating in other parts of the SSH Phase 1 programme were included where compatible with the objectives and timeframe of this study. This resulted in the following list of technologies for assessment:

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 (ASHP)
- Ground source heat pumps (GSHP)
- 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 (via indirect heat interface unit)

Some technologies have been partially included, excluded or deferred to future studies, as explained below:

- Supplementary resistive heating for use with heat pumps: this was modelled but found not to be necessary 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; if estimates of energy usage for resistive heating are required, these can be taken from simulation results of heat output required for space heating and domestic hot water obtained using other heat sources with similar emitter/water temperatures.

[17] see https://es.catapult.org.uk/projects/local-area-energy-planning/

- 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 **7**).
- Mechanical Ventilation with Heat Recovery (MVHR): external ventilation is modelled as heat exchange based on air changes per hour (ACH); MVHR could be represented by reduction in ACH, and along with improving air tightness is recognised as a key component of building fabric upgrades; however, it is difficult to reliably quantify the effect on ACH of a particular upgrade (such as sealing all window frames and skirting boards) – this may be the subject of future sensitivity analyses.
- Biomass boilers: whilst likely to play an important role in the future UK energy system[18], its reliance on carbon capture and storage to reduce overall emissions, together with concerns over air quality, make it unsuitable for wide scale deployment for domestic heat, and it has therefore not been modelled; for possible future study, it has been included in the technology suitability assessments for each home (**Appendix 9**).
- Solar thermal: this technology and its role in carbon reduction has not yet been modelled in IEHeat; for future study, it has been included in the technology suitability assessments for each home (**Appendix 9**).
- Solar PV: this has not yet been modelled in IEHeat; for future study, it has been included in the technology suitability assessments for each home (**Appendix 9**).
- Cooling: cooling 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.

Surveys of HEMS trial houses were used to create data sets for the five houses for this study, which were used to assess which upgrade technologies were suitable for each home. A list of the survey questions for each technology is provided in **Appendix 8.** The outcomes of the combined technical and household-based assessments for each house can be found in **Appendix 9** (note this is a filtering exercise prior to quantitative analysis by simulation, and does not consider effectiveness of the technology in the houses).

4.2. Low carbon heat upgrade pathway development

A flow chart showing the approach taken to pathway development is shown in Figure 4.2-1. The close cooperation shown between disciplines understanding consumers, physical practicalities of modifications in dwellings and dynamic simulation of home energy systems, is discussed below.

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

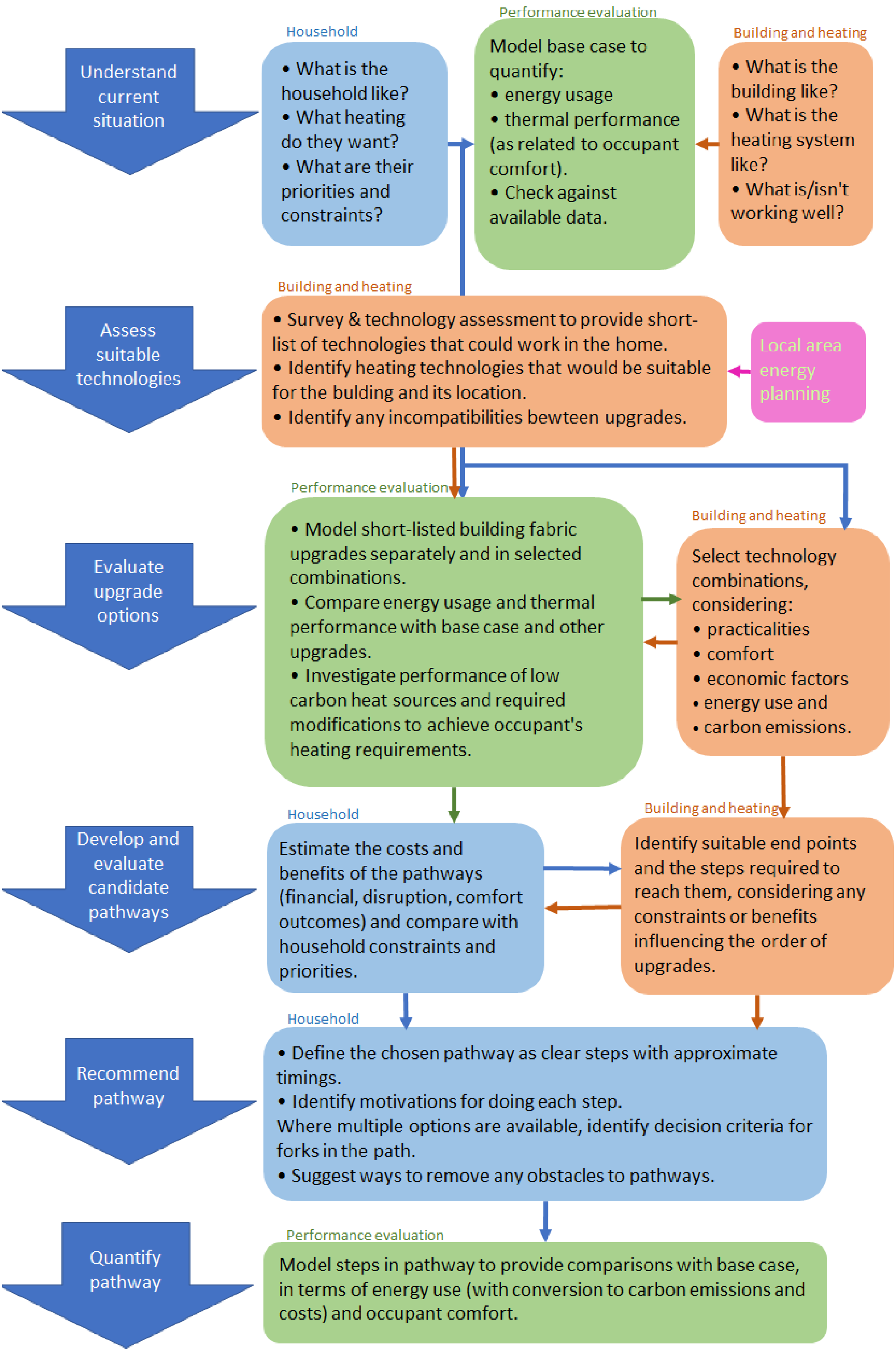

Figure 4.2-1 Pathway development process highlighting the necessary interactions between diciplines

Data gathered about each home allows technical assessments and household behaviour to inform detailed modelling of feasible building fabric upgrades, starting with simulations of base cases (the original home, first with single zone and then with multizone control). These quantified comparisons are evaluated alongside further practical and household concerns to select combinations of fabric upgrades suitable for inclusion in the pathways. Simulation is again used to investigate how to achieve good thermal comfort with low carbon heat sources, taking advantage of the proposed fabric upgrades. An informed choice of a full set of upgrades can then be made, with trade-offs made, where necessary, between disruption, comfort improvements and comparative capital costs, energy costs and carbon savings[19]. The full set of upgrades is then broken down into manageable, practical, steps for implementation, with each step's impact quantified by simulation. Where possible, each step is coordinated with other events within the home such as necessary maintenance or planned home improvements. For example, when a gas boiler reaches the end of its lifespan (typically around 15 years), this could be an opportunity to replace it with a heat pump.

The quantified performance evaluations needed to support the pathway development required more detail than typical building thermal models provide, particularly with regard to the interaction of heating systems and household behaviour. The tool-kit, referred to in this study as IEHeat, described in detail in **Appendix 2,** has been developed to meet the needs of this study, including the focus on occupant comfort and freedom to choose how they use their home heating.

The IEHeat tool-kit achieves these requirements at a high level of fidelity and time resolution (typically this study uses a 10 minutes maximum time step), including an appropriate level of detail of building fabric thermal properties to meet the objectives, and providing rigorous and flexible modelling of heat sources, heating control, heating medium hydraulics and householder behaviour.

Details of a model verification exercise, against test data from the Salford University "Energy House" (a real pre-1920 end-terrace house in a controlled environment), are given in **Appendix 7**, which demonstrates the ability of an IEHeat model to achieve very close matches to room temperatures and heating system measurements. Full details of the approach taken to model the five homes for this study can be found in **Appendix 2**.

The simulations have mainly focused on achieving the desired warmth in an acceptable time with low carbon heat sources. Cooling by opening windows in response to over-heating has not been included. This would not be precluded by the upgrades, nor would it add to carbon intensity in hot weather - unlike opening windows in over-heated rooms during colder weather, which is discussed when comparing multizone to single zone control (**Appendix 4**).

[19] It was not deemed appropriate to set a specific carbon emission target for the pathways as too many unknown external factors influence the outcomes, such as future regulation, market behaviour and the carbon intensity of the electricity supply, but rather to use current predictions of these unknowns to provide comparisons between pathway options.

A conservative approach to upgrade effectiveness has been adopted to avoid overstating predicted impacts. For example, double glazing is now available which claims to offer U-values substantially lower than the 2.0 W/m^2/K used for new windows in most of this study. However, this conservative value has been retained to allow for installation issues, such as thermal bridging, security features (metal parts) inside the window frames, increased heat losses around the wall apertures etc. which may not be considered in window suppliers' quoted data.

Similarly, to avoid over-optimistic predictions of comfort achievable with low output heat sources (such as heat pumps), all the modelled homes were subjected to weather from a typical mean year in Newcastle-upon-Tyne, in most cases using mid-winter conditions. It has been assumed that houses with party walls (terraced and semi-detached) are attached to properties with a similar heating profile, resulting in no heat transfer to the adjacent house.

The output generated by IEHeat includes a number of metrics valuable for comparison of the space heating and domestic hot water provision between simulation cases. These included the heat output from the home's heating appliance and the energy input (electricity, gas and/or heat consumption, in energy units), the ratio of which gives the effective heating efficiency. Measures of thermal comfort were based on the rooms' average air temperature, indicating warm-up times and fractions of specified warm-times spent outside the desired temperature range. It is recognized that comfort is dependent on much more than just average air temperature building fabric (e.g. wall surface temperatures are modelled but not included in overall metrics, although improvements in comfort are commonly reported when they are increased by improved wall insulation – see appendix section **A.5.2.4.1**).

In order to predict future household energy bills (based on the existing price-per-kWh business model) and related carbon emissions, it is necessary to understand which technologies are used for generation at different times, together with the capital and operational costs for those technologies and the associated energy network costs to deliver to the households. This requires and internally consistent view of the UK's future energy system, which has been provided for this analysis by the ESME "Patchwork" scenario[20] (see Table 4.2-1 and Table 4.2-2 below). These are national and annual average values, differing from the prices paid by consumers by the exclusion of VAT, supplier operating costs and any taxes and obligations on the energy industry**.** Although more recent predictions may indicate lower carbon intensities and the costs are lower than consumers will pay, this data is self-consistent and is valid for comparisons between cases to indicate the relative impacts of the pathways evaluated.

[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

Table 4.2-1 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

It is recognized that carbon intensities vary with generation mix, which itself can vary, over much shorter timescales than reflected in these annual averages, with weather, time of day, regional and national peak demands etc. These averages do, however, allow consistent comparisons to be made between annual costs and carbon emissions over the coming decades. 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 **7**) and heat pump-boiler hybrids as a transitional technology.

Note the ratio of costs of gas to electricity shown in Table 4.2-2 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 4.2-2 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 that the gross (higher) heating value of natural gas is used throughout when stating gas energy consumption values.

5. Upgrade pathway development

The following sections describe the pathways developed to upgrade each of the five houses to comfortable, low carbon heating. The process followed to arrive at each pathway is also described, together with the analysis and reasoning supporting the recommendations.

The pathways are defined up to and including the replacement of the heat source with fully electric or district heating. This is expected to occur within 15 years (based on the approximate life span of the existing gas boilers), with all other upgrades made in earlier steps. While the pathways are intended to allow further upgrades in subsequent years, no extra steps are foreseen to be necessary to further reduce emissions, based on projections of the carbon intensity of the electricity or heat supply to 2050 (Table 4.2-1).

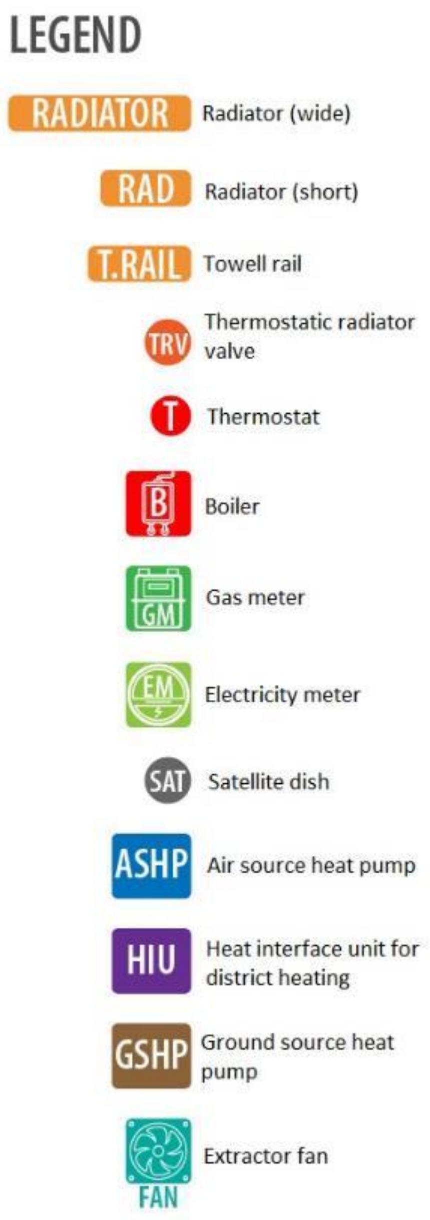

Figure 5-1 - floor plan symbols

The floor plans of the five houses are shown as they are at the start of the pathways, with the addition of proposed locations of their new heat sources (ASHP, HIU, or GSHP). The legend for these plans is shown in Figure 5-1.

Estimates of capital costs for upgrades are based on a publication for the UK government's Department for Business, Energy and Industrial Strategy, "What does it cost to retrofit homes? Updating the Cost Assumptions for BEIS's Energy Efficiency Modelling", J Palmer et al (2017), with additional estimates based on in-house experience.

Note: energy consumption figures quoted below for heat pumps refer to the electrical energy used to drive the heat pump and exclude the energy extracted from the air or ground sources.

5.1. House A (1950s semi-detached) upgrade pathway

5.1.1. Upgrading this house to low-carbon, high comfort, electric heat

The following upgrade pathway has been developed for this 1950s semi-detached three-bedroom home. The methodology outlined in section **4** has been followed to analyse the home's existing and potential building fabric and heating system, resulting in a pathway which both reduces CO_2 emissions and satisfies the needs and preferences of the household.

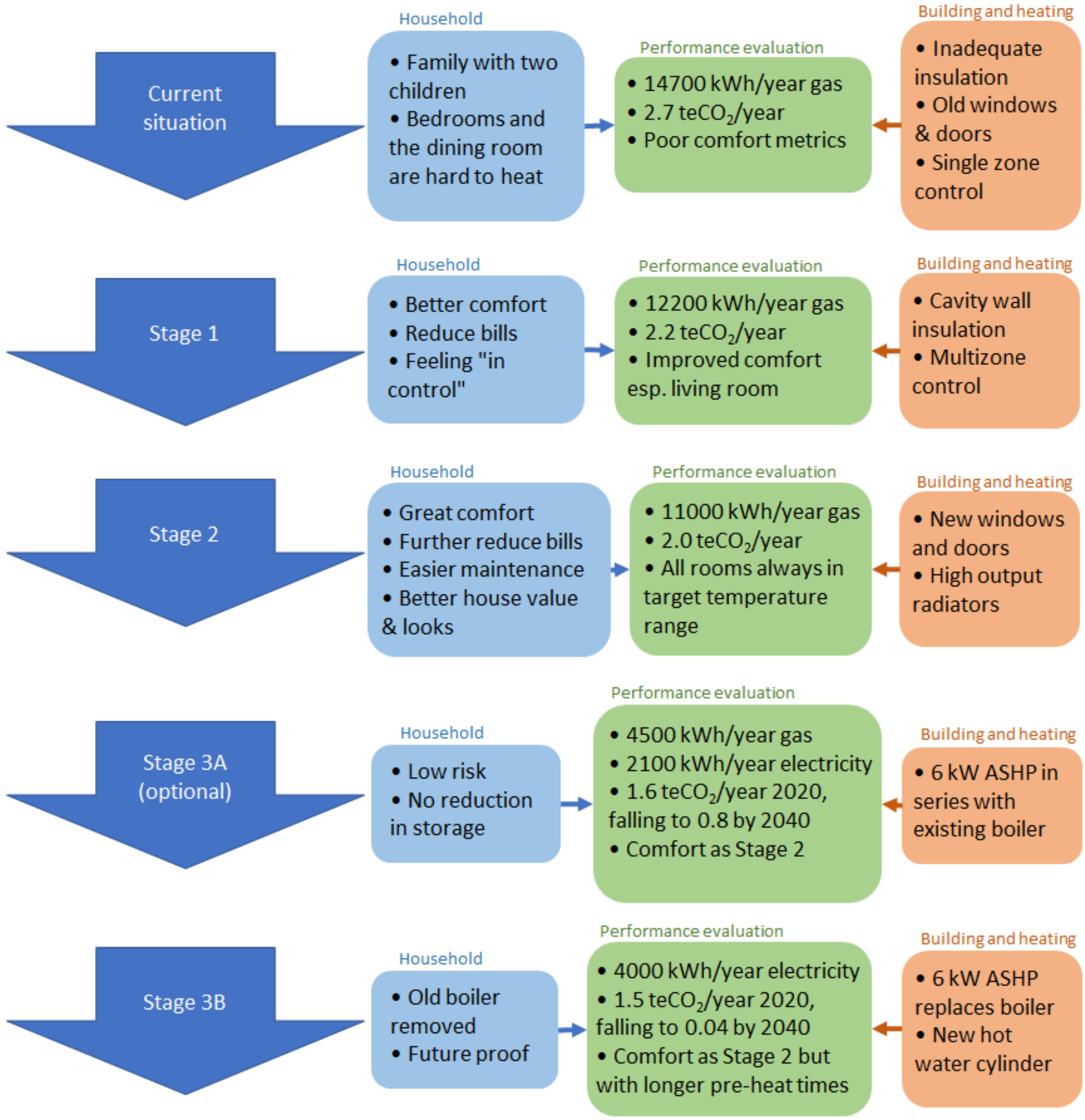

Figure 5.1-1 - House A upgrade pathway

The following sections describe how this pathway was developed and give details of how it achieves the household's desired level of thermal comfort, whilst achieving significant carbon savings, and considers the practical issues of carrying out the upgrades. This leads to a full description of the pathway in section **5.1.7**.

5.1.2. The house and household as they are now

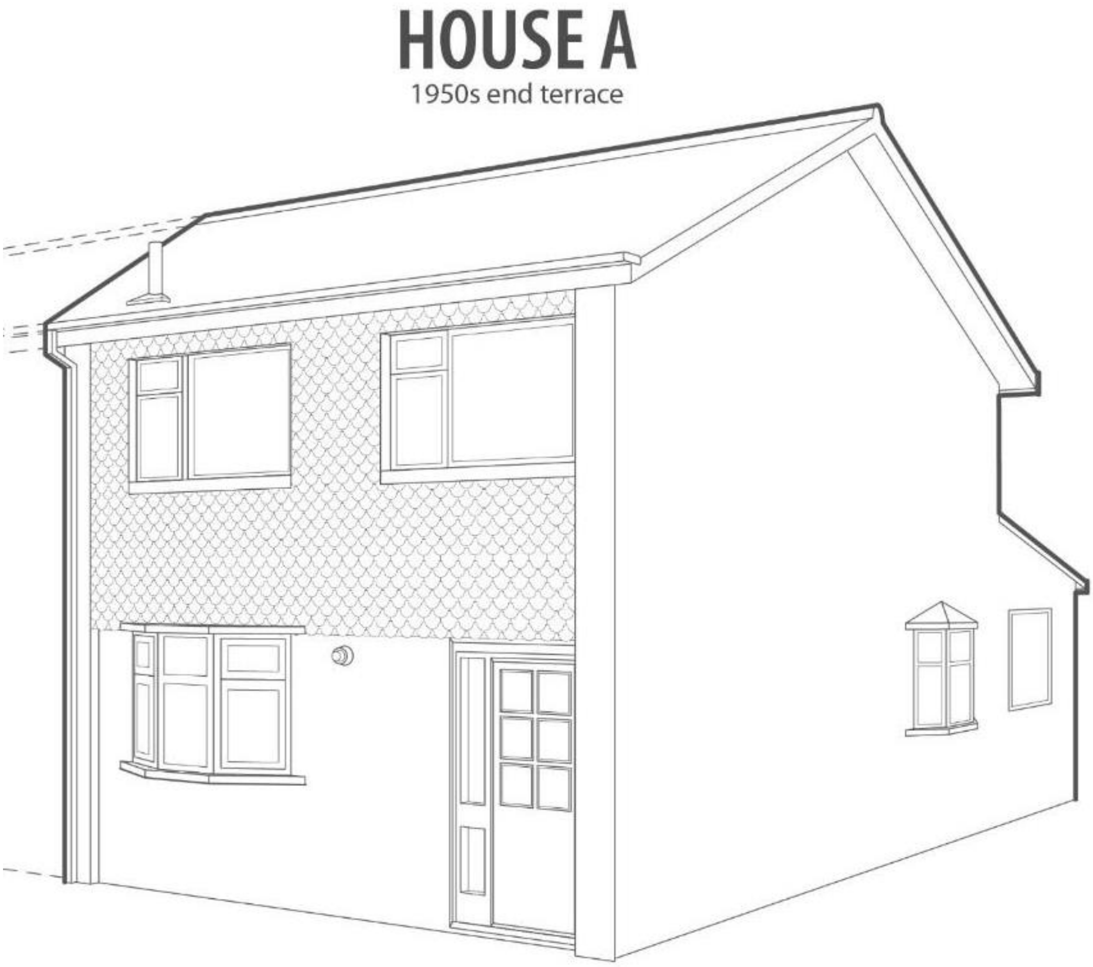

Figure 5.1-2 Impression of House A

5.1.2.1. The Household

House A belongs to a family with two young daughters (aged 8 and 12). The husband works full time, while the wife volunteers in a library during the day. Consequently, the house is usually only occupied (and therefore heated) in the morning and evening.

They have lived in the house for eight years, but they would like to move to a new house in the next few years. Comfort and convenience are their highest priorities, but they are also sensitive to wasting money and would like to have information to enable them to make the best decisions regarding how they heat their home. They are frustrated with their current heating control and do not know how to use it ("it's like technology you'd expect in the eighties"). The potential to update their control and set the heating in different rooms is attractive.

The householders take pride in the way their home looks. They did cosmetic decorating when they first moved into the house and they are now in the process of doing it up, with a view to selling it. This will mainly involve painting and fitting new carpets, but if they decide not to move they are also thinking of re-doing the kitchen (and/or bathroom). They realise that some disruption is inevitable, and they are prepared to accept this if there is a benefit – including a higher sale price.

They are a single-income family, but they can live comfortably within their means and their energy bills have never been a concern for them. The householders like their house to be quite warm – even if it means spending more money on heating and the daughters are accustomed to having long showers, one in the morning, the other in the evening. They are not particularly motivated by "the green agenda", avoiding waste is more of a consideration for them.

5.1.2.2. The house

The house is a 1950s semi-detached, three-bedroom home as illustrated in Figure 5.1-2 and Figure 5.1-3. Details of its physical characteristics are shown in Table 5.1-1.

Figure 5.1-3 - Floor plan of House A

Table 5.1-1 Characteristics of House A

House characteristic	Details
House type and age	Semi-detached house, constructed in late 1950s
Geographical location	Rural
Orientation	Front faces south west
Floor area	98 m^2
Number of heated rooms	8 heated rooms
Number of bedrooms	3 bedrooms
Wall construction and insulation	Cavity walls, filled on gable end Façade has hanging tiles between brick columns
Roof insulation level	75 mm of insulation between joists
Windows and doors	Pre-2002 double glazing on main house windows. Aging front doors with single glazing
Floor description	Solid ground floor, laminate covering in most ground floor rooms Upstairs mostly carpeted; joists run parallel to front of house
Heating system description	Condensing gas combi boiler (estimate about 10 years old), no hot water storage, single thermostat with programmer in the hall + TRV present on each radiator
Details of extensions / conservatories	Rear single storey, pitched roof, extension (late 1990s). Heated during day. Single glazed window and double-glazed sliding doors.
Description of garden(s) or other outside areas	Front: Lawn (5.1m x 5.4m), extending in front of neighbouring houses Rear: paved courtyard (6.7m x 7.2m) with shed, filled with tools Side: Path (including gate), 1.3m wide
Description of road	Secondary road on the front, public footpath to the side, leading to another secondary road. Communal footpath to the front serving the row of houses
Local Area Energy Planning - heating system choices[21]	ASHP or ASHP + gas boiler hybrid selected based on location and basic house characteristics.
Existing problems with house heating	Dining room difficult to warm up in winter. Front bedroom often feels cold.

[21] For information about the results of the geographical analysis from EnergyPath Networks modelling, see https://es.catapult.org.uk/projects/local-area-energy-planning/

5.1.2.3. Current comfort, energy use and carbon emissions

IEHeat modelling confirmed the householders' reports of some issues with heating performance for the base case with single-zone heating control (see Appendix section **A.5.1.2**). There were long periods below the room temperatures the household would prefer – especially in the bedrooms and dining room. The front bedroom, for example, is colder than the 2°C band the occupants would like to achieve for 64% of the time they want it heated, and the dining room is cooler than they would like for 40% of the time they want heating. This is mainly because the room thermostat, located in the hall, cuts off heating to the whole house as soon as the hall reaches the set-point temperature.

Using "typical mean" weather from Newcastle-upon-Tyne resulted in a prediction of annual energy use of roughly 14,700 kWh for space and water heating, giving carbon emissions of 2.7 tonnes CO_2 per year at a cost to the household of about £590 at 2018 energy prices.[22]

5.1.3. Evaluation of potential building fabric upgrades

A thorough assessment of possible upgrades indicated that the most promising improvements to building fabric in this house, from the perspective of comfort and thermal efficiency, are those in Table 5.1-2. The practicalities of each upgrade are discussed below.

Table 5.1-2 Potential fabric upgrades

Upgrade	Description
Top-up loft insulation	Adding up to 150 mm of extra loft insulation to the existing main roof insulation
Top-up roof insulation on rear extension	Adding up to 150 mm of extra insulation to the existing insulation of the single-storey extension
Upgrading double-glazed windows and patio doors	Replacing existing windows with a U-value of 2.8 with new ones with a U-value of 2.0 W/m^2K
Upgrading front (part-glazed) doors	Changing existing single glazed wooden doors with a U-value of over 5.0 to new ones with a U-value of 2.0 (external) and 3.0 (internal) W/m^2K
Insulation over the living and dining room concrete floor slabs	Adding 50 mm of insulation above the solid floors in the heated ground floor rooms
Improving incomplete cavity-wall insulation	Complete cavity wall insulation by adding 50mm of blown insulation to front and rear walls
Insulating the walls externally	Adding external wall (rendered after installation) – thicknesses evaluated from 10 mm to 100 mm
Insulating the walls internally	Adding internal wall insulation (with plasterboard and skim on top of the insulation) – thicknesses evaluated from 5 to 40 mm

[22] Assuming a carbon intensity of 184 gCO_2/kWh for natural gas (from BEIS (2017) Greenhouse Gas Conversion Factors 2016. London: BEIS), and a typical consumer price for gas of 4p/kWh.

Installing extra loft insulation for the main roof and the extension are relatively straightforward improvements – with care to be taken around the soil vent - but would cause some short-lived disruption since the loft is currently very full of stored items. Costs for the main roof would be around £450 for the main roof (plus about twice this for adding raised boards to ease use of the loft for storage) and £500-£1,000 for the extension (depending on the difficulty accessing the void from above). Renewing the windows and doors could probably be done by a window installation company in a few days, with any disruption likely to be limited to one room at a time. This may cost £8,000-£10,000, depending on quality and style of windows and doors chosen.

The other potential fabric upgrades for this house are more difficult and complicated to apply. Insulating beneath the floor coverings on the ground floor would mean removing the furniture and possessions as each room is treated and would be particularly complicated since they are solid floors. Insulating directly on top of the current solid floor would lead to the finished floor level rising. This is likely to cause issues with the first riser of the staircase, modification would be required to the doors and the head height throughout the ground floor would be reduced.

Insulating the walls internally would also be intrusive as it means moving the existing radiators in the bedrooms and moving any electrical sockets on external walls. As often happens, a plumber and electrician may need to do some work both before and after the wall insulation is installed. In the kitchen, there are cupboards and appliances running across both external walls, which would normally be a significant barrier to insulating, but if the family plans to install a new kitchen soon, the kitchen and insulation work could be combined. External wall insulation (EWI) would cause less disruption internally, but would mean removing and re-fixing boiler flue, waste and rainwater pipes and part of the garden fence. This would also mean re-hanging the gate to access the side pathway, which would become slightly narrower. For the single-storey extension, EWI would also require the eaves to be extended so that the roof protects the insulation from water ingress.

Due to the issues above, and the construction of the walls of this house, completing the cavity wall insulation is likely to be the least disruptive of the wall insulation options, and is estimated to cost about £700 for this house, provided the existing partial insulation does not obstruct the installation.

5.1.3.1. Combining fabric upgrades

With the selection of cavity wall insulation as the most appropriate wall treatment for this property, the fabric upgrades considered above would work well together, and serve to reduce heat loss from all elements (walls, floor, roof, fenestration). There are no specific issues about sequencing or applying multiple fabric interventions for this house as their effects reduce the U-values of different external interfaces and are therefore additive.

With the loft insulation in place, roof ventilation is likely to be needed (tile vents or ridge vents) to allow moisture to leave the loft space, since this is likely to have been blocked by insulating into the eaves.

5.1.3.2. Outcomes of fabric upgrade evaluation

Table 5.1-5 shows a summary of the impact of selected upgrades to this house. (As discussed later, multizone control was seen to lead to such significant advantages that it was included in all upgrade cases). The modelling showed that cavity-wall insulation (CWI) combined with new double-glazed windows throughout would save more energy than either external or internal wall insulation alone. CWI and new windows would be much less disruptive, and less expensive, than internal or external wall insulation and for this reason CWI and new windows were recommended for this house.

Replacing the windows and doors noticeably improves the proportion of time within the owners' desired temperature range in the front bedroom, making smaller improvements in the back bedroom and the dining room. Similarly, loft insulation also improves comfort in the front bedroom but makes less difference in the back bedroom or downstairs. While insulating the floors in this case makes negligible difference to average air temperatures, it is known to improve comfort by altering the temperature distribution, keeping the occupants' feet warmer. When all the fabric upgrades are combined, comfort metrics come into a range that would be acceptable to most households. Even on very cold days, all rooms except the front bedroom reach the desired temperature in less than an hour with warm-up times of less than half an hour in less extreme winter weather.

5.1.4. Evaluation of potential heating system upgrades

A detailed assessment of feasible heating system changes (see **Appendix 9** and section **A.5.1**) indicated that the most promising components to consider are those in Table 5.1-3.

Table 5.1-3 Potential heating upgrades

Upgrade/change	Description
Multizone heating control	Multizone control to allow independent control of each radiator
Air-source heat pump	6kW nominal output, with 200 litre hot water tank, with fabric upgrades (12 kW model also modelled with and without upgrades for comparison)
Air-source heat pump as hybrid system with existing gas boiler	6kW air-source heat pump, connected in series with existing boiler, with boiler generating domestic hot water and peak-load heating, with fabric upgrades
Reflective radiator foil	Insulated reflective foil behind radiators mounted on external walls, to reduce heat loss directly from radiators into the walls
High-output radiators throughout	Double-panel, double-convector radiator in all rooms (hall and back bedroom are this type already)

Multizone heating control (discussed in detail in **Appendix 4**) typically consists of wireless radiator valves and programmable thermostats installed in each room (valves with built-in programmers are also available). This is often a relatively straightforward upgrade with limited disruption and costs around £600 for a house with seven radiators with easily accessible TRVs. It is likely to both improve comfort and save energy by improving the match between heating and occupation. It also allows radiator balancing valves (lockshields) to be opened to increase water flow and hence radiator output powers. Therefore, multizone control was applied to the base case for the majority of the analysis and was an assumed upgrade.

A technical assessment indicated that it would be possible to install an air-source heat pump (ASHP) in this house. Costs range from £7,000-£11,000[23] depending on brand and power output. Ideally, the external unit would be located at the front of the house (which requires planning consent), with the internal unit installed in the adjacent downstairs WC which contains the existing boiler and pipework for space heating and hot water. A hot water storage cylinder would also be needed, costing around £400, because a heat pump on its own could not generate instantaneous hot water at a sufficient flow rate to satisfy the needs of the household. It may be problematic to find space for this, with the only suitable locations being the bathroom or a new landing cupboard. However, despite the popularity of combi-boilers, the householders may find well-managed hot water storage can provide a better service: drawing hot water will no longer interrupt space heating, there may be less time to wait for hot water to arrive at the tap (especially in summer with a cold boiler), the hot water will never exceed the storage temperature set by the household (unlike some combi-boilers, especially when cycling to maintain room temperatures after initial warm-up) and storage can offer higher output rates, perhaps doubling the 30 kW (10-15 litres/minute depending on weather) typically offered by combi boilers, allowing more powerful showers or reducing the time taken to fill a bath.

Alternatively, the technical assessment suggested it would be possible to use an air-source heat pump working as a hybrid system with the existing gas boiler. This may be preferable to the owners as a stepping stone towards a fully electric heating system. It would reduce the perceived risk of adopting unfamiliar technology and avoid the immediate need for installing hot water storage. A hybrid system also brings the benefit of limiting the heat pump's peak electricity demand in cold spells (often coinciding with peak demand for electricity), and lower CO_2 emissions compared to a stand-alone ASHP, if, during peak demand in cold spells, the marginal carbon intensity of electricity is higher than can be compensated for by the heat pump's COP. For example, a condensing gas boiler with an efficiency of 92% will emit about 200 gCO_2/kWh of heat delivered; to match this, an ASHP

[23] https://www.greenmatch.co.uk/heat-pump/air-source-heat-pump/air-source-heat-pump-cost

would need to achieve a COP better than 2.4 when supplied with electricity generated at 38% efficiency (gross CV) by an open cycle gas turbine.

5.1.4.1. Combining heating system upgrades

Both the fabric upgrades and multizone control give benefits on their own, but in combination are key to successful deployment of an ASHP. Independent temperature settings for each room would make it easier to capitalise on the potential savings of improved insulation. This would also help to optimise pre-heat times and achieve good comfort after installing a heat pump, so the upgrade options described above are consistent and complementary.

5.1.4.2. Outcomes of heating system upgrade evaluation

The modelling demonstrated that adopting multizone control, on its own, gives profound improvements in comfort, providing heating where and when it is needed, allowing each room to reach its target temperature range independently of the other rooms. Compared to the usual form of heating control, using a single room thermostat, this improves the comfort metric dramatically for most rooms (see Table 5.1-4), and simultaneously saves 3% of energy use (and carbon emissions) for heating.

Table 5.1-4 Results summary for base cases - two weeks in January using Newcastle-upon-Tyne weather

Case	**Energy for space and water heating over two cold weeks, kWh**[1]	**Fraction of heat demand time below household's preferred temperature range**[2]			
		Living Room	**Dining Room**	**Front Bedroom**	**Back Bedroom**
Base case (single zone control)	1044	3.2%	40.3%	63.7%	32.5%
Base (multizone control)	1010	0.0%	2.5%	10.7%	0.8%

Notes: 1. gas energy is gross (i.e. including the latent heat of water); 2. since there is no radiator in the kitchen there is no heating demand profile for this room, so there is no target to compare with the achieved temperature (see simulation results summary in Appendix section **A.5.1**).

Combining the effect of the fabric measures discussed above with multizone control and reflective radiator foil makes a considerable difference to both comfort metrics and energy use (see Table 5.1-5). There is uncertainty about how effective the radiator foil is at reducing heat loss to the wall, and this has a minimal impact on energy consumption when the walls have renewed and completed CWI, but it significantly improves the warm-up times and comfort. All rooms apart from the front bedroom come within the desired 2°C temperature range almost all the time, and there is a saving of 22% of energy use and carbon emissions for heating over two cold weeks. This is a good foundation for taking up electric heating in the form of a heat pump.

Table 5.1-5 Results summary for a selection of feasible fabric upgrades - two weeks in January using Newcastle-upon-Tyne weather

Case (all multizone control)	**Energy for space and water heating over two cold weeks, kWh**	**Fraction of heat demand time below household's desired temperature range**			
		Living Room	**Dining Room**	**Front Bedroom**	**Back Bedroom**
Base case	1010	0.0%	2.5%	10.7%	0.8%
150mm loft insulation	998	0.0%	2.6%	9.0%	0.9%
50mm floor insulation in living & dining rooms	989	0.0%	2.8%	10.6%	0.6%
100mm external wall insulation	848	0.0%	2.1%	0.1%	0.0%
Full CWI on all walls, new windows and doors	825	0.0%	2.0%	0.3%	0.0%
As above + reflective radiator foil	820	0.0%	2.2%	0.0%	0.0%

Note: The dining room comfort metric is kept high by the assumed daily opening of the patio door to access the garden.

Preliminary modelling and past work indicated that using a low temperature air-source heat pump with no other upgrades would result in unacceptable warm-up times and poor thermal comfort, even with a 12 kW nominal output heat pump. For this reason, model evaluations of heat pumps were carried out in combination with a 200 litre hot water cylinder and all the fabric upgrades recommended above implemented (except for one case, modelled without upgrades to illustrate this point - see full explanation in simulation results summary, Appendix section **A.5.1.5**). The heat pump outlet temperature to the space heating circuit was set to a maximum of 55 °C, decreasing linearly with rising external temperature. The decision to evaluate high temperature heat pumps was intended to achieve good comfort using the occupant-defined heating profiles whilst limiting the required level of building fabric upgrades and increases in radiator sizes. Domestic hot water heating was scheduled to occur outside normal space heating times to avoid any clashes, and a legionella cycle was defined to raise hot water to 60°C for an hour each day with the assistance of a 3kW immersion heater.

To maintain sufficient emitted power with the reduced flow temperature (relative to the gas boiler system) upgrades to high output double-panel, double-convector radiators were included (at a cost of about £800). A particularly effective modification also adopted was to use the radiators in place of a buffer or bypass loop by not fully closing the radiator control valves (WRVs) – but leaving them 1-5% open when their associated room temperature is within the desired range (see full description in Appendix section **A.4.4**).

These heating system upgrades, including multizone control, together with the fabric upgrades above, improved the home's thermal efficiency by about 25% allowing the heat pump to provide significantly better comfort than the current situation (although not quite as good as with the upgrades and a gas boiler – comparing Table 5.1-5 above with Table 5.1-6). Replacing the gas boiler with an air source heat pump brought the total electrical energy supplied to the home, for winter heating and hot water, down to about 31% of the gas energy currently consumed (for comparison with predicted gas/electricity price ratios in Table 4.2-2). The average effective COP during the two cold weeks in winter is 2.3-2.5. This falls in the height of summer, when the heat pump is only generating domestic hot water, due mainly to heat loss from the hot water tank, which has implications for claims that a seasonal average COP will always be higher than the winter value, despite the far smaller energy use in summer months.

The replacement of the gas boiler with a heat pump was investigated initially with a 12kW unit. This resulted in significant peak electricity demands of up to 10kW (see Table 5.1-6) which, if repeated in large numbers of homes, could place unacceptable demands on the electricity generation, transmission and distribution system. However, detailed modelling of the scroll compressor in the heat pump indicated that it was regularly operating at its minimum 17% of nominal speed, which depressed the coefficient of performance of the heat pump and indicated that it was oversized. Substituting this with a smaller heat pump (6kW nominal output) increased the COP and reduced the electrical energy usage. It was also found that reducing the impact on the electricity infrastructure by limiting the input power to the heat pump (nominally to 2.5 kW in this case) made a small improvement in average COP, and hence a corresponding small electricity saving, without significantly sacrificing comfort (see Table 5.1-6).

There are also charts in Appendix section **A.5.1.5** with different configurations of heat pump, plotting warm-up times room-by-room, with and without the fabric upgrades described above. This shows that the warm-up times can be acceptable using a heat pump, even on very cold days, as long as fabric upgrades have been applied.

In the hybrid heat pump-gas boiler system the boiler provides instantaneous domestic hot water on demand and heating during warm-up, while the heat pump meets the base load. This brings the benefit that no domestic hot water storage tank is required which saves space and removes the requirement for a legionella cycle. The hybrid system with building fabric upgrades brings possible savings of 71% in gas consumption relative to the equivalent combi-boiler only case. The electrical energy consumed for space heating is equivalent to about 30% of the savings in gas consumption (see Table 5.1-6, compare to gas/electricity price ratios in Table 4.2-2 and see section **5.1.6** below for more discussion on running costs).

Once again, there are charts in Appendix section **A.5.1.6** showing room temperatures, which show that the hybrid system achieves excellent warm-up times and comfort.

Table 5.1-6 Results summary for heating system upgrades - two weeks in January using Newcastle-upon-Tyne weather

Case (all using multizone control)	Energy used for heating, two cold weeks, kWh	Average effective COP of ASHP	Peak electricity demand, space & water heating, kW	Fraction of heat demand time below household's desired temperature range			
				Living Room	Dining Room	Front Bed	Back Bed
12kW ASHP	407	2.0	7.1	0.9%	3.1%	3%	1%
12kW ASHP, min WRV openings + fabric upgrades	319	2.26	10.0	5.7% (too warm)[1]	2.5% (2% too warm)	0%	0%
6kW ASHP with 2.5kW input limit, min WRV opening + fabric upgrades	286	2.52	2.5 (+brief use of 3kW immersion)	5.9% (too warm)[1]	3.1% (2.1% too warm)	0%	0%
6kW ASHP 2.5kW input limit (with min WRV opening + fabric upgrades) + gas boiler in series	176 (HP) 242 (boiler)	2.8	2.7	4.0% (too warm)[1]	2.1%	0%	0%

Note 1 – the pre-heat time and minimum WRV opening could both be reduced to correct this.

5.1.5. Carbon emissions

Table 5.1-7 shows the projected CO_2 emissions for 2020 to 2050 for each of the scenarios discussed. The best long-term option in terms of carbon emissions is using a 6 kW ASHP with all fabric upgrades. By 2040, if the carbon intensity of electricity continues to fall in the way projected in this data, this brings an 99% reduction in the base case carbon emissions for heating and domestic hot water.

However, with 2020 carbon intensities, the hybrid heat pump-boiler scenario with full fabric upgrades has only marginally higher emissions than the heat pump alone – bringing a 41% saving compared to the current situation.

Table 5.1-7 Annual results summary (energy and CO_2) - using Newcastle-upon-Tyne weather

	Energy used for heating and hot water, kWh		CO_2 emissions for heating and hot water, kg [1]			
Case	**Gas**	**Electricity**	**2020**	**2030**	**2040**	**2050**
Base case (combi boiler)	14668	0	2693	2693	2693	2693
Full CWI, new windows & doors, radiator foil[2]	11047	0	2028	2028	2028	2028
6kW ASHP working as hybrid with combi-gas boiler[2]	4462	2108	1585	1014	838	823
6kW ASHP with 2.5 kW input limit & full fabric upgrades[2]	0	4043	1469	374	36	7

Notes: 1 - see note in section **4.2** regarding the carbon intensities of the different energy sources; 2 – with multizone control.

5.1.6. Running costs

The annual running costs of this house at different stages of improvement are shown in Table 5.1-8, for weather typical of the UK's North East, using projections of energy costs from 2020 to 2050 which foresee that gas prices will more than double by 2040, while the cost of electricity is predicted to almost triple, before starting to fall by 2050.

Table 5.1-8 Annual results summary (costs) - using Newcastle-upon-Tyne weather

	Energy used for heating and hot water, kWh		Energy costs for heating and hot water, £*			
Case	**Gas**	**Electricity**	**2020**	**2030**	**2040**	**2050**
Base case (combi boiler)	14668	0	422	506	959	1320
Full CWI, new windows & doors, radiator foil	11047	0	318	381	722	994
6kW ASHP working as hybrid with combi-gas boiler	4462	2108	330	474	866	832
6kW ASHP with 2.5 kW input limit & full fabric upgrades	0	4043	386	613	1102	826

* see note in section **4.2** regarding the costs of the different energy sources.

This analysis, on narrow financial grounds alone, shows that retaining the gas boiler and carrying out the full fabric upgrades is cheaper than installing a heat pump, reaching parity as electricity costs start to fall towards 2050. The capital costs of around £20,000 for all the upgrades, of which the heat pump accounts for about 40%, would not be justified on a purely return-on-investment basis. This indicates that, for this home, the current regulatory and market environment is not conducive to driving the transition to low carbon heating in the required timescale.

However, the hybrid heat pump-boiler solution does match the running cost achieved by applying the fabric upgrades with the current gas boiler in the short term. This, however, is not the case during the peak electricity prices between around 2030 and 2040.

5.1.7. Proposed Pathway

Based on the results of the modelling, the pathway that offers optimum carbon emissions and comfort, with acceptable levels of disruption, comprises:

- Multi zone heating control
- Window and door upgrades
- Improvement of cavity wall insulation
- Reflective radiator foil behind radiators on external walls
- ASHP with some radiator replacements and a hot water cylinder OR
- Air-source heat pump as a hybrid system working with a gas boiler

There are clear advantages for the household in upgrading to multizone heating control, in terms of comfort and operating cost. Therefore, this should be the first step in the pathway and is not expected to require any significant triggers. Upgrading cavity wall insulation offers improvements in energy efficiency and comfort which are expected to be attractive to the household for minimal disruption. Therefore, these are expected to be adopted and, taken together, would save about 17% of the current energy bill.

Replacing the windows and doors is a more expensive and more involved upgrade. This might cost £8,000-£10,000. However, it would improve the appearance of the house and so would add value. It should also mean that the new doors and windows would last 30 years without further maintenance, and replacing the joinery is also an opportunity to improve security in the dwelling. Potentially, they may also be able to include secure ventilation (so they can address summer overheating in upstairs rooms, by leaving the windows partly open, but still secure).

The case for installing an ASHP is more difficult and it is unlikely that the household would get better service than with a gas boiler and multizone control, but to make the heating system low carbon, it is a necessary step. Triggers might be higher gas prices (or the expectation of higher gas prices), fears about gas shortages (linked to geopolitical events), or new legislation forcing or incentivising a switch.

Using the heat pump in tandem with the existing gas boiler is an attractive option for this home, bringing the benefit of fast warm-up times and hot water provision even on very cold days without giving up space for a hot water cylinder. It can also reduce peak electricity demand relative to the stand-alone ASHP (especially if this requires use of the immersion heater for a legionella cycle) and saves money on running costs. It also paves the way for the household to accept the heat pump alone once the boiler reaches the end of its life.

5.1.7.1. Upgrade pathway summary

Stage 0

- Existing problems
  - Bedrooms and dining room are hard to heat
- 2.7 tonnes CO_2/ year[24]

Stage 1 – Years 1 to 5:

- Upgrade to multizone heating control
- Fill gaps in existing cavity-wall insulation and add to front and rear walls
- Fit reflective foil behind radiators (a simple DIY measure)
- 2.2 tonnes CO_2/ year[24]

Stage 2 – Years 3 to 13:

- Replace old double-glazing and doors (including some blown units where condensation is visible between the panes), and align with new insulation layer in the middle of the cavity walls
- Install high output radiators to improve response times of cool rooms
- 2.0 tonnes CO_2/ year[24]

Stage 3A (optional) – Years 6 to 12:

- Install a 6 kW ASHP as a hybrid system working with the gas combi-boiler
  - No hot water cylinder is needed as the boiler can generate instantaneous hot water
- 1.6 tonnes CO_2/year in 2020 (41% reduction)
- 1.0 tonnes CO_2/year in 2030 (62% reduction)
- 0.8 tonnes CO_2/year in 2040 (69% reduction)

Stage 3B – Years 6 to 12:

- Install a 6 kW ASHP (if not installed in stage 3A)
- Remove gas boiler (at end of serviceable life)
- Install a 200 litre hot water cylinder in a landing cupboard
- 1.5 tonnes CO_2/year in 2020 (45% reduction)
- 0.4 tonnes CO_2/year in 2030 (86% reduction)
- 0.04 tonnes CO_2/year in 2040 (99% reduction)

[24] Carbon intensity of 184gCO_2/kWh for gas (from BEIS (2017) Greenhouse Gas Conversion Factors)

5.2. House B (1920s mid-terrace) upgrade pathway

5.2.1. Upgrading this house to low-carbon, high comfort, electric heat

The following upgrade pathway has been developed for this 1920s two-bedroom mid-terrace home. The methodology outlined in section **4** has been followed to analyse the home's existing and potential building fabric and heating system, resulting in a pathway which both reduces CO_2 emissions and satisfies the needs and preferences of the household.

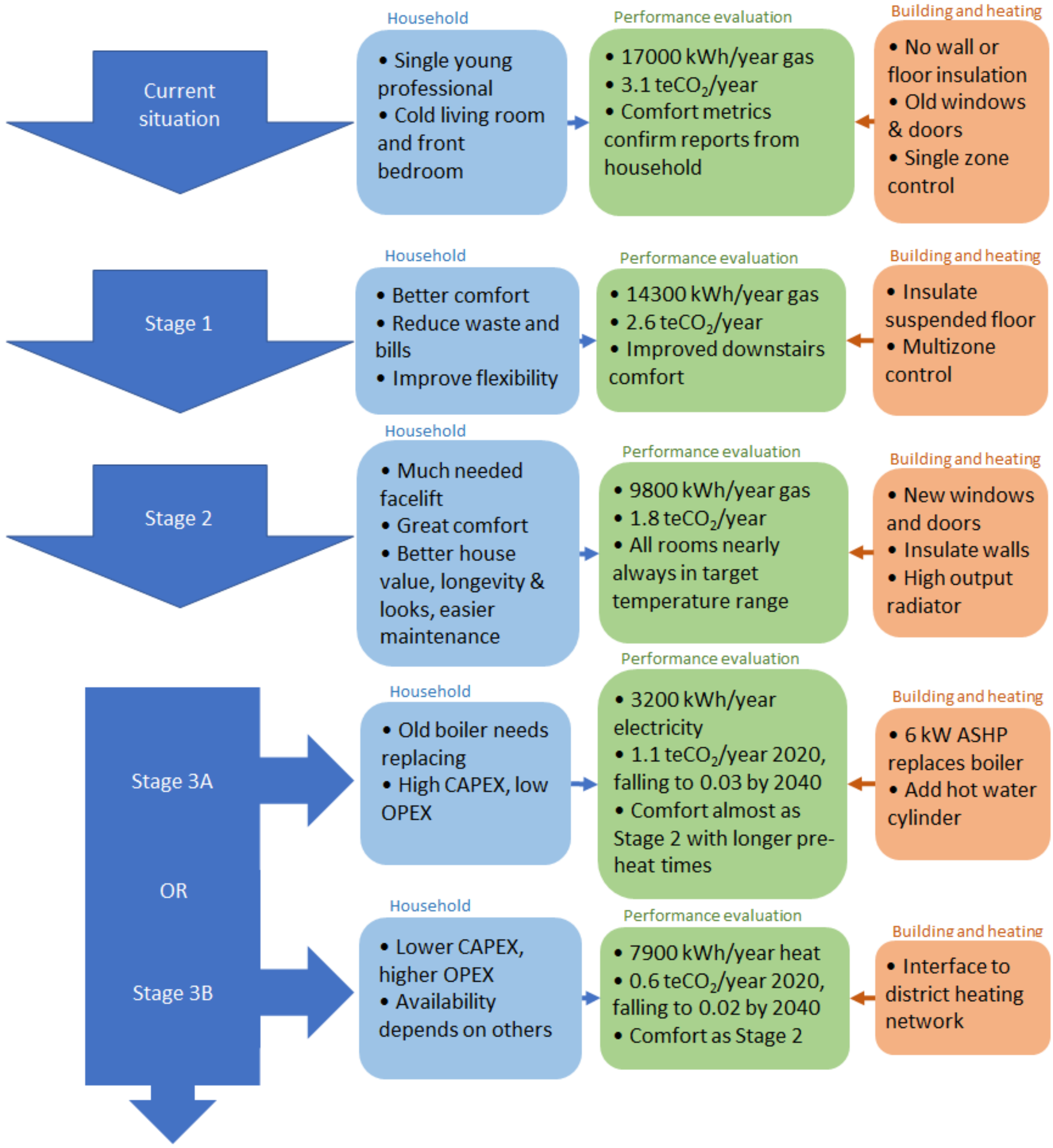

Figure 5.2-1 - House B upgrade pathway

The following sections describe how this pathway was developed and give details of how it achieves the household's desired level of thermal comfort, whilst achieving significant carbon savings, and considers the practical issues of carrying out the upgrades. This leads to a full description of the pathway in section **5.2.7**.

5.2.2. The house and household as it is now

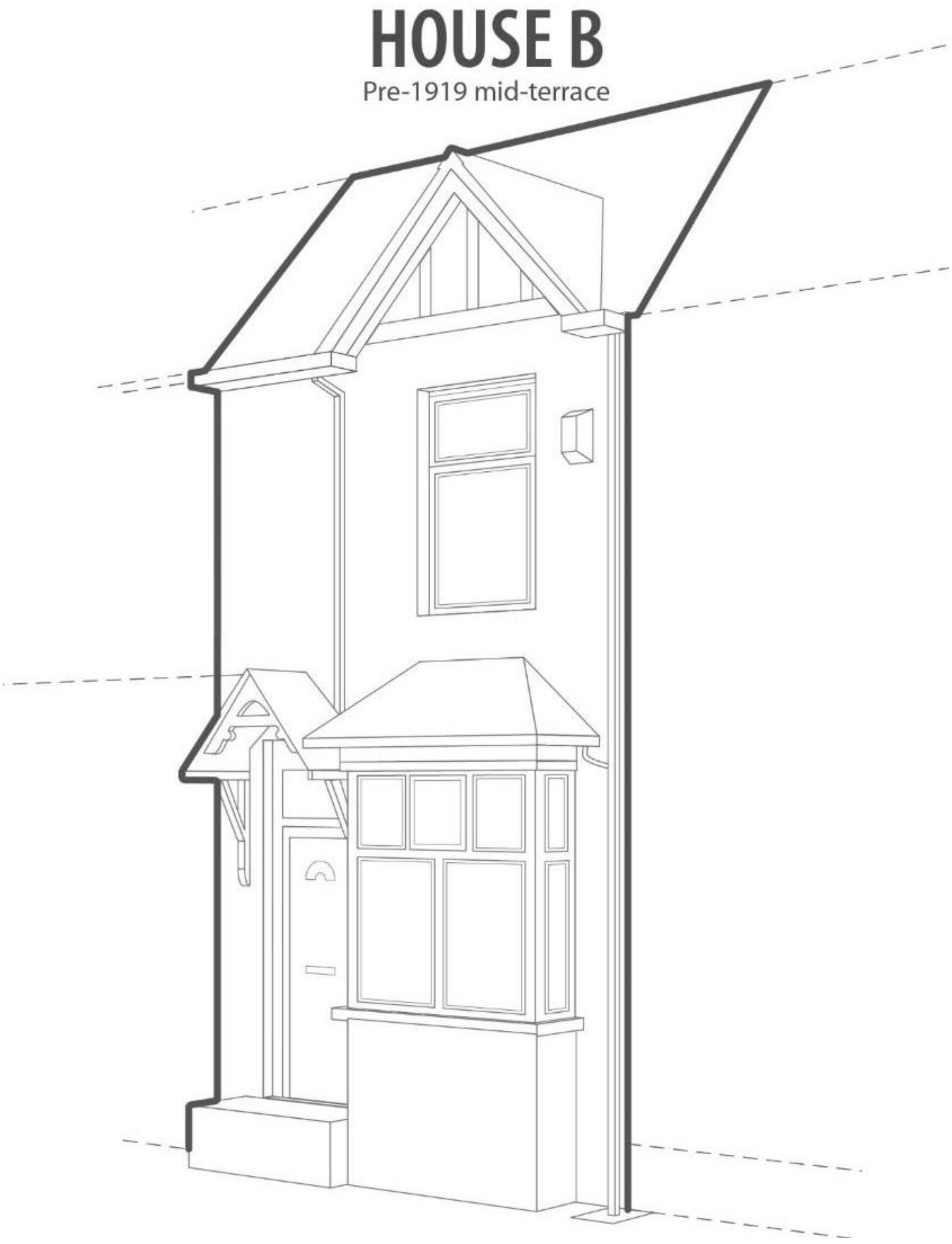

Figure 5.2-2– Impression of House B

5.2.2.1. The Household

The house belongs to a single male in his late 20s, who lives alone. He works from home four days a week, and travels by train to London one day a week. He purchased the house 18 months ago and expects to stay there for around six years.

He cares about aesthetics, and he wants his home to look good. He laid carpet over the wooden floor boards in front and dining room and put laminate flooring over the stone floor in the kitchen, which has made the ground-floor rooms warmer. He made attempts to draught-proof the front door and has bought draught excluders for internal ground-floor doors. He says he is accepting of change and tolerates the disruption of carrying out work in his home.

The owner is a financially secure young professional who has never had problems paying the energy bills and likes to be able to budget for energy costs. He thinks it is important to care for the environment, and he tries to avoid wasting energy, striking a balance between comfort and efficiency. However, he makes an effort to ensure that visitors (especially his grandparents) are comfortable in the house. His preferred temperature for the dining room (where he eats and watches TV) is 23°C, with the kitchen and living room (where he works 4 days a week) cooler – 20 or 21°C. He would prefer to be able to heat upstairs rooms only in the evenings, aiming to achieve 21°C in the bedrooms and 22°C in the bathroom.

The living room and kitchen are used for drying clothes in winter, preferring to avoid using the tumble-drier, which he believes is a waste of energy. For comfort reasons, he tends to keep internal doors closed in winter – especially doors leading to the staircase, which is unheated.

5.2.2.2. The House

House B is a two-bedroom, terraced house built in the 1920s, as illustrated in Figure 5.2-2 and Figure 5.2-3. Details of the physical characteristics are summarised in Table 5.2-1.

Figure 5.2-3 - Floor plan of House B

Table 5.2-1 Characteristics of House B

House characteristic	Details
House type and age	Terrace house built in 1920s
Geographical location	Urban
Orientation	Front faces north east
Floor area	68 m^2
Number of heated rooms	6 heated rooms
Number of bedrooms	2 bedrooms
Wall construction and insulation	Solid, un-insulated walls
Roof insulation	Approx. 20 m^2 of main roof is insulated to full height of joists (100 mm), but not continuous. Extension roof has 50 mm of insulation.
Windows	Fully double glazed. uPVC, fitted pre-2002.
Floor description	Suspended timber floor above a closed-up cellar. Kitchen has solid floor. Kitchen and rear bedroom have laminate floor covering, in good condition. Exposed floorboards in bathroom, quite old and valuable (potentially original, therefore not easily replaced without damage). The rest of the house (front bedroom, living room, dining room, stairs) is carpeted (very well maintained, although easy to replace).
Heating system description	Combi boiler (quite old), programmer, room thermostat and TRVs, no hot water storage
Extensions / conservatories	Conversion on rear wing single storey kitchen (may have originally been coal store).
Garden(s) or other outside areas	Tarmac to front (space to park cars off street). Side passageway 1.8m wide (concrete slabs). Concrete slab patio behind house, including shed (7m to rear). Large lawn behind house (33.1m x 7.4m)
Description of road	Secondary road
Local Area Energy Planning - heating system choices[25]	Located in area with prospect of district heat network being installed in future.
Existing problems with heating	The living room is cold at night, and there are cold draughts by the front door, even though it has been draught-sealed. The main bedroom is also below the owner's preferred temperature much of the time.

[25] For information about the results of the geographical analysis from EnergyPath Networks modelling, see https://es.catapult.org.uk/projects/local-area-energy-planning/

5.2.2.3. Current comfort, energy use and carbon emissions

IEHeat modelling confirmed the reported poor comfort in some rooms, with long periods below the room temperatures the household tries to achieve (see Appendix section **A.5.2**). For example, the time spent colder than the desired temperature range, as a percentage of the time the occupant wants it to be warm, is more than 40% for the living room and about 19% for the kitchen.

Using "typical mean" weather from Newcastle-upon-Tyne resulted in a prediction of annual energy use of roughly 17,000 kWh a year for space and water heating, resulting in annual carbon emissions of 3.1 tonnes CO_2, at a cost to the household of about £680 at 2018 energy prices.[26]

5.2.3. Evaluation of potential building fabric upgrades

A thorough assessment of possible upgrades indicated that the most promising improvements to building fabric in this house, from the perspective of comfort and thermal efficiency, are those in Table 5.2-2. The practicalities of each upgrade are discussed below.

Table 5.2-2 Potential fabric upgrades for House B

Upgrade	Description
Upgrading double-glazed windows	Replacing existing windows with a U-value of 2.8 with new ones with a U-value of 2.0 W/m^2K
Upgrading double-glazed doors	Replacing existing doors with a U-value of 2.8 with new ones with a U-value of 2.0 W/m^2K
Improving draught stripping of front door	Reported by the owner to still be draughty
Top-up loft insulation	Adding up to 150 mm of extra loft insulation to the existing 100 mm of main roof insulation
Top-up extension roof insulation	Adding up to 100 mm of extra insulation to the existing 50 mm of insulation of the single-storey extension
Floor insulation for ground floor suspended timber floor	Adding 50, 75 or 100 mm of insulation below the floor boards on the suspended ground floor
Insulating the walls externally	Adding external wall insulation (EWI) using expanded polystyrene with render on top
Insulating the walls internally	[As an alternative to EWI] Adding internal wall insulation, using expanded polystyrene with plasterboards and skim on top

[26] Assuming a carbon intensity of 184 gCO_2/kWh for natural gas (from BEIS (2017) Greenhouse Gas Conversion Factors 2016. London: BEIS), and a typical consumer price for gas of 4p/kWh.

Topping-up the loft insulation in this house is likely cost less than £400 and cause little disruption as it is not currently used for storage, although access is restricted dues to the size and shape of the roof spaces. Similarly, upgrading the windows and doors could probably be done by a window installation company in a few days, for about £4,000-£6,000, with any disruption likely to be limited to one room at a time. These upgrades could therefore be carried out without significantly affecting the homeowner's usual routine. However, some re-plastering and re-painting is likely to be needed after the window and door work is complete.

However, the other possible improvements for this house are more intrusive. Insulating underneath the suspended floor would be likely to cost over £2,000, as it would mean lifting all the floor boards because there is insufficient crawl-space under the living room floor to carry out the work from below. This would require all furniture to be cleared from the living room and possibly the dining room (depending on access to the disused cellar). There is some chance of damaging the floorboards when they are raised, and some may need to be replaced.

Wall insulation could be installed either internally or externally, although space and other constraints affect either upgrade. The impact on the house's appearance in the terrace means that EWI is less likely to be appropriate for the front of the house, although the appearance of the back is typically less sensitive. Using IWI at the front (at around £2,000-£3,000) and EWI at the back (for £6,000-£9,000) is a common solution. The principle concern about IWI is the loss of floor space, and the need to re-fit and sometimes re-configure the kitchen and bathroom because equipment attached to the wall has to be moved. In this house, using EWI at the rear would bring much less disruption, particularly as the eaves overhang is sufficient to protect the insulation from rain, and this would mean that the kitchen and bathroom would not need additional work.

The owner's acceptance of disruption during any work, and the single-occupancy, with spare rooms, makes it easier to chart an upgrade pathway than for House A. His environmental/ waste-avoiding outlook, and the desire to make the house more comfortable, means it may be easier to justify carbon-saving interventions. However, the fact that he only intends to live in the house for six more years may act against more expensive upgrades unless they add to the resale value of the house.

The house already being in a good state of repair means there are limited opportunities to combine energy efficiency work with other decoration/renovation work. Good carpets and wall coverings may inhibit retrofit work because they will need to be made good after some of the possible upgrades (e.g. internal wall insulation, floor insulation, new heating pipework, penetrations through the wall to install a heat pump or district heat interface unit, etc.).

5.2.3.1. Combining fabric upgrades

The fabric upgrades proposed above would work well together and serve to reduce heat loss from all external surfaces (walls, floor, roof, fenestration). There are no specific issues about sequencing or applying the fabric interventions, although, it would be better to link the wall insulation and glazing replacement so that the windows sit in line with the insulation and thermal bridging can be reduced around the perimeter of the windows.

Loft insulation also needs to take account of the wall insulation, and ideally it will form a continuous insulated layer, aligning with the (internal or external) wall insulation at the junction between roof and wall. This will minimise thermal bridging around the insulation. However, roof ventilation will need to be installed (tile vents or ridge vents) to allow moisture to leave the loft space since this is likely to have been blocked by insulating into the eaves.

5.2.3.2. Outcomes of fabric upgrade evaluation

Detailed modelling described in Appendix section **A.5.2** indicated that improved glazing saved 4.3% of heating energy in winter – roughly three times the saving from improved external doors (1.6%). This would also make a noticeable improvement to comfort metrics.

Extra loft insulation would make only a small difference to energy use – a saving of only 1.5% with 250mm total insulation for the main roof and 150 mm for the kitchen extension - while making only a minor improvement to comfort. Insulating the suspended floor would have a bigger impact on energy use - applying only 75mm saves around 5.6% of heating energy in winter, as well as improving comfort in the living room, dining room and kitchen (the kitchen door is usually open, so it benefits from a warmer dining room). Increasing the depth of floor insulation to 100mm saves 6.1% of heating energy, with negligible further improvements in comfort. Given the considerable disruption of lifting floorboards, and the small difference in the cost of materials, it would make sense to insulate as much as is practical. However, due to services running under the floor, it was decided that 75mm would be appropriate.

Wall insulation (whether internal or external) revealed the largest potential savings of all fabric upgrades, with up to 22% saving for 100mm of EWI and up to 18% saving from 40mm of IWI (see Figure 5.2-4). The savings are usually slightly greater with IWI than with the same thickness of EWI because less energy is needed to raise the room temperature. However, rooms with IWI also cool faster than those with EWI because they do not benefit from the thermal mass of the walls. IWI may also bring an increased risk of cold spots due to thermal bridging around the insulation, and potentially condensation forming at cold spots around the corners of the room at junctions. Ideally, the insulation 'returns' of around 400mm along internal walls should minimise this thermal bridging.

Insulating the walls with a thickness of 40mm or more also improves the warm-up times upstairs – from 45 minutes to reach the owner's comfort temperature in the back bedroom to just 20 minutes with IWI.

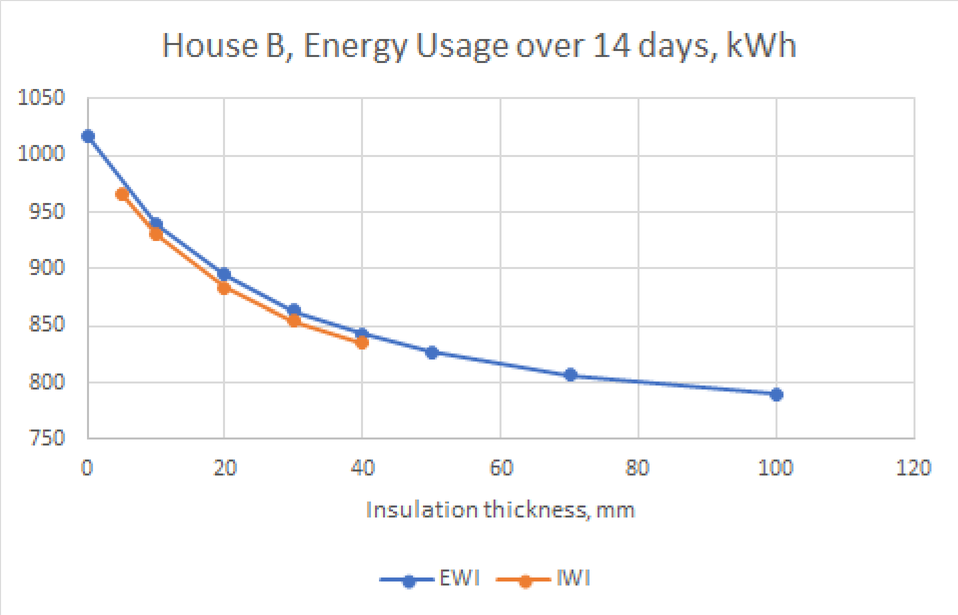

Figure 5.2-4 - Reduction in energy consumption with increasing wall insulation thickness – showing diminishing returns

5.2.4. Evaluation of potential heating system upgrades

A further detailed assessment of possible heating system upgrades (see **Appendix 9** and section **A.5.2**) indicated that the most promising components to consider are those in Table 5.2-3.

Table 5.2-3 Potential heating upgrades

Upgrade/change	**Description**
Multizone heating control	Independent on/off control of each radiator
High-output radiator for back bedroom	Double-panel, double-convector radiator in the one room with a single panel radiator
Air-source heat pump	6 kW nominal output, with 200 litre hot water tank with fabric upgrades (also modelled without for comparison)
District heating	Using an indirect Heat Interface Unit (HIU) with two separate heat exchangers – one for space heating, the other for hot water, with or without fabric upgrades

As for House A, multizone heating control can be a relatively straightforward upgrade (see **Appendix 4**) with limited disruption and costs around £500 for a house with six radiators with easily accessible TRVs. It is likely to both improve comfort and save energy by improving the match between heating and occupation. Arguably, this is more important for single-occupant homes where most of the rooms are unoccupied much of the time.

An air-source heat pump would need the external unit to be mounted on the kitchen wall at the rear with the internal unit and pipework entry in the bathroom, to simplify connection to the existing heat distribution system and avoid lifting floorboards where possible. This would cost around £7,000-£8,000 for a low power unit. Planning permission is not normally needed providing the heat pump complies with the Microgeneration Certification Scheme standards, is no more than 0.6m^3 in size, and at least 1 m from the site boundary[27]. A hot water storage cylinder would also be needed because a heat pump could not generate instantaneous hot water like the existing combi boiler. There is potentially space in the bathroom for both a heat pump internal unit and a new hot water cylinder in the existing boiler cupboard. Pipes from the external unit could enter through the side wall of the bathroom, in the cupboard, which would require less work to make good than entering through the back wall, which would mean re-plastering and/or re-tiling.

Alternatively, a low-carbon heat network connection may be possible at some point in the future because of the high housing density, urban setting. However, this is outside the owner's direct control and dependent on energy suppliers and/or local authority support. If available, it would be better to locate the heat interface unit for district heating at the front of the house, close to the district heating main, requiring significant lengths of piping to connect with the existing system, but it would not need a hot water cylinder. A typical HIU would cost around £1,500 plus installation.

5.2.4.1. Combining heating system upgrades

Both the fabric upgrades and multizone control give benefits on their own, but in combination are key to successful deployment of an ASHP. Independent temperature settings for each room would make it easier to capitalise on the potential savings of improved insulation. This would also help to optimise pre-heat times and achieve good comfort after installing a heat pump, so the upgrade options described above are consistent and complementary. The key decision is between an air-source heat pump or district heating as a source of low-carbon heat.

5.2.4.2. Outcomes of heating system upgrade evaluation

The modelling demonstrated that adopting multizone control, on its own, gives profound improvements in comfort, providing heating where and when it is needed, avoiding heating rooms that are not used. Compared to the usual form of heating control, using a single room thermostat and thermostatic radiator valves, this improves the comfort metric dramatically for most rooms (see Table 5.2-4), and simultaneously saves 9% of energy use (and carbon emissions) for heating.

The modelling showed that one of the issues with this house is that the living room is uncomfortably cold for around two-fifths of the time. This was found to be because the single-zone thermostat is located in the dining room, and it cuts off the heating before all rooms reach the desired temperature. Table 5.2-4 shows the dramatic difference multizone control could make.

[27] https://www.planningportal.co.uk/info/200130/common_projects/27/heat_pumps/2

Table 5.2-4 Results summary for base case - two weeks in January using Newcastle-upon-Tyne weather

Case	**Energy for space and water heating over two cold weeks, kWh***	**Fraction of heat demand time below household's desired temperature range**				
		Living Room	**Kitchen**	**Front Bedroom**	**Back Bedroom**	**Dining Room**
Base case (single zone control)	1124	41.8%	15.9%	7.1%	0.5%	1.4%
Base (multizone control)	1018	1.4%	1.2%	0.5%	2.0%	0.5%

* Gas use is gross (i.e. including the latent heat of water)

Combining the effects of the fabric measures above with multizone control and high-output radiators makes a considerable difference to both comfort metrics and energy use (see Table 5.2-5). All rooms come within the desired 2°C temperature range almost all of the time, with warm-up times less than an hour even on the coldest days, and there is a parallel saving of 34% of energy use and carbon emissions for heating over two cold weeks. This is a good foundation for taking up low-carbon heating in the form of a heat pump or district heating system.

Table 5.2-5 Results summary for a selection of building fabric improvements

Case (all multizone control)	**Energy for space and water heating over two cold weeks, kWh**	**Fraction of heat demand time below household's desired temperature range**				
		Living Room	**Kitchen**	**Front Bedroom**	**Back Bedroom**	**Dining Room**
Base case	1018	1.4%	1.2%	0.5%	2.0%	0.5%
New windows, floor insulation (75mm) draught proofing front door	885	0.3%	0%	0.1%	0.1%	0.1%
As above plus 100mm EWI rear, 40mm IWI front	672	0.5%*	0%	0%	0%	0.3%

*The living room comfort metric deteriorates because the front door is opened when it is warm.

Preliminary modelling and the results from House A indicated that using a low temperature air-source heat pump with no other upgrades would result in unacceptable warm-up times and poor thermal comfort. Hence the modelling considered installing a heat pump with a nominal output of 6 kW coupled with a 200 litre hot water cylinder and all of the fabric upgrades listed above. The flow water temperature of the space heating circuit was set to a maximum of 55 °C, decreasing linearly with rising external temperature. Domestic hot water heating was scheduled to occur outside normal space heating times to avoid any clashes, with a legionella cycle defined to raise the stored hot water to 60°C for an hour each day.

To achieve good thermal comfort with this heat source it was also proposed to upgrade the radiator in the back bedroom to a high output double-panel, double-convector radiator (at a cost of about £200), and to suggest to the occupant that he changes his habit by keeping the bathroom door normally closed in cold weather.

The fabric upgrades above together with multizone control improved the home's thermal efficiency by about 42%, which, together with the updated radiator allowed a high temperature heat pump to provide better comfort than the current situation (comparing Table 5.2-5 with Table 5.2-6). Replacing the non-condensing gas boiler (with an efficiency of around 79%) with an air source heat pump brought the total electrical energy supplied to the home, for winter heating and hot water, down to about 20% of the gas energy currently consumed (for comparison with predicted gas/electricity price ratios in Table 4.2-2). The average effective COP during the two cold weeks in winter is 2.6. This falls in the height of summer, when the heat pump is using less energy, only generating domestic hot water, due mainly to heat loss from the hot water tank.

Table 5.2-6 Results of ASHP and fabric improvements

Case	**Electricity used for heating, two cold weeks, kWh**	**Peak electricity demand, space & water heating, kW**	**Fraction of heat demand time below household's desired temperature range**				
			Living Room	**Kitchen**	**Front Bed**	**Back Bed**	**Spare Bed**
6kW ASHP with fabric upgrades	204	2.62	1.3%	0.0%	0.5%	0.0%	0.0%

There is a concern that replacing gas boilers with heat pumps would put unacceptable demands on the electricity grid in peak periods – principally between 5pm and 7pm in the evening. The modelling included exploring the effect of limiting the heat pump peak electrical demand, and as Table 5.2-6 shows, the heat pump specified here requires a maximum of only 2.6 kW peak. Figure 5.2-5 plots the 24-hour profile of electricity demand by the heat pump in cold weather, showing that the heat pump draws full power for only short periods, spaced fairly evenly from 3.30am to 11pm. For modest numbers of individual houses using heat pumps this is likely to be manageable, although if large numbers of homes supplied on the same network adopt electric heating, this would require grid reinforcement and probably additional generating capacity. Alternatively, use of thermal storage in the home could spread the load to reduce the peak electricity demand (see section **7** for further details).

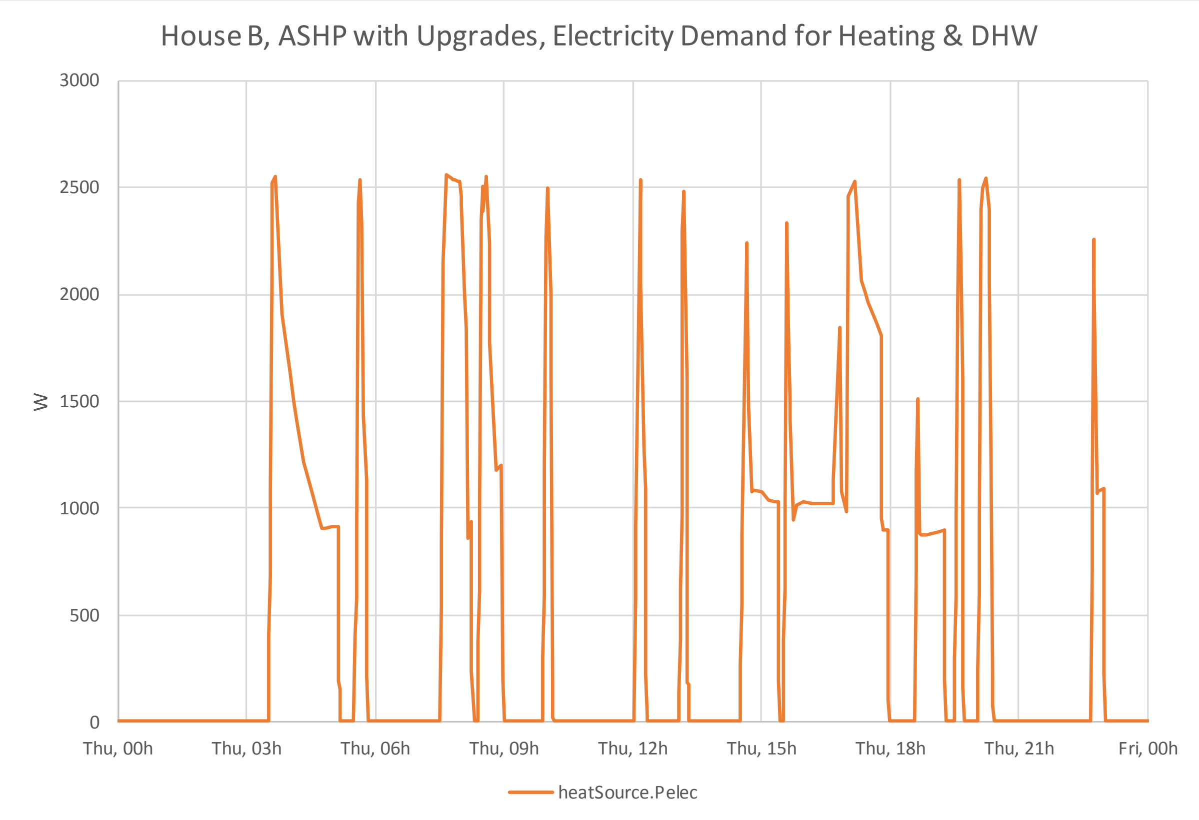

Figure 5.2-5 Electricity profile for ASHP limited to 2.5 kW input power over 24 hours in cold weather

There are further charts in Appendix section **A.5.2.5** showing warm-up times of each room in House B with an ASHP, with and without the fabric upgrades described above. Further modelling investigated what would happen in the event of very cold winter weather – 10°C below the Newcastle January weather used elsewhere (presented in **A.3.8**). This is also described in Appendix section **A.5.2.5.2**. This suggested that with the fabric upgrades discussed above, room temperatures would seldom fall more than 2°C below the desired temperature. Considering the severity of the outside temperatures (and how unusual dropping to -14 °C would be in the UK), this indicates that fears about unacceptable performance of ASHPs in very cold weather are not warranted in this case.

As an alternative to a heat pump for this house, the use of District Heating was also investigated by modelling a Heat Interface Unit (HIU) with two heat exchangers – one of 20 kW for space heating, and a second of 36 kW for hot water. The supply temperature was controlled from 80°C in milder weather to 110 °C in the coldest weather[28], see Appendix section **A.5.2.6**.

The modelling suggested that a radiator flow temperature of 70°C would give acceptable warm-up times, even without the wall insulation, see Table 5.2-7. With the wall insulation, it would be possible to run the flow temperature at 55°C and have acceptable warm-up times,

[28] From "District heating manual for London", Greater London Authority, February 2013

although markedly longer than with a flow temperature of 70°C. The major benefits of running a cooler flow temperature are reduced network heat losses, higher energy centre efficiency and lower peak demand for heat from the heat network. This becomes important if the number of homes connected to the network means that demand approaches the maximum heat generation capacity of the system.

Table 5.2-7 Results from District Heating with and without fabric upgrades

Case	Energy input from DH, two cold weeks, kWh*	Peak demand from DH, space & water heating, kW	Maximum warm-up time, minutes				
			Living Room	Kitchen	Front Bed	Back Bed	Dining Room
District Heating no wall insulation, outlet=70°C	715	37.3	19.4	27.2	38.4	29.4	25.3
District Heating outlet=70°C, 40/100 mm wall insulation	543	35.7	17.0	12.3	19.8	11.7	12.4
District Heating outlet=55°C, 40/100 mm wall insulation	537	38.1	52.2	23.4	39.7	34.6	23.3

* Energy usage does not include losses in the district heating network.

The peak demands shown in Table 5.2-7 occur at the start of each heating period or DHW demand when the exchangers in the HIU are first warmed, and typically only last for a very short duration – just one or two minutes.

District heating can be supplied from different sources, and these often vary through the year and/or through the day. Waste heat from local industrial processes or power generation may be available at certain times, there may be a local combined heat and power (CHP) installation, or a source of biomass fuel. Alternatively (or alongside this) district heating can incorporate large-scale heat pumps, using cooling water from data centres, the sea, a river, or other sources. This means the carbon intensity of district heating varies, and (like the generation cost) it may vary through the year and from hour to hour.

5.2.5. Carbon emissions

Table 5.2-8 shows the projected annual CO_2 emissions for 2020 to 2050 for each of the scenarios discussed. The best option in terms of carbon emissions, both long term and short term, is using an ASHP with all fabric upgrades. At 2020 emission intensities this brings a saving of 63% compared to CO_2 emissions using the current gas boiler with no fabric upgrades, and a 99% reduction by 2040.

Table 5.2-8 Annual results summary (energy and CO_2) - Newcastle-upon-Tyne weather

	Energy used for heating, and hot water, kWh		CO_2 emissions for heating and hot water, kg[1]			
Case	**Gas, DH**	**Electricity**	**2020**	**2030**	**2040**	**2050**
Base case (combi boiler)	17024	0	3126	3126	3126	3126
Base case with new windows, draught-proof front door, 75mm floor insulation+40/100mm wall insulation[2]	9817	0	1802	1802	1802	1802
6kW ASHP with full fabric upgrades[2]	0	3163	1149	293	28	6
District heating at 70°C with full fabric upgrades[2]	4043	0	650	554	18	7

Notes: 1- see note in section **4.2** regarding the carbon intensities of the different energy sources; 2 – with multizone control.

The district heating option also shows CO_2 emissions savings both long and short term, with those in 2040 nearly in line with using an ASHP, based on predictions used by EnergyPath Networks (Table 4.2-1). However, it should be noted that the assumptions that district heating will become low carbon over this timescale are less well tested than the assumptions behind the reductions in carbon intensity of electricity.

5.2.6. Running costs

The annual running costs of this house at different stages of improvement are shown in Table 5.2-9, for weather typical of the UK's North East, using projections of energy costs in from 2020 to 2050 which foresee gas prices more than doubling by 2040, while the cost of electricity is predicted to almost triple, before starting to fall by 2050.

Table 5.2-9 Results summary (costs) - two weeks in January using Newcastle-upon-Tyne weather

	Energy used for heating and hot water, kWh		Heating cost for heating and hot water, £*			
Case	**Gas/DH**	**Electricity**	**2020**	**2030**	**2040**	**2050**
Base case (combi boiler)	17024	0	490	587	1113	1532
Base case with new windows, draught-proof front door, 75 mm floor insulation+40/100 mm wall insulation	9817	0	283	339	642	884
6kW ASHP with full fabric upgrades	0	3163	302	480	862	646
District heating at 70°C with full fabric upgrades	4043	0	433	657	1304	1179

* see note in section **4.2** regarding the costs of the different energy sources.

Table 5.2-9 shows that the fabric upgrades and the ASHP both reduce energy costs compared to the base case in every decade estimated, but the ASHP doesn't show a saving, compared to the gas boiler with similar fabric upgrades, until sometime after 2040. The table also suggests that the energy costs when connected to a district heating scheme are significantly higher than the other alternatives, with the margin peaking around 2040. Again these costs are based on predictions used by EnergyPath Networks, which use broader assumptions than for the other energy sources. However, whilst the running costs are significantly higher, the capital costs for the household of installing a heat interface unit are much lower than those of a heat pump (about £5,000 less). The DH option could also be effective, albeit with higher running costs, without all the fabric upgrades recommended (that together would cost about £16,000-£19,000).

Although running costs will be reduced with upgrades and a heat pump, the pay-back time for the costs of these changes will be much longer than householders would typically hope for when making decisions on major expenditure, suggesting that the current regulatory and market environment may not be conducive to driving the transition to low carbon heating in this case.

5.2.7. Proposed Pathway

Based on the results of the modelling, the pathway that offers optimum carbon emissions and comfort, with acceptable levels of disruption, comprises:

- Multizone heating control
- Draught-proofing the front door
- 75 mm of insulation under the suspended timber floor
- New double-glazed windows
- 100mm of EWI at the rear
- 40 mm of IWI at the front
- Upgraded back bedroom radiator to high-output radiator
- Air-source heat pump with a hot water cylinder OR
- District heating (with no hot water cylinder needed)

As for House A, there are clear advantages for House B upgrading to multizone heating control, and this would bring immediate carbon savings, improve comfort and reduce operating costs. This could be coupled with installing draught-stripping on the front door. The improvements experienced may help to motivate the household to embark on the more expensive and disruptive parts of the upgrade pathway.

Compared to the other possible upgrades, insulating the suspended timber floor is relatively inexpensive, but it still causes considerable disruption.

Internal wall insulation is more appropriate than EWI for the front of the house because of the appearance of the terrace – accepting that IWI means sacrificing a little living space. However, installing IWI is disruptive.

The appearance of the back of the house is somewhat rundown already and this would benefit from a facelift. (This may add value too, if the owner looks to re-sell as he intends in six years' time.) It is generally less important to maintain uniformity in a terrace at the back. Combining external wall insulation with the facelift is sensible, and space is much less constrained than for IWI at the front. This means the owner can afford to install 100 mm of insulation at the rear. External insulation is better than IWI at protecting the original building fabric and brings the benefit of thermal mass inside the insulated envelope, smoothing variations in internal wall temperatures.

It would be wise to upgrade the old double-glazed windows front and back at the same time as insulating the walls, because this would allow the glazing to be aligned with the insulated layer in the window reveal. This reduces thermal bridging around the windows, and the risk of condensation forming where the glazing meets the wall.

Floor and wall insulation and replacing glazing are relatively expensive. Taken together, they might cost £16,000 - £19,000. However, the owner says he has a good disposable income, so he can undertake improvements faster than other households. As well as improving amenity for him, this investment will also add value to the house when he comes to sell.

There is a strategic choice for the owner to make about whether to adopt district heating or a heat pump plus a hot water cylinder. There are pros and cons of each – high CAPEX/low OPEX (upgrades and heat pump) versus low CAPEX/high OPEX (district heating) - but ultimately whether district heating becomes available is out of the owner's hands and dependent on a local energy company or the local authority making investments to establish a local heat network.

There are important practical considerations relating to installing district heating or a heat pump. The boiler is currently in the upstairs bathroom, at the back of the house, and it would be possible to put an external ASHP unit on the kitchen wall and run insulated pipes up the wall externally, leading into the existing boiler cupboard in the bathroom. The new internal control box for the heat pump and a new water cylinder could be installed in the cupboard, maintaining the existing hot water distribution circuit.

Installing district heating is more complicated: the distribution network would probably run in the street, making rear access very difficult, so the heat interface unit would need to be at the front of the house. If the HIU is external this may be detrimental to the house's appearance or parking space, whereas if is internal it could be inconvenient, taking space out of an already small living room, which is used for home-working.

The benefit of using district heating, which emerged from modelling, was that it has the potential to provide low-carbon heating, even without the wall insulation upgrades, and still give acceptable comfort metrics.

Whichever heat source is chosen, it would be sensible to switch to a new, low-carbon heating source when the boiler is approaching the end of its service life – which may be relatively soon as this house has a non-condensing boiler which was last manufactured in 2005 and so may have less than ten years serviceable life remaining. This requires the plans for district heating to be available to the public in advance of 2025 to allow an informed choice to be made. The change of heat source has the potential to make a dramatic difference to carbon emissions for heating, but, in the case of the heat pump, at the cost of longer warm-up times and very slightly inferior comfort metrics compared to the gas boiler with full fabric upgrades.

5.2.7.1. Upgrade pathway summary

Stage 0:

- Existing problems
    - Living room and front bedroom often feel cold
    - Draughty around front door
- 3.1 tonnes CO_2/ year [29]

Stage 1 – Year 1:

- Upgrade to multizone heating control
- DIY draught stripping around the front door
- Insulate under the living room and dining room floors with 75 mm of mineral wool, supported under the floor joists using netting or trays
- 2.6 tonnes CO_2/year (at 2020 CO_2 intensities)

Stage 2 – Year 3:

- Fit 40 mm of IWI at the front, ideally to fit in with planned redecorating work
- Replace back bedroom radiator with one of high output (after IWI fitted)
- Install 100 mm of EWI at the back
- Replace old double-glazing and align with new insulation layer
- Improved appearance should increase resale value
- 1.8 tonnes CO_2/year (at 2020 CO_2 intensities)

Decision fork: either

Stage 3A – Years 6-10:

- Install a 6 kW air-source heat pump with a hot water cylinder
- 1.1 tonnes CO_2/year in 2020 (63% reduction on start point)
- 0.3 tonnes CO_2/year in 2030 (91% reduction)
- 0.03 tonnes CO_2/year in 2040 (99% reduction)

Or

Stage 3B – Years 6-10:

- If district heating becomes available at this location before the boiler needs replacing, the owner has the option to install a heat interface unit, plumbed into the existing heating distribution in place of the boiler
- 0.6 tonnes CO_2/year in 2020 (79% reduction on start point)
- 0.6 tonnes CO_2/year in 2030 (82% reduction)
- 0.02 tonnes CO_2/year in 2040 (99% reduction)

[29] Carbon intensity of 184gCO_2/kWh for gas (from BEIS (2017) Greenhouse Gas Conversion Factors)

5.3. House C (1930s semi- detached) upgrade pathway

5.3.1. Upgrading this house to low-carbon, high comfort, electric heat

The following upgrade pathway has been developed for this 1930s semi-detached three-bedroom home. The methodology outlined in section **4** has been followed to analyse the home's existing and potential building fabric and heating system, resulting in a pathway which both reduces CO_2 emissions and satisfies the needs and preferences of the household.

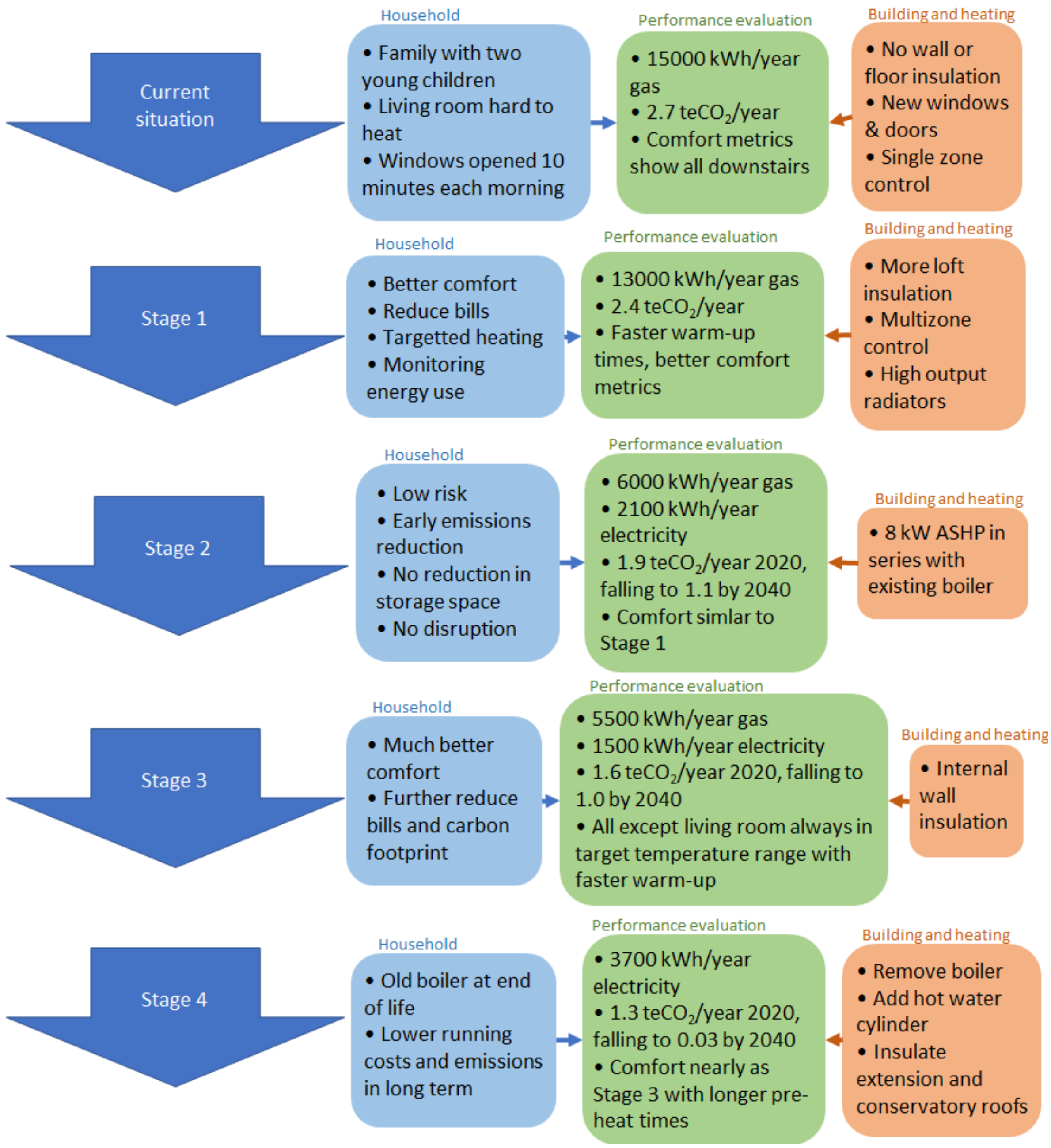

Figure 5.3-1 - House C upgrade pathway

The following sections describe how this pathway was developed and give details of how it achieves the household's desired level of thermal comfort, whilst achieving significant carbon savings, and considers the practical issues of carrying out the upgrades. This leads to a full description of the pathway in section **5.3.7**.

5.3.2. The house and household as they are now

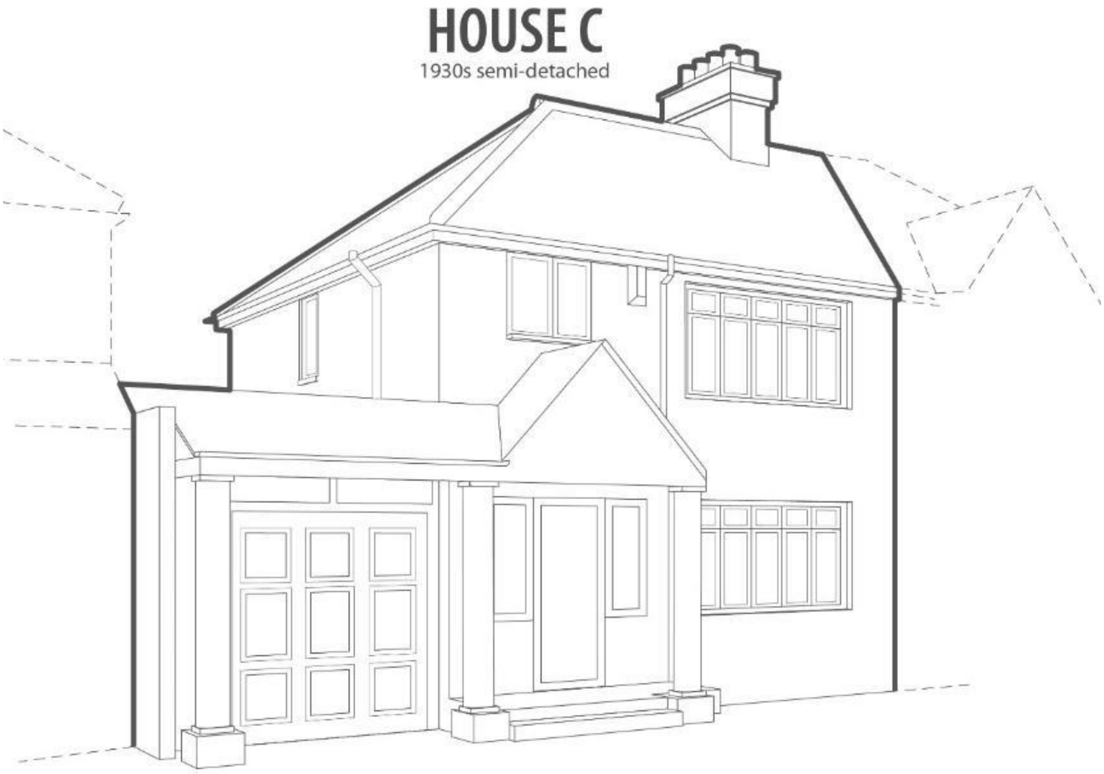

Figure 5.3-2 - Impression of House C

5.3.2.1. The Household

The occupants of house C are a family with two young daughters, aged three and eight. The husband works full time, while the wife is self-employed, fitting her work around child-care. They use all rooms of the house, but typically only in the morning and evening. They have lived in the house for eight years and intend to stay long-term.

The family put a high priority on comfort, although they do not always agree about the best way to stay comfortable. The husband puts on a jumper if he feels cold, while his wife (who feels the cold) turns up the heating. They both like to monitor energy use – largely for budgeting reasons and to avoid any nasty surprises when the bill arrives, rather than to provide feedback on their energy use. They are both attracted to the idea of using technology to help them monitor energy use.

The household is financially secure, but they still aim to save money where they can, and they use comparison websites to get the best deal for energy. They have done a lot of home-improvement work, including making a utility room out of the garage, improving the conservatory, and installing a solid oak floor. They have also done smaller DIY projects aimed at draught-proofing and addressing damp problems. They have become used to the disruption of building work, which they tolerate because they see this improves their home once the work is complete.

The owners say they tend to set their room thermostat to 19°C, with the heating on from 6am to 7.30am in the morning and 3.30pm to 8pm in the evening. They override this if they feel cold, and they leave all the TRVs set at 5. Monitoring found that this gives them around 21°C in most rooms, even in cold weather.

They use secondary heating in the living room and small bedroom if they need more heat. Altogether, they usually have two five-minute showers in the morning, and one bath every evening.

They value fresh air, and open all of the windows for 10 minutes or more every morning. However, they always keep the living room door closed in the winter to avoid cold draughts from the front door.

The husband says he is aware of his carbon footprint, and he tries to avoid wasting energy.

They are a little frustrated with the existing heating system because they find the living room hard to heat, and sometimes when they use the electric heater they find the central heating has gone off in the rest of the house, so it is cold apart from the living room.

They sometimes use the radiators to dry clothes, and if they are doing this they tend to turn up the heating.

5.3.2.2.The House

House C is a three-bedroom, semi-detached house built in the 1930s, but extended to the side more recently, home as illustrated in Figure 5.3-2 and Figure 5.3-3. Details of its physical characteristics are summarized in Table 5.3-1.

Figure 5.3-3 – Floor plan of House C

Table 5.3-1 Characteristics of House C

House characteristic	Details
House type and age	Semi-detached house, constructed in 1930s
Geographical location	Suburban
Orientation	Front faces south west
Floor area	125 m^2 (108 m^2 excluding unheated conservatory and garage)
Number of heated rooms	7 heated rooms
Number of bedrooms	3 bedrooms
Wall construction and insulation	Main house: solid brick wall, no insulation Extension and conservatory: insulated cavity walls.
Roof insulation level	Insulated to full height of joists (75mm), discontinuous. Extension: flat roof (uninsulated)
Windows and doors	Double glazed throughout (uPVC). Windows quite new (installed since 2010)
Floor description	Suspended timber floors (joists parallel to the road). Solid floor in the utility room/garage conversion High quality oak floor boards newly laid through living room and hallway
Heating system description	Wet radiator system, gas fed (combi boiler), no hot water tank present, programmable thermostat and TRVs
Details of extensions / conservatories	Kitchen and subsequent garage / utility room, and separate conservatory
Description of garden(s) or other outside areas	Front: Drive is in good state, materials are tarmac and gravel. House has been extended to next property, therefore there is no path. Rear: there is a large garden. Immediately behind the house is flagstone paving (6.2m x 10.2m), behind which is a lawn (23.5m x 10.1m) with shed at the rear of the garden
Description of road	Secondary road
Local Area Energy Planning - heating system choices[30]	ASHP or ASHP + gas boiler hybrid selected based on location and basic house characteristics.
Existing problems with house heating	Living room is hard to heat and often cold.

[30] For information about the results of the geographical analysis from EnergyPath Networks software modelling (see https://es.catapult.org.uk/projects/local-area-energy-planning/)

5.3.2.3. Current comfort, energy use and carbon emissions

IEHeat modelling of the base case (see Appendix section **A.5.3.2**) was consistent with occupant reports of poor comfort metrics, with long periods below the room temperatures the household tries to achieve, particularly downstairs. For example, in the base case, the living room is colder than the household's desired temperature range for more than half of the defined warm-time (occupied hours). Warm-up times on cold days are also longer than most households would tolerate, and often more than 90 minutes. This is mainly due to the lack of wall insulation giving the house high rates of heat loss. Uneven heating is reported which results from using single-zone control, running the whole heating system off a single room thermostat.

Using "typical mean" weather from Newcastle-upon-Tyne resulted in a prediction of annual energy usage of roughly 15,000 kWh for space and water heating. This level of gas use means annual carbon emissions of 2.7 tonnes CO_2, at a cost to the household of about £600 at 2018 energy prices.[31]

5.3.3. Evaluation of potential building fabric upgrades

A thorough assessment of possible upgrades indicated that the most promising improvements to building fabric to this house, from the perspective of comfort and thermal efficiency are those in Table 5.3-2. The practicalities of each upgrade are discussed below.

Table 5.3-2 Potential building fabric upgrades

Upgrade	Description
Top-up loft insulation	Increasing the existing 75mm of loft insulation to 150mm or 250mm (which means laying insulation over the roof joists or extending the joists)
Roof insulation for extension	Adding 100mm of extra insulation to the existing 50 mm of insulation of the single-storey extension
Putting an opaque, insulated roof on the conservatory	Adding a solid, insulated roof to the conservatory, to achieve a U-value of 0.6 W/m2k
Insulating the walls internally	Adding up to 50mm of expanded polystyrene insulation, with plasterboard and skim on top

Installing extra loft insulation on top of the existing 75mm insulation between the joists could be carried out relatively simply by laying mineral wool over the top of the current insulation, perpendicular to the joists. The household does not currently use the loft space for storage, so disruption would be minimal, and the cost would be around £500. Even if they do require the space for storage in the future, solutions are available to board over the additional insulation, although this would add significant extra expense.

For roof insulation in the extension, the assessment suggested it would be relatively straightforward to lift the existing roof felt, add mineral wool insulation to a total depth of 150mm, extend the parapet around the edge of the existing roof, and re-lay new roof felt on the roof. It would be best to do this work when the flat roof already needs some

[31] Assuming a carbon intensity of 184 gCO_2/kWh for natural gas (from BEIS (2017) Greenhouse Gas Conversion Factors 2016. London: BEIS), and a typical consumer price for gas of 4p/kWh.

maintenance. This work should achieve a U-value of around 0.5 W/m^2K. The insulation materials are low cost, but the work would be quite labour-intensive so is likely to cost in the region of £1,000-£3,000[32].

Adding a solid roof to the conservatory and insulating it properly is likely to be expensive work, depending on the roof structure chosen and how the weight of the new roof is transferred to the ground. As an estimate, it might cost £2,000 to £5,000. However, as well as improving winter comfort and reducing heat losses from the kitchen, building an opaque roof would also improve comfort in the conservatory in summer, and make it less likely to overheat. This improved amenity and extra usable space may be attractive to the family. Like insulating the flat roof, it would be less disruptive than other fabric upgrades because most of the work is external.

The upgrade assessment suggested that internal wall insulation (IWI) may be suitable for this house, because the walls are solid (so thermally poor, and cavity wall insulation is not suitable). The rooms are generally large (except the store room and utility room in the extension which already has insulated cavity walls) so the modest sacrifices of space needed for IWI should be acceptable to the household. The main exceptions here are the kitchen and bathroom, where there are cupboards, appliances and bathroom equipment on the outside walls. It would make sense to insulate these rooms at the same time as refitting the kitchen or bathroom. When added to the complication of the staircase on an external wall, this means that internal insulation is likely to be complicated and disruptive, and could cost as much as £16,000.

The assessment of upgrades rejected replacement windows or doors for this house because they had been replaced recently. Similarly, floor insulation was discounted because of recently fitted high quality oak flooring and a lack of crawl space underneath. It also rejected external wall insulation (EWI) because rendering on top of EWI would make the house look different from the other half of the semi-detached house. It would also mean that the front wall does not align with the neighbour, which was deemed visually unacceptable by the household.

5.3.3.1. Combining fabric upgrades

The fabric upgrades proposed here (loft, extension roof and conservatory roof insulation and internal wall insulation) would work well together. There are no specific issues about sequencing or applying the fabric interventions either, although it would probably be simpler and more economical to insulate the flat roof and build the solid conservatory roof at the same time as they both require scaffolding in the same area.

5.3.3.2. Outcomes of fabric upgrade evaluation

Detailed modelling, described in Appendix section **A.5.3.4** indicated that extra loft insulation made only a small difference to energy use – savings of less than 2%, even with 250mm of loft insulation. Nor did additional loft insulation make much difference to comfort, with only very minor reductions in the proportion of time below the household's desired temperature range.

[32] J Palmer et al (2017) What does it cost to retrofit homes? Updating the Cost Assumptions for BEIS's Energy Efficiency Modelling. London: BEIS.

However, internal wall insulation made a bigger difference to both energy and comfort. This saved 8% of heating energy for 10mm of insulation up to 18% of heating energy for 50mm of expanded polystyrene wall insulation. Poly-isocyanurate (PIR), which has better thermal performance, would achieve the same saving with roughly 40% thinner insulation. The wall insulation would also improve the occupants' comfort by reducing the time outside the desired temperature range from over 10% to about 5% for the downstairs rooms, and down to 1% or less upstairs, with 50mm insulation (all with multizone control).

Building a solid, insulated roof on the conservatory and installing extra insulation for the extension roof, would both make modest improvements to energy use, but more significant improvements to comfort in the kitchen during winter and conservatory in summer.

5.3.4. Evaluation of potential heating system upgrades

A detailed assessment of possible heating system upgrades (see **Appendix 9** and section **A.5.3**) indicated that the most promising components to consider are those in Table 5.3-3.

Table 5.3-3 Potential heating system upgrades

Upgrade/change	**Description**
Multizone heating control	Multizone control to allow independent control of each radiator
High output radiators	Installing double panel, double convector radiators in rooms that do not already have them
Air-source heat pump	8 kW nominal output, with 250 litre hot water tank
Hybrid ASHP with a gas boiler	8 kW heat pump, linked in series to the existing combi- boiler

Multizone heating control typically consists of wireless radiator valves and programmable thermostats installed in each room. This is likely to both improve comfort and save energy by improving the match between heating and occupation (see **Appendix 4**). It is often a relatively straightforward upgrade (see Appendix section **A.4.5**) with limited disruption and costs around £600 for a house with seven radiators with easily accessible TRVs. Therefore, multizone control was applied to the base case for the majority of the analysis and was an assumed upgrade.

Some of the rooms in this house are currently slow to warm up because the radiators are undersized for the size of rooms and heat loss. This means that increasing these radiators' outputs would be a simple way to improve comfort. This change also opens up the possibility of reducing the temperature of the heating system water flow. This would give efficiency advantages for the current gas boiler and would make it easier to use a heat pump, which typically uses lower flow temperatures. This would coast around £800 and would be a relatively unobtrusive upgrade.

The technology assessment indicated that an air-source heat pump is an option for this house, and that the heat pump external unit could be located on the first-floor wall, above the flat roof of the extension, which being 3 m wide allows the ASHP to comply with the planning requirement of 1 m minimum distance to the external edge[33]. This would cost around £7,000-£9,000 for a low-medium power unit. It would be possible to install a hot

[33] https://www.planningportal.co.uk/info/200130/common_projects/27/heat_pumps/2

water cylinder in the ground floor utility room, where there is sufficient space, for about £400. The hot water storage cylinder would also be needed because a stand-alone heat pump could not generate instantaneous hot water like the existing combi boiler.

As an alternative to full heating provided by a stand-alone heat pump, it would be possible to install a heat pump upstream of the existing gas boiler to form a hybrid system. Here the gas boiler would continue to provide instantaneous hot water and some heating during warm-up (particularly in cold weather), while the heat pump provides the rest of the space heating. This may not reduce carbon emissions as much (depending on the peak loads and marginal carbon intensity of the electricity supply, see sections **3** and **7**), but it may be reassuring to the family to know that they are not entirely dependent on heat pumps – an unfamiliar technology – from Day 1. It may also allow earlier introduction of the heat pump before all the fabric upgrades are complete. They would potentially be able to switch to completely electric heating at some point in the future, perhaps when the boiler reaches the end of its service life.

5.3.4.1. Combining heating system upgrades

Both the fabric upgrades and multizone control give benefits on their own, but in combination are key to successful deployment of an ASHP or hybrid heating system. Independent temperature settings for each room would make it easier to capitalise on the potential savings of improved insulation. This would also help to optimise pre-heat times and achieve good comfort after installing a heat pump, so all the upgrade options described above are consistent and complementary.

5.3.4.2. Outcomes of heating system upgrade evaluation

As with other homes, the modelling demonstrated that adopting multizone control gives profound improvements in comfort, providing heating where and when it is needed, avoiding over-heating some rooms while other rooms are still warming up and avoiding heating rooms that are not used. Compared to the usual form of heating control, using a single room thermostat, this improves the comfort metric dramatically for most rooms (see Table 5.3-4), while saving 9% of energy use (and carbon emissions) for heating.

Table 5.3-4 Results summary for base cases - two weeks in January using Newcastle-upon-Tyne weather

Case	Energy for space and water heating, kWh	Fraction of heat demand time below household's desired temperature range				
		Living Room	Kitchen	Front Bedroom	Back Bedroom	Spare Bedroom
Base case (single zone control)	1086	52.1%	38.7%	2.4%	1.5%	0.5%
Base (multizone control)	989	12.7%	9.9%	1.4%	8.3%	1.8%

The poor "too cold" comfort metrics in Table 5.3-4 for single zone control result from two issues. First, the loss of radiator power inherent in trying to balance a system with a single thermostat and thermostatic radiator valves (see Appendix section **A.4.3**). Second, mis-match of the single room thermostat programme relative to the TRV settings (see Appendix section **A.5.3.2**). Multizone control can avoid these problems, but aiming to heat the bedrooms to a lower temperature (19 °C during the week) weakens the comfort metric because long warm-up times, previously masked by over-heating, are now revealed by the heating sometimes being late to reach the desired temperature.

Figure 5.3-4 shows how adopting multizone control (and the increased radiator flows it allows, by opening the balancing valves) dramatically improves the warm-up times for most rooms, especially at the weekend when the household prefers not to use heating in the morning, leading to a very long warm-up time in the evening. On a particularly cold weekend the single-zone system fails to reach its target temperature for the living room (where the single thermostat is located) for nearly the whole seven hours it was occupied (see blue dotted line in Figure 5.3-4).

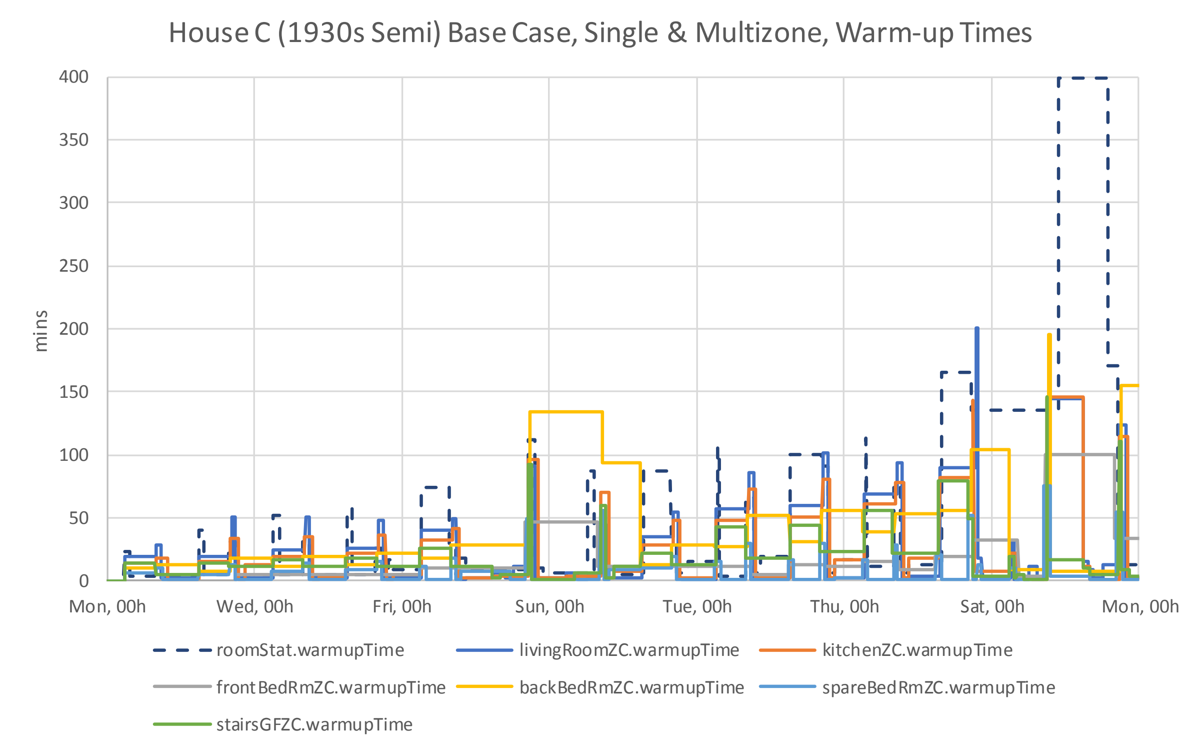

Figure 5.3-4 – Reduction in warm-up times in different rooms for the base case with multizone control (solid lines) compared to single zone control with room thermostat located in the living room (dashed line)

The combined effect of the fabric measures discussed earlier, with multizone control and high-output radiators, makes a considerable difference to both comfort metrics and energy use (see Table 5.3-5). All rooms come within the desired temperature range almost all the time, with warm-up times less than an hour, even on the coldest days. These measures also give savings of 24% of energy use and carbon emissions for heating over two cold weeks. This is a good foundation for taking up electric heating in the form of a heat pump or hybrid heat pump system.

Table 5.3-5 Results summary for fabric upgrades - two weeks in January using Newcastle-upon-Tyne weather

Case	Energy for space and water heating, kWh	Fraction of heat demand time below household's desired temperature range				
		Living Room	Kitchen	Front Bedroom	Back Bedroom	Spare Bedroom
Base case (multizone control)	989	12.7%	9.9%	1.4%	8.3%	1.8%
Multizone, upgraded radiators, 50mm IWI, 250mm loft insulation, 150mm flat roof insulation, solid roof on conservatory	749	1.8%	0.8%	0%	0%	0%

Preliminary modelling, and the results obtained from modelling carried out on House A, indicated that using a low temperature air-source heat pump with no other upgrades would result in unacceptable warm-up times and poor thermal comfort. For this reason, modelling was carried out based on the installation of a heat pump in conjunction with all of the upgrades listed above, and with the lockshields opened and a higher water flow rate to increase the power output of radiators. Also, the flow water temperature of the space heating circuit was set to a maximum of 55 °C, decreasing linearly with rising external temperature. Domestic hot water heating was scheduled to occur outside normal space heating times to avoid any clashes, and a legionella cycle was defined to raise hot water to 60°C for an hour each day.

This combination of measures brings dramatically better comfort metrics than the current situation for the house (although slightly weaker than the gas boiler case with all fabric upgrades above). Also, the electricity consumption for winter heating and hot water is reduced to about 24% of the gas energy consumed in the single zone base case (for comparison with predicted gas/electricity price ratios in Table 4.2-2). This arises from efficiency savings from fabric and control upgrades of about 34%, together with savings from removing boiler losses (about 11%) and the benefit of the effective coefficient of performance (COP) of the heat pump, which averages around 2.5 during the two cold weeks. This reduces to just below 2.0 in the height of summer, when the heat pump is only generating domestic hot water, due to heat loss from the hot water tank.

Due to the concerns over the peak demand placed on the grid by large numbers of heat pumps, the modelling included investigation into the effect of limiting peak electrical demand, and as shown in Table 5.3-6, good comfort was achieved with a peak of only 3.1 kW.

In the hybrid heat pump-boiler system the boiler provides instantaneous domestic hot water on demand and heating during warm-up, while the heat pump meets the base load. This brings the benefit that no domestic hot water storage tank is required, which saves space and removes the requirement for a legionella cycle. For this house, modelling was carried out on two different scenarios with the hybrid heat-pump-boiler system: one with all building fabric and heating system upgrades listed above, and the other with more limited fabric upgrades (without the insulated conservatory roof or wall insulation).

The modelling showed that in both scenarios, the hybrid heating system could almost fully meet the comfort requirements of the household (see Table 5.3-6) provided high output radiators had been installed. Overall, the 'full upgrades' case shows 55% savings in gas use compared to the equivalent scenario with a gas combi boiler.

Table 5.3-6 Results summary for heating system upgrades - two weeks in January using Newcastle-upon-Tyne weather

Case	Energy used for heating, kWh, gas/ electric	Peak electricity demand, space & water heating, kW	Fraction of heat demand time below household's desired temperature range				
			Living Room	Kitchen	Front Bed	Back Bed	Spare Bed
8kW ASHP +combi with partial upgrades	376/167	3.2	7.3%	0.7%	0.5%	1.0%	0%
8kW ASHP +combi with full upgrades	339/123	3.2	3.7%	0.5%	0%	0%	0%
8kW ASHP with full upgrades	263	3.1	2.6%	1.6%	0.3%	0.5%	0.1%

5.3.5. Carbon emissions

Table 5.3-7 shows projected CO_2 emissions for 2020 to 2050 for each of the scenarios discussed. The best long-term option in terms of CO_2 emissions is the installation of the 8kW ASHP with all fabric upgrades. By 2040, this is projected to give 99% reduction in annual emissions. Even with current CO_2 intensities, the ASHP scenario has the lowest emissions, although with less dramatic reductions. Using a hybrid heating system with full upgrades brings similar carbon emissions to the ASHP-only scenario in the short term, but does not decline as much with the fall in grid carbon intensity.

Table 5.3-7 Annual results summary (energy and CO_2) - using Newcastle-upon-Tyne weather

	Energy used for heating and hot water, kWh		CO_2 emissions for heating and hot water, kg [1]			
Case	**Gas**	**Electricity**	**2020**	**2030**	**2040**	**2050**
Base case (no upgrades)	14969	0	2748	2748	2748	2748
Gas boiler, 50mm IWI, 250mm loft insulation, 150mm flat roof insulation, solid roof on conservatory, upgraded radiators[2]	9842	0	1807	1807	1807	1807
8kW ASHP +combi hybrid with partial upgrades (no IWI) [2]	6043	2074	1863	1302	1128	1113
8kW ASHP +combi hybrid with full upgrades[2]	5532	1492	1558	1154	1029	1018
8kW ASHP with full upgrades[2]	0	3695	1342	342	33	7

Notes: 1 - see note in section **4.2** regarding the carbon intensities of the different energy sources; 2 – with multizone control.

5.3.6. Running costs

The annual running costs of this house at different stages of improvement are shown in Table 5.3-8, for weather typical of the UK's North East, using projections of energy costs from 2020 to 2050 which foresee gas prices more than doubling by 2040, while the cost of electricity is predicted to almost triple, before starting to fall by 2050. This will make the cost of running an air-source heat pump only become cheaper than gas sometime between 2040 and 2050.

Table 5.3-8 Annual results summary (costs) - using Newcastle-upon-Tyne weather

	Energy Used for heating and hot water, kWh		Energy cost for heating and hot water, £*			
Case	**Gas**	**Electricity**	**2020**	**2030**	**2040**	**2050**
Base case (no upgrades)	14969	0	431	516	979	1347
Gas boiler, 50mm IWI, 250mm loft insulation, 150mm flat roof insulation, solid roof on conservatory, upgraded radiators	9842	0	283	340	644	886
8kW ASHP +combi with partial upgrades (no IWI)	6043	2074	372	523	961	968
8kW ASHP +combi with full upgrades	5532	1492	302	417	769	803
8kW ASHP with full upgrades	0	3695	353	561	1007	755

* see note in section **4.2** regarding the costs of the different energy sources.

This analysis, on grounds of energy costs alone, suggests that the best option until sometime after 2040 may be to carry out the full upgrades and retain the gas boiler. The capital costs of around £30,000 for all the upgrades, of which the heat pump accounts for nearly 30%, would not be justified on a purely return-on-investment basis. For this home, it is unlikely that the current regulatory and market environment provides enough incentive to drive the transition to low carbon heating.

However, when considering capital costs, the hybrid heat pump-boiler solution without wall insulation initially saves the household the £16,000 outlay for IWI and reduces operating costs relative to the current situation. These savings are small until 2050 and would still not justify the investment in the heat pump on their own.

5.3.7. Proposed Pathway

Based on the results of the modelling, the pathway that offers optimum carbon emissions and comfort, with acceptable levels of disruption, comprises:

- Multizone heating control
- Top-up loft insulation and roof insulation on the extension
- High-output radiators
- Air-source heat pump (initially in tandem with boiler)
- Internal wall insulation (IWI)
- Putting an insulated roof on the conservatory

As for the previous houses, there are clear advantages for House C in upgrading to multizone heating control, and this would bring immediate carbon savings as well as improving comfort. Like multizone control, installing top-up loft insulation is simple and inexpensive, so it is proposed that these form part of the first step on House C's upgrade path. To reduce the long warm-up times suffered in this house, upgrading four radiators would also be a relatively painless and effective upgrade, especially if fitted with low-loss isolation valves to facilitate easier removal when internal wall insulation is later installed. Taken together these measures would improve comfort and bring financial savings, which may help to motivate the household to embark on the more demanding (or intrusive) parts of the upgrade path and perhaps to start saving towards more expensive improvements.

With the high output radiators installed and an existing boiler with at least another 10 years' service life, it would be possible to install a hybrid heat pump in series with the boiler to reduce carbon emissions and as a way to build familiarity with this new technology. This household is open to new technologies, and forward-looking, but perhaps not to the extent they are prepared to gamble with their comfort. Having the security of their existing gas heating system should give them an opportunity to experiment, while also providing a safety net. Fitting an 8 kW heat pump would give them enough heating power to allow them to remove the boiler later and rely solely on the heat pump. Ideally they would carry out insulation improvements first (for both comfort and carbon-saving reasons), but adopting a heat pump would bring some carbon saving even before investing in insulation work. This would also be less disruptive than fabric improvements.

Internal wall insulation would bring a significant comfort improvement and, taken together with the multizone heating and loft insulation, would make the living room and kitchen much more comfortable. However, installing IWI can be very disruptive. In this case it would require re-hanging radiators on external walls in the bedrooms, refitting electrical sockets on external walls (if any), and re-plastering over the top of the insulation boards. Work would also be needed to make good any damage to floorings or carpets after the work is complete. From a practical perspective, it is best to carry out IWI as and when the household redecorates, one room at a time. This keeps down the cost of the work as well as reducing disruption. This is particularly true for the kitchen and bathroom.

IWI will save energy and bring improved comfort, which should again help to motivate the final set of improvements: insulating the extension and building an insulated roof for the conservatory. These are relatively expensive and disruptive upgrades. The boiler could be removed (and a hot water cylinder installed) when it reaches the end of its service life – which may be when it is over 15 years old (it may already be more than 5 years old). This would make a further reduction in carbon emissions for heating in the medium to long term, because of anticipated falls in the carbon intensity of electricity, but at the cost of longer warm-up times and marginally inferior comfort metrics. Insulating the extension and conservatory roofs properly would help to mitigate this effect.

5.3.7.1. Upgrade pathway summary

Stage 0:

- Existing problems
  - Householders feel the cold and have to use secondary heating to achieve desired temperature
  - Living room is hard to heat, and using secondary heating means heating goes off elsewhere
  - Choose not to heat in morning at weekends, and takes a long time to come back to temperature
- 2.7 tonnes CO_2/ year

Stage 1 – Year 1:

- Upgrade to multizone heating control
- Increasing the depth of loft insulation to 250 mm by laying mineral wool across the rafters in the loft
- Replace single-panel radiators with high-output radiators
- 2.4 tonnes CO_2/year (at 2020 CO_2 intensities)

Stage 2 – Years 2 to 5:

- Install the 8 kW ASHP, but retain the existing boiler as a hybrid system, which means a hot water cylinder is not needed
- 1.9 tonnes CO_2/year (at 2020 CO_2 intensities)

Stage 3 – Years 5 to 10:

- Fit 50 mm of IWI gradually over time, room-by-room, to fit in with planned redecorating work
- 1.6 tonnes CO_2/year (at 2020 CO_2 intensities)

Stage 4 – Years 10-15:

- Remove boiler (end of life)
- Install a hot water cylinder in utility room
- Insulate the extension roof, and build an insulated roof for the conservatory
- 1.3 tonnes CO_2/year in 2020 (51% reduction)
- 0.3 tonnes CO_2/year in 2030 (88% reduction)
- 0.03 tonnes CO_2/year in 2040 (99% reduction

5.4. House D (1970s mid-terrace) upgrade pathway

5.4.1. Upgrading this house to low-carbon, high comfort, electric heat

The following upgrade pathway has been developed for this 1970s three-bedroom mid-terrace home. The methodology outlined in section **4** has been followed to analyse the home's existing and potential building fabric and heating system, resulting in a pathway which both reduces CO_2 emissions and satisfies the needs and preferences of the household.

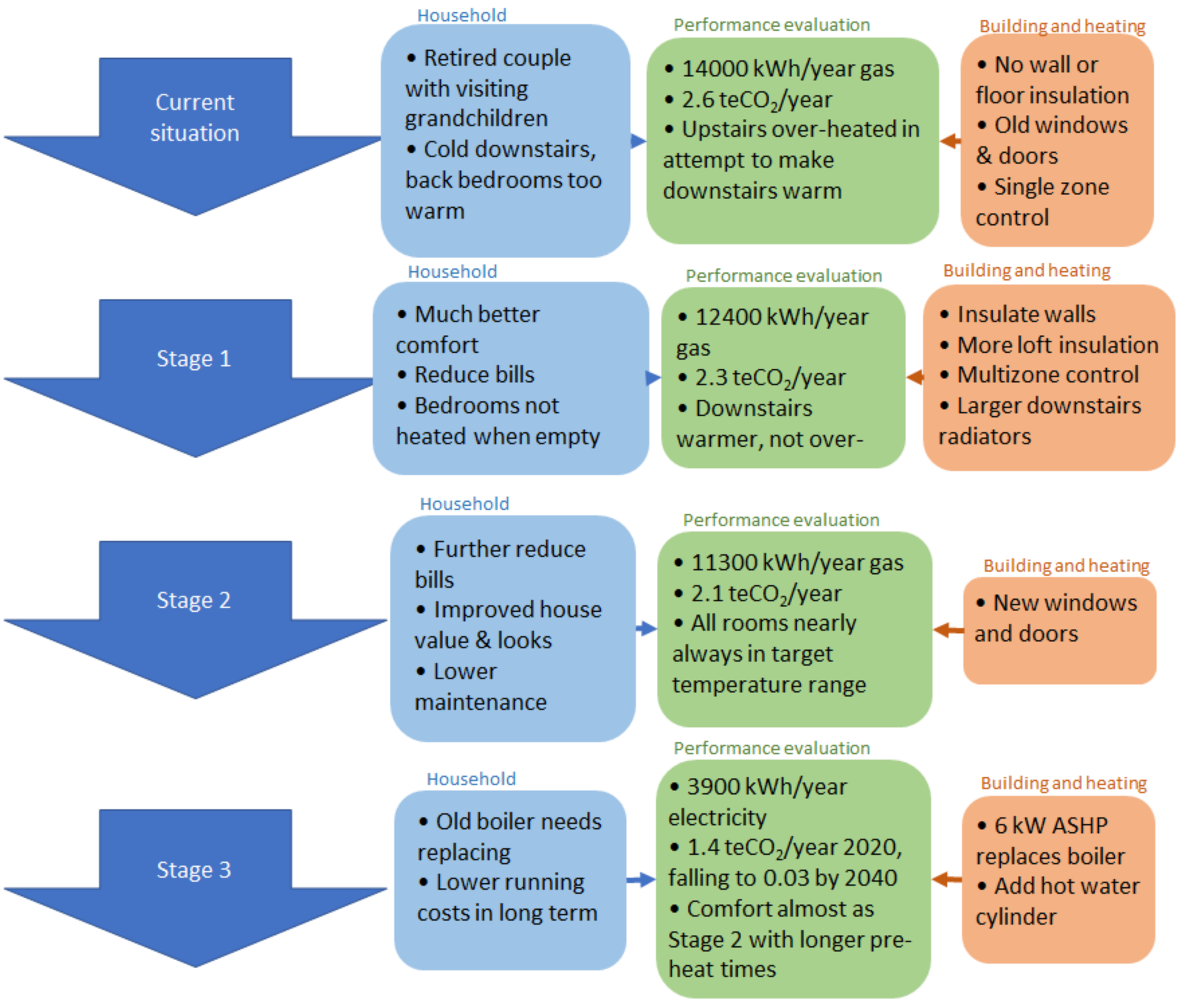

Figure 5.4-1 - House D upgrade pathway

The following sections describe how this pathway was developed and give details of how it achieves the household's desired level of thermal comfort, whilst achieving significant carbon savings, and considers the practical issues of carrying out the upgrades. This leads to a full description of the pathway in section **5.4.7**.

5.4.2. The house and household as they are now

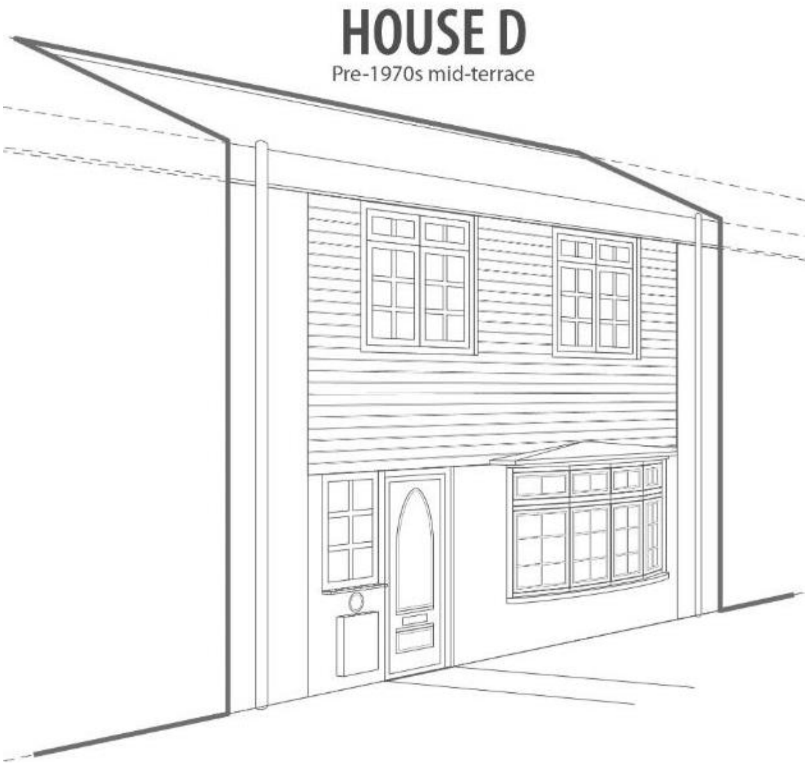

Figure 5.4-2 - Impression of House D

5.4.2.1. The Household

House D belongs to an elderly, retired couple who have lived in the house for many years and intend to stay long-term.

In principle they are prepared to accept the disruption of building work if it improves their lives, but in practice the hassle of getting work done has put them off making home improvements in the past.

The owners try to save energy, although they are not particularly motivated by cost savings or carbon emissions. Convenience is the most important thing to them. They welcome the prospect of being able to control heating better to provide different temperatures in different rooms. They say that neither of them really feels the cold, and they usually leave the bedroom window open overnight unless it is really cold.

They set the room thermostat to 22°C, leaving the downstairs radiator TRVs set at 5 and the bedrooms set at 1 or 2. Although there is a programmable timer, they are unsure how to set it and they control heating manually through the thermostat. They usually leave the heating on all day every day (6am to 11pm on weekdays, and from 8am to 11pm at weekends), however, they are often out in the daytime.

They replaced an old hot-air heating system with a boiler and radiators themselves, and they say the radiators are a big improvement - they disliked the dry air caused by the hot-air system. They are considering installing a walk-in shower, but they do not currently plan other work in their home.

They both have showers most days. They would like to be able to keep the bathroom warmer than other rooms – even if it costs more: *"I would prefer multizone control because I like the fact that you can have different temperatures in any room. You can have what you want, particularly the bathroom."*

Their grandchildren often come to visit, which makes it harder to keep internal doors closed, but they do not go out of their way to close internal doors anyway. They also have a dog, who tries to find the coolest places in the house, and who makes it more difficult to close internal doors.

They sometimes dry clothes in the spare bedroom, but they are aware of potential humidity problems, so they always open the window when they do this.

5.4.2.2. The house

House D is a three-bedroom, mid-terrace house built in the 1970s as illustrated in Figure 5.4-2 and Figure 5.4-3. Details of its physical characteristics are listed in Table 5.4-1.

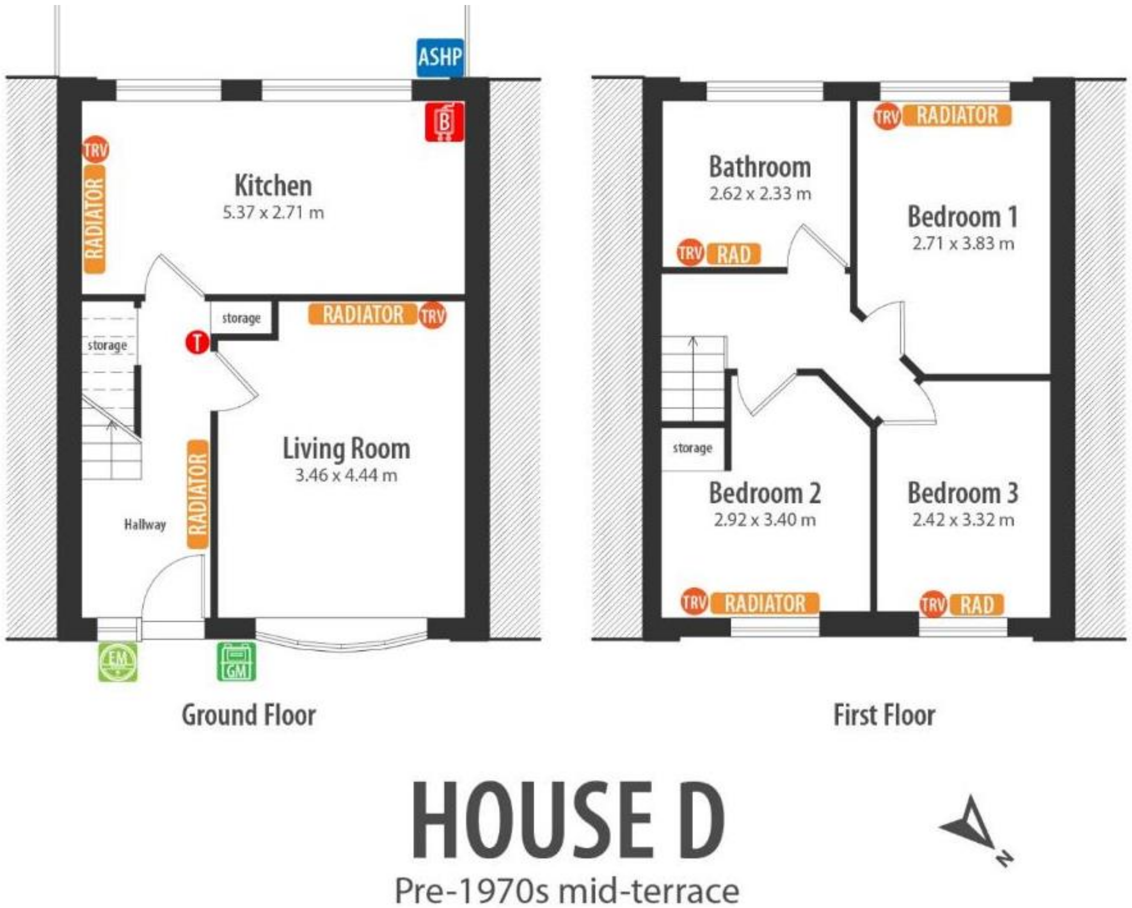

Figure 5.4-3 - Floor plan of House D

Table 5.4-1 Description of House D

House characteristic	**Details**
House type and age	Mid terrace, circa 1970s
Geographical location	Sub-urban
Orientation	Front faces north east
Floor area	76 m^2
Number of heated rooms	7 heated rooms
Number of bedrooms	3 bedrooms
Wall construction and insulation	Un-insulated cavity blockwork external walls, rendered on ground floor and tiled on first floor.
Roof insulation	100 mm of insulation between the joists
Windows	uPVC double glazing; some poorly installed, fitted pre-2002.
Floor description	Solid ground floor. Kitchen and bathroom have tiled floor, quite recent; hall and living room have laminate floor covering, not particularly expensive; master bedroom and stairs are carpeted, not very good condition and easy to replace.
Heating system description	Condensing gas combi boiler, programmable thermostat, TRV present on each radiator, all radiators except hall high output (DPDC).
Details of extensions / conservatories	None.
Description of garden(s) or other outside areas	First part of rear garden is paved (1.7m*5.7m), as is far part of back garden (2.8m*5.7m), majority of it is grass (6.4m*5.7m). Accessible from back road via an alleyway. Front garden has small, open grass lawn immediately in front of house. Also, a large common green facing the houses (approx. 13m x 16m).
Description of road	Secondary road - dead end
Local Area Energy Planning - heating system choices[34]	ASHP selected based on location and basic house characteristics.
Existing problems with house heating	The living room and kitchen are often colder than the owners would like, and the back bedrooms often overheat in both summer and winter.

[34] For information about the results of the geographical analysis from EnergyPath Networks software modelling (see https://es.catapult.org.uk/projects/local-area-energy-planning/)

5.4.2.3. Current energy use and carbon emissions

IEHeat modelling of the base case confirmed the household's reports of poor comfort, including overheating of the bedrooms with single zone control (see Appendix section **A.5.4**). Downstairs rooms take a long time to warm up in cold weather, because of high heat loss and poor radiator sizing and balancing, and there are long periods during which the room temperatures are below the range that the household tries to achieve. The living room, for example, is outside the owners' preferred temperature range for two-thirds of occupied hours, and the kitchen is also cooler than they would like for nearly 60% of occupied hours, taking over an hour to reach temperature on the coldest days.

Using "typical mean" weather from Newcastle-upon-Tyne resulted in a prediction of annual energy use of roughly 14,000 kWh for space and water heating, giving carbon emissions of 2.7 tonnes CO_2 per year at a cost to the household of about £560 at 2018 energy prices.[35]

5.4.3. Evaluation of potential building fabric upgrades

For House D, the thorough assessment of upgrades suggested that the most promising improvements to building fabric, from a perspective of comfort and thermal efficiency, are those shown in Table 5.4-2, the practicalities of which are discussed below. Floor insulation was initially rejected as not suitable because of the solid floor and low ceilings on the ground floor – as well as limited potential savings from insulating a solid floor. However, different ways of insulating the ground floor were evaluated – including insulating the external walls below ground, where most of the heat loss through floors occurs – see Appendix section **A.5.4.4.1**.

Table 5.4-2 Potential fabric upgrades for House D

Upgrade	Description
Upgrading double-glazed windows and renewing the fully-glazed back door	Replacing existing windows with a U-value of 2.8 with new ones with a U-value of 2.0 W/m^2K
Upgrading front door	Replacing existing door with a U-value of 2.8 with a new one with a U-value of 2.0 W/m^2K
Insulating solid ground floor	Adding insulation on top of the existing ground floor and/or insulating external walls from outside, below the damp course, to stop horizontal losses
Top-up loft insulation	Adding extra loft insulation to make 250 mm of roof insulation
Cavity wall insulation	Filling the 50mm wall cavity with expanded polystyrene beads

[35] Assuming a carbon intensity of 184 gCO_2/kWh for gas (from BEIS (2017) Greenhouse Gas Conversion Factors 2016. London: BEIS), and a typical consumer price for gas of 4p/kWh.

For House D, carrying out cavity wall insulation and top-up loft insulation are relatively simple and un-intrusive. The additional loft insulation could be installed perpendicular to, and over the top of the existing insulation, with access gained through the existing loft hatch. The owners only store a small number of items in the loft, so a small area could be boarded using one of the systems designed for this purpose which raise the boards above the insulation level, though this could increase the cost from about £400 to as much as £1,500. Cavity wall insulation can be installed entirely from outside, without scaffolding and should cost no more than £500.

Replacing the windows and doors is usually a more disruptive and expensive upgrade and requires expert installation. It would also require some decorating work to be carried out to repair any damage around the windows and doors, giving a total cost around £8,000. On the positive side, replacing the doors and windows is an opportunity to modernise the home's appearance and to make it look more attractive, as well as to reduce maintenance.

The owners' acceptance of disruption during any work, and the spare bedrooms, makes it easier to chart an upgrade pathway than for some of the other homes in the Upgrade Analysis study. Similarly, their desire to save energy where they can – without sacrificing convenience – means it is easier to justify carbon-saving interventions. Likewise, long warm-up times and the owners' intention of staying in the house permanently, make it easier to construct a case for doing improvement work.

5.4.3.1. Combining fabric upgrades

All of the fabric upgrades considered above would work well together and would serve to reduce heat loss from all elements of the house (walls, floor, roof, fenestration). There are no specific issues about sequencing or applying multiple fabric interventions as their effects are additive, without interference with each other.

As with other houses considered in this Upgrade Analysis, with the loft insulation in place, roof ventilation is likely to be needed (tile vents or ridge vents) to allow moisture to leave the loft space since this is likely to have been blocked by insulating into the eaves.

5.4.3.2. Outcomes of fabric upgrade evaluation

Detailed modelling explored the effects of carrying out the fabric upgrades discussed above (see Appendix section **A.5.4.4**). The modelling considered upgrading windows and doors first because the existing windows are already old and in need of replacement. This indicated that improved glazing saved 6.5% of heating energy in winter – far more than the saving from an upgraded back door (0.5%). Both upgrades combined would also make a worthwhile improvement to the comfort metric for the kitchen.

Extra loft insulation would only make a more modest difference to energy use – a saving of only 1.6% with 250mm total insulation in the roof. This would also only make a minor improvement to comfort, although this upgrade does have minimal disruption and relatively low costs.

The modelling suggested that insulating the ground floor would save 2.2% of heating energy at most – even with insulation below the floor slab and insulation below the damp-proof course around the external walls. This would come at the cost of considerable disruption and expense, so this intervention would be hard to justify even though the modelling did show improvements in the comfort metrics.

Cavity wall insulation offered the largest potential savings of all fabric upgrades: a 12% saving from insulating the front and back walls. This would also significantly improve comfort metrics, although the kitchen and living room are still left with warm-up times that most households would find hard to live with: 2 hours 40 minutes in the kitchen on the coldest days, and 2 hours 15 minutes in the living room. This is due to under-sizing of the radiators in these rooms (see Appendix section **A.5.4.4.1**).

The resulting proposed building fabric upgrades were full cavity wall insulation on front and back walls, upgrading doors and windows to modern standards, and increasing the loft insulation to 250 mm.

5.4.4. Evaluation of potential heating system upgrades

A detailed assessment of possible heating system upgrades (see **Appendix 9** and section **A.5.4**) indicated that the most promising components to consider are those in Table 5.4-3.

Table 5.4-3 Potential heating upgrades for House D

Upgrade/change	Description
Multizone heating control	Independent on/off control of each radiator
Larger radiators in kitchen and living room	Radiators increased in length in the kitchen from 0.7 to 1.2 m and in living room from 0.9 to 1.3 m.
Air-source heat pump	6 kW nominal output, with 200 litre hot water tank, with recommended fabric upgrades

As for the other houses in this Upgrade Analysis, multizone heating control is a relatively straightforward upgrade (see **Appendix 4**) with limited disruption and costs around £600 for a house with seven modern radiators. It is likely to both improve comfort and save energy by improving the match between heating and occupation especially in a home with only two occupants for most of the time.

Larger radiators in the downstairs rooms would tackle the comfort issues identified by the household. The heating system will need to be drained down to install new radiators, with a total cost of about £400, and limited disruption if carried out in summer.

The technical assessment showed that an air-source heat pump (ASHP) is a feasible option for House D at a cost around £7,000-£8,000 for a low power unit. A hot water storage cylinder would be required to provide hot water on demand, costing around £400. There is space for a this in the cupboard on the upstairs landing. The ASHP could be located on the rear wall close to the existing boiler, to tie into the current heating pipework. The ASHP's internal control unit could be mounted in place of the existing boiler.

5.4.4.1. Combining heating system upgrades

Both the fabric upgrades and multizone control give benefits on their own, but in combination are key to successful deployment of an ASHP. Independent temperature settings for each room make it easier to capitalise on the potential savings of improved insulation and would also help to optimise pre-heat times and achieve good comfort after installing a heat pump. The upgrade options described above are therefore consistent and complementary.

5.4.4.2. Outcomes of heating system upgrade evaluation

As with other homes, the modelling demonstrated that, on its own, multizone control gives profound improvements in comfort, providing heating where and when it is needed, and avoiding over-heating some rooms while others are still warming up. In other homes this improves comfort while simultaneously reducing energy use and carbon emissions for heating. However, in this instance there is no saving in energy use from adopting multizone control, and in fact energy use goes up slightly (0.6%). This is because the occupants take advantage of the improved control, and the ability to heat different rooms to different temperatures, by setting a desired temperature of 24 °C in some rooms (compared to the 22 °C target for single zone control and TRVs). This inevitably comes at the cost of increased energy use (see Table 5.4-4).

Table 5.4-4 Results summary for base cases & fabric upgrades - two weeks in January using Newcastle-upon-Tyne weather

Case	**Energy for space and water heating over two cold weeks, kWh**	**Fraction of demand time below household's desired temperature**				
		Living Room	**Kitchen**	**Front Bed**	**Back Bed**	**Spare Bed**
Base case (single zone control)	1027	67%	59%	0%	0%	0%
Base (multizone control)	1034	3.8%	6.7%	0%	0.7%	0.2%
Full building fabric upgrades	821	1.2%	2.5%	0%	0%	0.2%
Full BF upgrades with larger radiators downstairs	797	0.6%	0.5%	0%	0.1%	0.2%

Combining the effect of the fabric measures above with multizone control and larger radiators downstairs makes a considerable difference to both comfort and energy use. All rooms come within the desired 2°C temperature range almost all of the time, with warm-up times less than an hour even on the coldest days, and there is an associated saving of up to 23% of energy use and carbon emissions for heating over two cold weeks. This is a good foundation for taking up low-carbon heating in the form of a heat pump.

Note that with multizone control, increasing the size of the downstairs radiators gave a further 2-3% energy saving. With single zone control the same change to the radiators only provided a 1-1.5% saving. These savings are achieved through improved boiler efficiency due to a reduction in return temperature (which means the boiler works in condensing mode for longer, so raising boiler efficiency) and also through reduced boiler cycling.

Modelling was carried out on the installation of a 6 kW heat pump together with a 200 litre hot water cylinder and all of the upgrades listed above, with a higher water flow rate to increase the power output of radiators. As with other houses in this Upgrade Analysis, the flow water temperature of the space heating circuit was set to a maximum of 55 °C, decreasing linearly with rising external temperature. Domestic hot water heating was scheduled to occur outside normal space heating times to avoid any clashes, and a legionella cycle was defined to raise hot water to 60°C for an hour each day.

With the faster warm-up times achieved by the larger downstairs radiators, it was conjectured that the occupants would no longer need temperature settings greater than 22°C – as the current system rarely reached higher temperatures in the living room, particularly, despite the higher setting. This change showed a further 5% saving in energy use for heating was possible, though without consent from the household this was not adopted for any other cases.

The use of the ASHP as described above, together with the fabric upgrades above, resulted in electricity used for heating and hot water falling to about 26% of the gas energy consumed in the base case with multizone control (c.f. predicted gas/electricity price ratios in Table 4.2-2) – with a 30% improvement in home energy efficiency from the building fabric upgrades and removal of the boiler losses. The rest of the reduction in metered energy resulting from the average effective coefficient of performance (COP) of the heat pump of about 2.6 (see Table 5.4-5). This also brings dramatically better comfort metrics than the current situation for the house (although still weaker than the case with gas boiler and fabric upgrades above). The average effective COP falls in the height of summer, due to increased proportion of the heat pump output lost from the domestic hot water cylinder).

The modelling also explored the effect of limiting the heat pump peak electrical demand. As Table 5.4-5 shows, the heat pump largely met the comfort requirements when the peak demand was limited to a maximum of 2.6 kW.

Table 5.4-5 Results summary for ASHP with fabric upgrades and larger radiators - two weeks in January using Newcastle-upon-Tyne weather

Case	Electricity used for heating, two cold weeks, kWh	Peak electricity demand, space & water heating, kW	Fraction of heat demand time below household's desired temperature range				
			Living Room	Kitchen	Front Bed	Back Bed	Spare Bed
6kW ASHP with fabric upgrades and larger radiators downstairs	268	2.6	4.1	1.7	0	1.0	0.2

There are charts in Appendix section **A.5.4.5** showing warm-up times of each room in House D with an ASHP, with and without the room temperature set-point limit described above, showing that they improve in all rooms, with the biggest improvement in the living room on very cold days.

5.4.5. Carbon emissions

Projected annual emissions for 2020 to 2050 are shown in Table 5.4-6. The figures are indicative because carbon intensities vary over time, and there may be higher emissions in periods of high electricity demand.

Table 5.4-6 Annual results summary (energy and CO_2) - using Newcastle-upon-Tyne weather

	Energy used for heating and hot water, kWh		CO_2 emissions for heating and hot water, kg[1]			
Case	**Gas**	**Electricity**	**2020**	**2030**	**2040**	**2050**
Base case (no upgrades)	14087	0	2586	2586	2586	2586
Full fabric upgrades with larger radiators downstairs[2]	11320	0	2078	2078	2078	2078
6kW ASHP with fabric upgrades and larger radiators downstairs[2]	0	3909	1420	362	34	7

Notes: 1 - see note in section **4.2** regarding the carbon intensities of the different energy sources; 2 – using multizone control.

The best option in terms of carbon emissions is the installation of an ASHP with all fabric upgrades. At current emission intensities this brings a saving of 49% compared to using the gas boiler with no fabric upgrades, and a 99% reduction in emissions for heating by 2040.

Keeping a gas boiler and applying fabric options, in this case, achieves only a modest 20% saving in emissions, and this serves to illustrate the difficulty of achieving radical carbon savings without moving away from heating using natural gas.

5.4.6. Running costs

The annual running costs of this house at different stages of improvement are shown in Table 5.4-7, for weather typical of the UK's North East, using projections of energy costs from 2020 to 2050 which foresee gas prices more than doubling by 2040, while the cost of electricity is predicted to almost triple, before starting to fall by 2050. This will make the cost of running an air-source heat pump only become cheaper than gas sometime between 2040 and 2050.

The table shows that the fabric upgrade scenarios reduce running costs compared to the base case by 20% (in line with gas savings) whereas installing a heat pump increases running costs by 16-22% when electricity prices peak around 2030-2040, but is predicted to save about 37% of costs by 2050. As for other houses, hoping to motivate householders towards low carbon using return on their £18,000 capital investment over an acceptable time frame is unlikely to be successful.

Table 5.4-7 Annual results summary (energy costs) - using Newcastle-upon-Tyne weather

	Energy used for heating and hot water, kWh		Energy cost for heating and hot water, £*			
Case	**Gas**	**Electricity**	**2020**	**2030**	**2040**	**2050**
Base case (combi boiler)	14087	0	406	486	921	1268
Full fabric upgrades with larger radiators downstairs	11320	0	326	391	740	1019
6kW ASHP with fabric upgrades and larger radiators downstairs	0	3909	373	593	1066	799

* see note in section **4.2** regarding the costs of the different energy sources.

5.4.7. Proposed Pathway

Based on the results of the modelling, the pathway that offers optimum carbon emissions and comfort, with acceptable levels of disruption, comprises:

- Multizone heating control
- Top-up to 250mm loft insulation
- 50mm of cavity-wall insulation front and back
- New double-glazed windows
- New insulated front and back door
- Larger radiators in the kitchen and living room
- Air-source heat pump with a hot water cylinder

As with other houses considered in the Upgrade Analysis, there are clear advantages for House D upgrading to multizone heating control, and this would bring improved comfort and flexibility. Therefore, this, together with the top-up loft insulation, should form part of the first step in the pathway. Installing cavity-wall insulation and installing larger radiators in the downstairs rooms are further relatively inexpensive upgrades, causing minimal disruption, which would bring additional significant comfort improvements and energy/CO_2

savings. Therefore, they are also strong candidates for the first round of upgrades. The benefits seen from these upgrades may help to motivate the household to take on more difficult or expensive parts of the upgrade path.

Given that the home owners wish to stay in the house long term, there is a strong case for making their home easier and more economical to heat. If they have savings that allow them to install new windows and doors, this would improve comfort (by reducing cold down-draughts across the glass) and it would mean they do not have to do further maintenance work on their doors and windows. It may also improve the appearance of their home.

The case for installing an ASHP is more difficult and it is unlikely that the household would get better service than with a gas boiler and multizone control, but to make the heating system low carbon, it is a necessary step. However, if the home owners were to go ahead with this, it would be logical to replace their existing boiler when it is approaching the end of its useful service life and before it incurs major servicing costs.

5.4.7.1. Upgrade pathway summary

Stage 0:

- Existing problems
  - Living room and kitchen tend to be cool and take too long to warm-up
  - Upstairs overheats on hot afternoons in summer, and even in winter (because downstairs radiators are too small)
- 2.6 tonnes CO_2/ year [36]

Stage 1 – Year 1:

- Upgrade to multizone heating control
- Larger radiators downstairs dramatically improve warm-up times, and bring a small saving in heating energy
- Extra loft insulation in the form of 150 mm insulated boards on top of roof joists
- Filling wall cavities front and back with 50 mm of expanded polystyrene beads
- 2.3 tonnes of CO_2 (at 2020 CO_2 intensities)

Stage 2 – Year 6:

- Replace old double-glazing (including some blown units where condensation is visible between the panes)
- Replace front and back doors with modern units (including fully-glazed back door)
- 2.1 tonnes of CO_2 (at 2020 CO_2 intensities)

Stage 3 – Year 10:

- Install a 6kW air-source heat pump with a hot water cylinder
- 1.4 tonnes CO_2/year in 2020 (37% reduction)
- 0.4 tonnes CO_2/year in 2030 (84% reduction)
- 0.03 tonnes CO_2/year in 2040 (98% reduction)

[36] Carbon intensity of 184gCO_2/kWh for gas (from BEIS (2017) Greenhouse Gas Conversion Factors)

5.5. House E (1980s detached) upgrade pathway

5.5.1. Upgrading this house to low-carbon, high comfort, electric heat

The following upgrade pathway has been developed for this 1980s detached three-bedroom home. The methodology outlined in section **4** has been followed to analyse the home's existing and potential building fabric and heating system, resulting in a pathway which both reduces CO_2 emissions and satisfies the needs and preferences of the household.

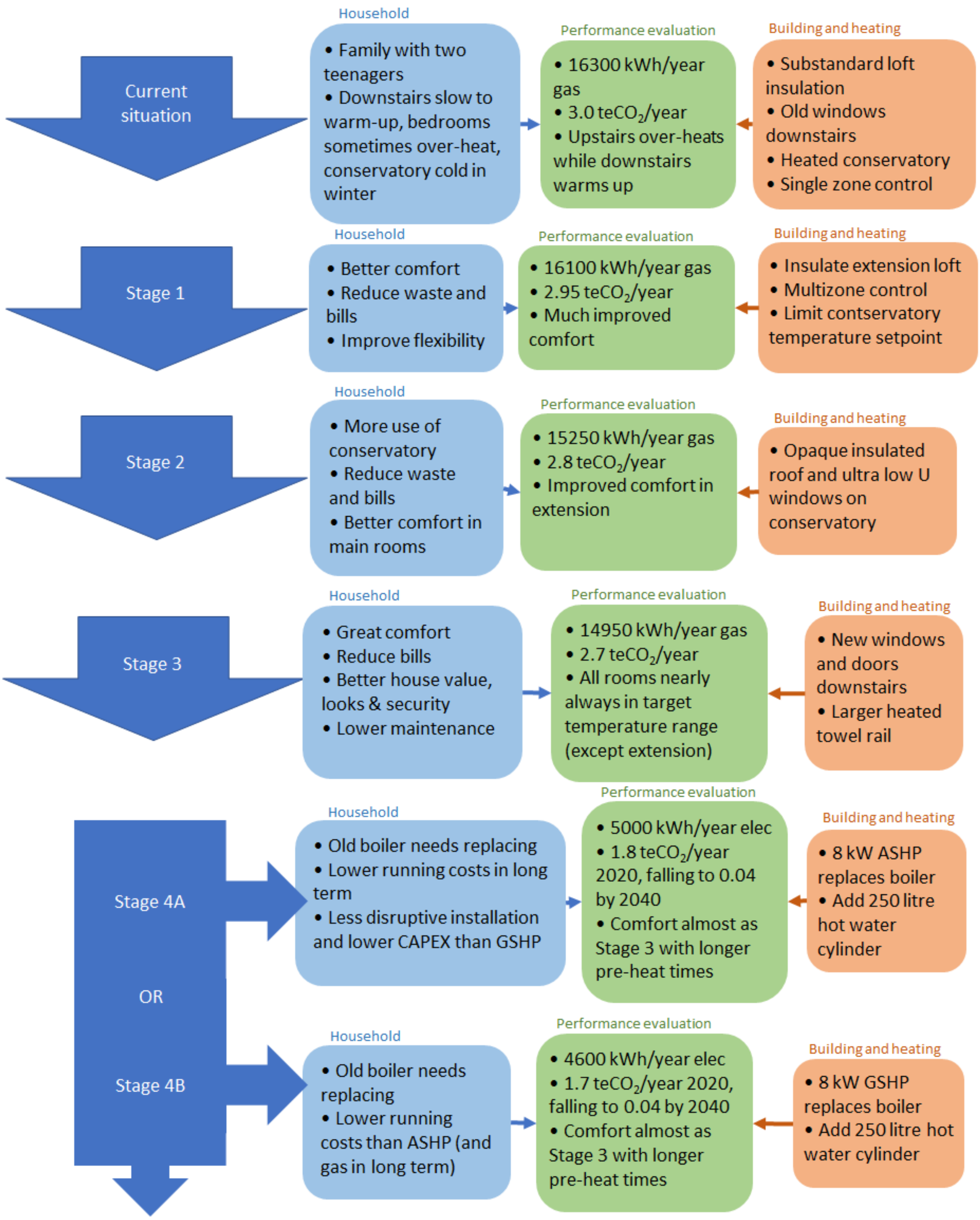

Figure 5.5-1 - House E upgrade pathway

The following sections describe how this pathway was developed and give details of how it achieves the household's desired level of thermal comfort whilst achieving significant carbon savings and considers the practical issues of carrying out the upgrades. This leads to a full description of the pathway in section **5.5.7**.

5.5.2. The house and household

Figure 5.5-2 - Impression of House E

5.5.2.1. The Household

The house belongs to a family with two teenage children (aged 13 and 15). They have lived in the house for 10 years and have no plans to move. Both husband and wife work full-time, and the husband works long hours. Consequently, the house is usually unoccupied during the daytime.

They have carried out some home improvements since moving in, including adding a conservatory, landscaping the garden, laying a new driveway, and building the master bedroom extension. They feel as if there has always been building work going on, but now they feel the house is as they want it. They are accustomed to disruption in the house from some sort of construction work, and they accept this disruption when it improves their enjoyment of the home.

Reducing energy use or CO_2 emissions is not a high priority for this family. To a degree, they put more weight on comfort than cost, but they still need to be in control of energy costs. They are a middle-income family, and describe themselves as 'the squeezed middle', having to budget carefully for their outgoings. Avoiding wasting money is important to them, and they switch energy suppliers to get the best prices.

They are proud of their home, motivated by social recognition and the good opinion of others. They also feel it is important that others are comfortable when they come to visit. Broadly, they trust the opinions of family and friends and they are most likely to adopt new technologies if their friends or family have recommended them.

They never open downstairs windows in winter, but they sometimes open the main bedroom window to air it in the evening, and they usually open the bathroom window to ventilate after baths or showers.

5.5.2.2. The House

The house is a three-bedroom, detached home built in the 1980s, significantly extended on both sides, as illustrated in Figure 5.5-2 and Figure 5.5-3. Details of its physical characteristics are shown in Table 5.5-1.

Figure 5.5-3 – Floor plan of House E

Table 5.5-1 Characteristics of House E

House characteristic	**Details**
House type and age	Detached, constructed in 1980s
Geographical location	Suburban area
Orientation	Front faces west
Floor area	149 m^2
Number of heated rooms	11 heated rooms
Number of bedrooms	Four (one used as a study)
Wall construction and insulation	Cavity walls (of different thicknesses) insulated at construction as per 1982 Building Regulations
Roof insulation	Main loft mostly boarded; insulation to full height of joists (100 mm). Extension's loft poorly installed, with large gaps.
Windows and doors	Fully double glazed, downstairs windows are original with signs of blown seals, upstairs windows were replaced about 5 years ago
Floor description	Solid ground floor
Heating system description	Condensing gas combi boiler feeding wet system. Programmable single room thermostat, TRVs present on each radiator.
Details of extensions / conservatories	Three extensions + conservatory; most recent one (on top of the garage) built in 2016; all built using cavity walls
Description of garden(s) or other outside areas	Front: Paved (5.6m x 12.8m), Rear: First portion of garden is covered with wooden decks (4.1m x 12.8, not including conservatory), remainder is grass (7.5m x 12.8m). Side passage width of 0.83 m between concrete pillars and wall of house.
Description of road	Secondary road
Local Area Energy Planning – heating system choices[37]	GSHP selected based on location and basic house characteristics.
Existing problems with house heating	Conservatory rarely warm in winter, downstairs rooms slow to warm up, bedrooms sometimes too hot.

[37] For information about the results of the geographical analysis from EnergyPath Networks modelling, see https://es.catapult.org.uk/projects/local-area-energy-planning/

5.5.2.3. Current comfort, energy use and carbon emissions

IEHeat modelling revealed very poor comfort metrics for the extension (below the desired temperature for 45% of heated hours), and in the kitchen and living room (see Appendix section **A.5.5.2**). The extension is a large room (about 23 m^2) with a large front window and a large patio door to the conservatory (which is very cold in mid-winter), which makes it slow to warm-up. The bedrooms tend to overheat, despite their TRVs being set nominally to 22°C, due to relatively large radiators and the heating continuing when they are warm but the extension, where the thermostat for single zone control is located, is still below its target temperature. The ensuite shower room remains cold owing to an undersized towel rail, made worse by poor radiator balancing.

Using "typical mean" weather from Newcastle-upon-Tyne resulted in a prediction of annual energy use of roughly 16,300 kWh for space and water heating, giving carbon emissions of 3.0 tonnes CO_2 per year at a cost to the household of about £650 at 2018 energy prices.[38]

5.5.3. Evaluation of potential building fabric upgrades

For House E, the assessment of possible upgrades suggested that the most suitable improvements to building fabric for improving comfort and reducing energy consumption would be those in Table 5.5-2.

Table 5.5-2 Potential fabric upgrades for House E

Upgrade	Description
Top-up loft insulation for main roof	Adding extra loft insulation to parts of the loft that are currently boarded and used for storage, bringing it up to 250 mm of insulation
Top-up loft insulation for extension	Adding extra loft insulation to bring it up to 250 mm of insulation
Upgrading double-glazed windows downstairs	Replacing existing windows with a U-value of 2.8 with new ones with a U-value of 2.0 W/m^2K
Upgrading old back door and poorly-insulated front door	Replacing external doors with new ones with a U-value of 1.8 W/m^2K
Installing new windows in the conservatory	Replacing existing conservatory glazing with new glazing with a U-value of 2.0 W/m^2K, or ultra-efficient conservatory glazing with a U-value of 1.5 W/m^2K
Installing a solid conservatory roof	Replacing the glazed roof of the conservatory with opaque roof panels to give improved thermal performance and reduce summer overheating.

For House E, the options for fabric measures are more limited than other houses because the walls are already insulated, and the un-insulated part of the ground floor is surrounded on

[38] Assuming a carbon intensity of 184 gCO_2/kWh for natural gas (from BEIS (2017) Greenhouse Gas Conversion Factors 2016. London: BEIS), and a typical consumer price for gas of 4p/kWh in 2018.

two sides by insulated extensions (reducing horizontal losses just below ground level) and has a high-cost floor covering that would be both disruptive and expensive to replace.

Extra loft insulation for the extension and main house is relatively straightforward – access is good and using insulated loft boards would reduce heat loss without losing easy access to the storage space in the main loft, though this could increase the cost from about £400 to as much as £1,500. However, the main loft is completely filled with the family archive and sentimental possessions. It would be a lot of work to clear the loft – only justified if there are significant savings or improvements in comfort.

As for the other houses investigated in this Upgrade Analysis, replacing the windows and doors is usually expensive and requires expert installers. However, in this case there is the additional incentive of installing new windows downstairs to match the modern ones used upstairs, which would improve the house's appearance. It is also an opportunity to install lockable windows on the ground floor, and so upgrade security.

Similarly, the current back door offers poor security and new doors (front and back) would be an opportunity to address this. The family may also wish to install new locks that use the same key for front and back doors – improving amenity. Depending on the glazing and doors chosen and the installation company, new ground floor windows (excluding the conservatory) and new doors could cost £5,000 to £6,000. Given that they intend to stay in the house long term, they may think this is a worthwhile investment, and it should mean the doors and windows need no maintenance for 30 years.

The conservatory is the hardest room in the house to heat in winter because of the large glazed area and the glazed roof. There is a legitimate discussion about whether it is wise to try to heat a conservatory, and current Building Regulations stipulate that it should be independent of the heating for the main house[39]. However, given that there is already a radiator in the conservatory, and the family do use it sometimes in winter, it is worth considering how to make the conservatory less wasteful of heat.

There are two principal options. First, to insulate the roof, by using opaque building elements. This means reducing the daylight in the conservatory, but it also helps to reduce summer overheating from sun shining in through the roof, which can add a thermal gain of up to 1000 W per m^2. Ordinary MDF-reinforced uPVC panels were evaluated as a base-case roofing material against which to compare higher-performance roofing panels (e.g. insulated with polyurethane). Depending on finishes and specification, this would cost between £5,000 and £10,000.

The second option for improving the thermal performance of a conservatory is substituting a higher specification of glazing. Typical U-value for a modern conservatory would be around 2.0 W/m^2K, but higher performance glazing is available achieving up to 1.5 W/m^2K. This would cost around £3,000-£5,000. Improved glazing and a solid roof would help to make the

[39] https://www.planningportal.co.uk/info/200130/common_projects/10/conservatories/3

conservatory more comfortable and extend the period when it is usable to all but the coldest periods.

5.5.3.1.Combining fabric upgrades

Since the walls are already insulated in this house, the risk of thermal bridges between newly insulated building elements is lower than for the other houses examined here. Nevertheless, it would be wise to align the new doors and windows with the centre of the cavity (or as close as possible) or insulate around the aperture so that heat does not bypass the improved glazing. Carrying out work on the glazed conservatory walls at the same time as installing a new solid roof, with insulation and a plastered ceiling, should make it easier to avoid thermal bridges at the junction between walls and roof in the conservatory, as well as adding suitable ventilation where necessary (to help prevent condensation forming).

With the loft insulation in place, roof ventilation is likely to be needed (tile vents or ridge vents) to allow moisture to leave the loft space, since this is likely to have been blocked by insulating into the eaves.

5.5.3.2.Outcomes of fabric upgrade evaluation

Detailed modelling described in Appendix section **A.5.5** explored each of the upgrades outlined above. This suggested that replacing the downstairs windows with higher performance units would save just under 5% of the energy used for heating. The conservatory improvements bring an additional 3% energy saving in winter, along with small comfort improvements. However, the 1% saving in heat output to the radiators from using the very high specification glazing or roofing on the conservatory is negated by the decrease in gas boiler efficiency resulting from the higher return water temperature.

Modelled comparisons between the impact of extra insulation in the main loft and the extension's loft showed that insulating the main loft would save more heating energy (around 1.5% saving in winter from the main loft versus 0.8% saving in the extension). Insulation in the main loft also has a greater impact on warm-up times. However, the fact that the main loft is full of stored possessions, and part of it is boarded, means that stripping out the loft and re-insulating would be hard to justify. In contrast, insulating the extension loft is simple and would be less costly, without loss of amenity as the low head-room means the household does not use it for storage.

Upgrading the front door makes a very small difference to energy use (around 0.5%), but this does bring a small improvement in comfort in the kitchen and living room (the door between the living room and kitchen has been removed and the living room door to the hall is often open). This may be worth doing if the family is conscious of cold draughts in the affected rooms.

5.5.4. Evaluation of potential heating system upgrades

A detailed assessment of possible heating system upgrades (see **Appendix 9** and section **A.5.5**) indicated that the most promising components to consider are those in Table 5.5-3.

Table 5.5-3 Potential heating upgrades for House E

Upgrade/change	**Description**
Multizone heating control	Independent on/off control of each radiator
Upgraded boiler pump	Fitting a larger pump to the existing boiler to take better advantage of the radiators' power output potential
Larger towel heater in ensuite	1.2m high towel rail to allow warm-up in reasonable time
Limit on conservatory heating	15°C maximum temperature setpoint in the conservatory
Air- or ground-source heat pump	8 kW nominal output, with 250 litre hot water tank, with full fabric upgrades

As for the other houses, multizone heating control is a relatively straightforward upgrade (see **Appendix 4**) with limited disruption and costs around £800 for a house with eleven radiators. It is likely to both improve comfort and save energy by improving the match between heating and occupation. Therefore, multizone control was applied to the base case for the majority of the analysis and was an assumed upgrade.

Like most homes with combi boilers, this house has a boiler sized to provide instant domestic hot water (30 kW), so has more than enough power to deliver space heating. However, the large house and long pipe runs mean the installed water pump struggles to supply sufficient flow rate to the radiators to deliver their potential power output. A scenario was modelled with a larger pump – increasing nominal flow rate from 17 l/minute currently up to 23 l/minute, with corresponding increase in nominal available head. Note that the upgraded nominal design would stay well within typical system working pressure and velocity limits, but due to the system pressure drops these nominal flow rates would not be achieved, with predicted boiler flows increasing from about 15 to 21 l/min.

To improve comfort in the ensuite shower room, which struggles to achieve desired temperature, the effect of a larger heated towel rail was evaluated. This would cost under £200.

The conservatory, as discussed above, is rarely warm enough to use in winter and is a major source of heat loss, which could be reduced by limiting the temperature setpoint to a maximum of 15°C.

The technical assessment suggested that it would be possible to use a heat pump in this house. In this case, it could be either an air source or a ground source heat pump as the property has a large garden suitable for ground collector. It would cost £13,000-£20,000 for a GSHP, almost double the £7,000-£11,000 cost of an ASHP[40]. In both cases there would be space for both the internal unit and a hot-water cylinder (costing about £400) in the utility room, which means the heat pump would be able to provide hot water as well as space heating.

5.5.4.1. Combining heating upgrades

Work on other houses in this Upgrade Analysis has already shown that both the fabric upgrades and multizone control give benefits on their own, but in combination are key to successful deployment of a heat pump. Independent temperature settings for each room make it easier to capitalise on the potential savings of improved insulation. This also helps to optimise pre-heat times and achieve good comfort after installing a heat pump.

The upgraded boiler pump is only relevant while the gas boiler is the source of heat (as heat pumps typically have larger pumps). However, the other upgrade options described above are consistent and complementary.

5.5.4.2. Outcomes of heating system upgrade evaluation

As with other homes, the modelling demonstrated that, on its own, multizone control gives profound improvements in comfort, providing heating where and when it is needed, and avoiding over-heating rooms while other rooms are still warming up. In House E, multizone control in combination with increased roof insulation for the extension, upgrading all downstairs windows and external doors, and fitting high spec double glazing and a solid (insulated) roof to the conservatory, saves 9% of energy used in winter compared to the multizone base case. Comparison of this small saving with the other houses studied illustrates how much improvement has been made in dwelling energy efficiency over recent decades – which should mean modern houses can make the transition to electric heat more easily than older houses. This set of upgrades also provides significantly better comfort in the extension and the conservatory. Nevertheless, even with improved thermal performance of the conservatory, it remains cold in winter (less than 18°C most days).

Using a maximum temperature setting in the conservatory of 15°C results in a further energy saving of just over 3%.

The up-rated boiler pump mentioned above did improve warm-up times in most rooms (see Appendix section **A.5.5.4.2**) but also increases gas use. The effect of installing a larger heated towel rail in the ensuite shower room was also investigated (the existing towel rail is small: 0.8m tall). This dramatically improved the warm-up time of the ensuite, from 86 to 40

[40] https://www.greenmatch.co.uk/blog/2014/08/the-running-costs-of-heat-pumps

minutes and also improved warm-up times in other rooms by reducing the time spent with water flowing to the towel rail.

Table 5.5-4 Modelling results for fabric upgrades - two weeks in January using Newcastle-upon-Tyne weather

Case (all multizone control)	Energy for space and water heating over two cold weeks, kWh	Fraction of heat demand time below household's preferred temperature range						
		Living Room	Kitchen	Front Bed	Back Bed	Side Bed	Extension	Study
Base case	1266	1.2%	0.2%	0.1%	0.0%	0.0%	2.2%	0.0%
Upgraded windows & doors, 250mm extension loft insulation, high spec windows and solid roof on conservatory	1149	0.9%	0.3%	0.1%	0.0%	0.0%	1.1%	0.0%
Full upgrades as above, with conservatory heating limited to 15°C	1109	0.8%	0.3%	0.2%	0.0%	0.0%	1.6%	0.0%
Full upgrades as above, with conservatory heating limited to 15°C, 1.2m ensuite towel rail and radiator foil in extension	1105	1.1%	0.3%	0.1%	0.0%	0.0%	1.0%	0.0%

Previous work indicated that using a low temperature heat pump with no other upgrades would result in unacceptable warm-up times and poor thermal comfort. Consequently, modelling was carried out on both high temperature heat pump scenarios using all the fabric and control improvements above: upgraded windows and doors, 250mm loft insulation in the extension, high spec windows and a solid roof on conservatory, together with the 15°C limit for the conservatory, and a larger towel rail in the ensuite shower room.

Again, the heat pump outlet temperature to the space heating circuit was set to a maximum of 55 °C, decreasing linearly with rising external temperature. Domestic hot water heating was scheduled to occur outside normal space heating times to avoid any clashes, and a legionella cycle was defined to raise hot water to 60°C for an hour each day.

An 8 kW nominal output ASHP and the same size of GSHP were selected, both with input power limiting control, set to reduce compressor speed if the demand exceeds 3 kW.

The resulting heating system with the fabric upgrades described above brings dramatically better comfort metrics than the current situation for the house (see Table 5.5-5). It also resulted in electricity used for winter heating and hot water falling to about 27-29% of the gas energy consumed in the base case (c.f. predicted gas/electricity price ratios in Table 4.2-2) – combining the 12% savings from the fabric upgrades with the efficiency gain from removal of the boiler (about 13%) and the benefit of the heat pump COP. The average effective COP during the two cold weeks in winter is 2.6 for the ASHP and about 2.8 for the GSHP (the ground temperature is more stable, which benefits the GSHP). This falls in the height of summer, when the heat pump is only generating domestic hot water, due mainly to heat loss from the hot water tank.

Table 5.5-5 Modelling results using heat pumps

Case	**Electricity used for heating, two cold weeks, kWh***	**Peak electricity demand, space & water heating, kW**	**Fraction of heat demand time below household's preferred temperature range**						
			Living Room	**Kitchen**	**Front Bed**	**Back Bed**	**Side Bed**	**Extension**	**Study**
8kW ASHP with upgrades	362	3.1	0.4%	0.4%	0.8%	0.3%	0.0%	6.1%	1.4%
8kW GSHP with upgrades	342	3.1	0.4%	0.4%	0.9%	0.1%	0.0%	6.3%	1.3%

The modelling indicated that heat pumps can achieve good comfort performance (better than the current situation, based on room temperatures during desired warm-times), without excessive peak demand on the electricity grid. This relies on building fabric upgrades to reduce heat loss from the dwelling, plus increased flow of hot water to radiators. The warm-up times in mid-winter are, as expected, longer than the upgraded case with a gas boiler, but generally less than 60 minutes – with the exception of the extension, ensuite and bathroom. Even in these rooms, on the coldest days, temperatures are rarely less than 1.5 °C below the target range by the start of the required warm-time.

The COPs of both types of heat pump would be higher in warmer parts of the country (e.g. 10% higher for a 3 °C increase in mean temperature). The heating performance of the GSHP is very similar to the ASHP, in part thanks to using the same settings for the outlet temperature, input power limit and water flow rates.

Appendix section **A.5.5.5.1** explores why there is such a small difference between the COP of the GSHP and the ASHP, which is found to result from a relatively small difference between the average air temperature of about 3.6 °C and the soil temperature of about 7 °C (in January) at the relatively shallow depths (1-1.5 m) of the horizontal heat source trenches modelled. The difference would be expected to be higher with a lower heat pump outlet temperature. In the South of the UK the COPs of both heat pumps should be higher, and a vertical bore hole would give the GSHP a larger seasonal average COP in most cases. In this instance, however, the benefit does not seem to justify the increased effort and cost required to install pipework to access a ground source of thermal energy (particularly considering the restricted access to the garden for digging or drilling equipment).

There are also charts in Appendix section **A.5.5.5.1** plotting warm-up times room-by-room, with both the air and ground source heat pumps.

5.5.5. Carbon emissions

Table 5.5-6 shows projected CO_2 emissions for 2020 to 2050 for selected scenarios. The best option, in terms of carbon emissions, for all dates is the GSHP with all fabric upgrades, with the ASHP marginally less efficient. At current emission intensities the GSHP brings a saving of 44% compared to using the current gas boiler with no fabric upgrades, and a 99% reduction in emissions for heating by 2040).

Table 5.5-6 Annual results summary (energy and CO_2) - using Newcastle-upon-Tyne weather

	Energy used for heating and hot water, kWh		CO2 emissions for heating and hot water, kg[1]			
Case	Gas	Electricity	2020	2030	2040	2050
Base case (combi boiler)	16320	0	2996	2996	2996	2996
Full fabric upgrades with 15°C limit in conservatory, radiator foil and larger ensuite towel rail[2]	14948	0	2744	2744	2744	2744
8kW ASHP with upgrades[2]	0	4995	1815	463	44	9
8kW GSHP with upgrades[2]	0	4631	1682	429	41	8

Notes: 1 - see note in section **4.2** regarding the carbon intensities of the different energy sources; 2 - using multizone control.

Fabric options alone in this case achieve only a very modest 8.5% saving in emissions, even with a limit on the heating supplied to the conservatory and the larger ensuite towel rail. Once again this emphasises the difficulty of achieving radical carbon savings without moving away from natural gas heating.

5.5.6. Running costs

The annual running costs of this house with different upgrades are shown in Table 5.5-7, for weather typical of the UK's North East, using projections of energy costs from 2020 to 2050 which foresee gas prices more than doubling by 2040, while the cost of electricity is predicted to almost triple, before starting to fall by 2050. This will make the cost of running a heat pump only become cheaper than gas sometime between 2040 and 2050.

Table 5.5-7 Results summary (costs) - two weeks in January using Newcastle-upon-Tyne weather

	Energy used for heating and hot water, kWh		Energy cost for heating and hot water, £*			
Case (all multizone)	Gas	Electricity	2020	2030	2040	2050
Base case (combi boiler)	16320	0	470	563	1067	1469
Full fabric upgrades with 15°C limit in conservatory, radiator foil and larger ensuite towel rail	14948	0	431	516	978	1345
8kW ASHP with upgrades	0	4995	477	758	1362	1020
8kW GSHP with upgrades	0	4631	442	702	1262	946

*see note in section **4.2** regarding the Carbon intensities of the different energy sources.

This analysis, on narrow financial grounds, shows that in the near term there is little difference between the energy costs - indeed the air source heat pump is slightly more expensive. By 2030 the costs of all scenarios are projected to increase, more so for the heat pump options. This trend continues to the projections for 2040 but shifts in favour of heat pumps thereafter.

The capital costs of around £16,000 to £23,000 for all the fabric upgrades, plus £9,000-£15,000 for the heat pump, would not be justified on a purely return-on-investment basis. Yet again, this underscores the message that the current regulatory and market environment is not conducive to driving the transition to low carbon heating.

5.5.7. Proposed Pathway

Based on the results of the modelling, the pathway that offers optimum carbon emissions and comfort, with acceptable levels of disruption, comprises:

- Multizone heating control
- Limit on conservatory temperature
- Top-up to 250mm loft insulation in extension
- New double-glazed windows downstairs
- New insulated front and back doors
- Solid roof and higher spec glazing for the conservatory
- Larger ensuite towel rail
- Air-source heat pump OR ground-source heat pump, each with a hot water cylinder

As with the other houses discussed in this upgrade analysis, multizone heating control brings considerable benefits and is an obvious first step that brings additional control and comfort benefits as well as paving the way towards low carbon heating. Linking this with a limit on the conservatory temperature means that energy-saving advantages are not simply lost by providing extra heat to the conservatory, which still fails to reach acceptable comfort conditions for the coldest part of the year. The temperature limit is controversial, and may be unpalatable to owners, but they would effectively be trading some loss of comfort – or time they can use the conservatory comfortably in winter – against improved utilization in summer, better comfort elsewhere in the house and lower energy bills and emissions.

Extra loft insulation is likewise a straightforward improvement. In this instance insulating the extension also improves comfort and warm-up times, which are reported as problems by the owners.

New windows and external doors downstairs would be more expensive, but they would then be consistent up- and downstairs and would improve the appearance of the home. The improved windows and doors could be chosen to give better security, with lockable windows, which could result in lower insurance costs. With or without better security, it would make the downstairs rooms more comfortable and save around 5% of energy used for space heating. Even beyond the room-temperature benefits, new doors would be very likely to reduce cold draughts into the house in winter, which would bring additional comfort.

Replacing the conservatory roof with a solid roof and upgrading the glazing are also big steps with significant cost implications. This would turn the conservatory into a much more usable space – in summer, as well as mid-season. It would mean the room would not be as bright or as prone to glare as it is now, but this could also bring a secondary saving in electric lights in other rooms. There is evidence that people moving from a very bright, heavily-glazed room, to a room with more conventional glazing ratios, tend to switch lights on when otherwise they would not.

A larger towel rail for the ensuite shower room may seem like a minor detail, but this makes a noticeable difference to comfort in that room (and other rooms, via the radiator network). It also brings the benefit of providing more space to dry towels. The cost and disruption of fitting a new towel rail is minimal.

Finally, there is a strategic decision for the owners to make about which form of electric heating they prefer. If they accept that they will have to deal with difficult access into the back garden for diggers, and (more important) if they are prepared to reinstate their garden after the trench is refilled, the higher capital cost of the GSHP would achieve a better COP and so slightly lower running costs and carbon emissions than the ASHP. Alternatively, if they do not object to some noise in their garden from the external unit of an ASHP, with simpler and less disruptive installation, they may choose the air-source option.

There is a large difference in the installation costs of a GSHP versus an ASHP, with the ground-source more expensive. It is too early to know for sure, but maintenance and repair costs for the ASHP may be higher because there is a fan in the external unit, vulnerable to weather and debris. In either case, the capital costs are high, and significantly higher than using a conventional gas boiler.

5.5.7.1. Upgrade pathway summary

Stage 0:

- Existing problems
  - Conservatory, extension, living room and kitchen tend to be cool and take time to warm up (if they reach temperature at all)
  - Bedrooms tend to get too warm
- 3.0 tonnes CO_2/year

Stage 1 – Year 1:

- Upgrade to multizone heating control
- Set control to prevent heating conservatory over 15°C
- Extra loft insulation in extension (150mm mineral wool on top of current insulation)
- 2.95 tonnes CO_2/year

Stage 2 – Year 4:

- Replace glazing in the conservatory with more thermally-efficient glazing
- Build a solid, insulated roof on top of conservatory
- 2.8 tonnes CO_2/year

Stage 3 – Year 7:

- Replace doors and windows on the ground floor with more thermally-efficient ones
- Install a larger towel rail in the ensuite bathroom
- 2.7 tonnes CO_2/year

Decision fork: either

Stage 4A – Year 10:

- Install an 8 kW air-source heat pump with a hot water cylinder
- The heat pump would save 40% of carbon emissions for heating at today's carbon intensities, rising to 99% of carbon emissions by 2040

Or

- Install an 8 kW ground source heat pump with a hot water cylinder
- The heat pump would save 44% of carbon emissions for heating at today's carbon intensities, rising to 99% of carbon emissions by 2040

6. Key findings from pathway development

The five pathways developed show that it is possible in all cases to design a series of upgrade steps leading to greatly reduced CO_2 emissions while providing excellent thermal comfort and hot water supply – far better than the homes in their original conditions. These were developed considering the needs and priorities of the householders and without subjecting them to unacceptable disruption.

However, a simple CAPEX/OPEX return-on-investment case to motivate upgrades is not tenable as it would require a pay-back term of decades (beyond the life span of some of the upgrades). The running costs of these homes with electric heat are only predicted to become appreciably cheaper than gas heating after about 2040, with the exception of House B. This is the oldest building with the worst original energy efficiency, for which an air source heat pump has lower running costs as soon as sufficient building fabric improvements are made. However the savings in running cost are still not sufficient to justify the required capital expenditure of up to £27,000.

The current energy market and government incentives are inadequate to persuade consumers that the capital costs for these pathways would be justified purely by savings in their energy costs, despite containing the level of investments by focusing on upgrades giving the maximum benefits. The improvements in comfort and to the appearance, value and maintenance requirements of the houses may motivate some of the proposed fabric upgrades but will do little to encourage the change to electric heating. Some surrogate for carbon pricing or subsidies for low carbon heating will almost certainly be required to drive the necessary transition.

In each of the five case studies, heat pumps, especially using outside air as a heat source, featured as the final heat source option. House B was in a location where district heating may become available, but running costs are projected to be far higher than those for a heat pump (see section **4.2** for cost assumptions). Ground source heat pumps and hybrid gas boiler/ASHPs were also considered but were not deemed to be suitable (or necessary) final solutions for these houses.

Achieving good comfort with heat pumps, with reasonable building fabric upgrades, relied on the following factors:

- Use of high-temperature heat pumps (maximum 55 °C outlet to radiators) achieving 2.5-2.7 more useable heat output than electric power input (using the severe case of weather data from Newcastle-upon-Tyne) and allowing pre-heat times up to an hour.
- Upgrade to high output (double panel, double convector) radiators – of the same size as existing radiators except where severely undersized for the current heat source
- Increase flow of hot water to the radiators by ensuring the water circulation pump is adequately sized (without needing to replace existing piping, unless it is microbore tubing) and opening balancing valves (enabled by use of multizone control)

- 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).

In all cases replacing a single thermostat and TRVs with independent control of each room's temperature (multizone control) was fundamental to achieving good comfort results and final energy savings, despite noticeable variation in the savings it provided without any other changes. Most householders reported issues with single zone control, such as rooms not reaching desired temperatures quickly enough, some rooms over-heating, unnecessarily heating rooms when not in use, or not having enough flexibility (or understanding) in their heating control interfaces (including the "programmer", boiler temperature settings, TRVs and balancing valves). Multizone control inherently addresses all these issues except the interfaces to setting temperature profiles and heat source settings – even these issues may be helped by provision of a modern, well designed, user-friendly control system interface, as suggested by feedback from the 30-house HEMS field trial.

The upgrades listed above allowed heat pumps to successfully provide all the heat and hot water needs of the houses without the need for major work to replace the radiator piping and/or install much larger emitters, as is often expected to be the case. 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 limit setting accessible via a third-party interface.

A key part of the pathway development has been to quantify the impact of feasible changes to the homes using detailed dynamic simulation. Table 6-1 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, to achieve significantly better thermal comfort. The differences in energy savings between "full fabric upgrades" and the ASHP cases are a combination of removing the losses from a gas boiler (typically 9-11% for a condensing boiler) and the performance of the heat pumps (typically producing about 2.5 times more useful heat than energy input). Greater savings would be possible if the heat pumps' COPs were increased by running with lower outlet temperatures, but this would be at the expense of comfort, longer warm-up times and considerable disruption and costs of further fabric and heat emitter upgrades.

Table 6-1 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 multizone	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 multizone 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 multizone control, but also provide improved comfort.

Comparing the cost ratios shown in Table 4.2-2 with the final energy savings in Table 6-1 gives an indication of when these upgrades will produce lower running costs than 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 coming years, especially if the market size 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 well as a hybrid heat source. This was seen as preferable to an "off the shelf" hybrid product since most 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 is 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 setpoint. 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 tying in to 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, relative to the ASHP, than was expected. This was partly due to using a high outlet temperature, but was also found to relate to the modest difference in average air temperature and ground temperature around the "slinky" when buried at a depth of 1-1.5 m. Vertical bore holes and regions with greater extremes in both seasonal and diurnal air temperature variation would 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 to connect to a district heat 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 (minimizing the impact of scheduled and unplanned maintenance).

Regarding building fabric upgrades, Table 6-2 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 6-2 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.

One of the characteristics of using dynamic simulation is that it often provides unexpected insights into the systems under investigation. In this study, detailed modelling of the wet heating systems illustrated some aspects of their behaviour which seem not to be widely appreciated:

- Gas combi-boilers suffer from shortcomings that people have learnt to live with. Foremost among these are the effects of the compromise between maximum and minimum power output. A combi-boiler is sized to provide domestic hot water, typically limited to 10-15 litres/minute, giving a maximum output around 24-30 kW. The minimum output is constrained by flame stability and combustion efficiency and is usually between 25-40% of maximum firing rate, or around 7-13 kW. With typical houses, such as those in this study, losing around 3-8 kW when warm, most combi-boilers would need on/off cycled to avoid over-heating when trying to maintain a steady temperature, leading to reduced comfort, shorter boiler life and loss of effective efficiency. This can also lead to DHW demands coinciding with high exchanger temperatures (when a heating cycle is stopped to prevent over-heating) giving either a much hotter water than expected, or a long wait for hot water (while the boiler cools down), depending on the design.
- Radiator balancing is vital for single zone control to limit over or under heating rooms other than the one containing the thermostat, but tends to reduce water flowrates to the radiators (and hence their output power), especially if balanced to avoid over-heating. Few homes are likely to have well balanced systems as it is a complicated procedure trying to reach a compromise between conflicting goals. Multizone control greatly reduces the influence of radiator balancing, allowing faster room warm-up by more fully opening the radiator valves.
- TRVs position their valve in proportion to the room temperature (or an approximation thereof) so they do not achieve a set temperature, nor can they completely prevent over-heating. In order for them to have an effect on radiator power (and hence room temperature) they must restrict the water flow to the radiator and hence reduce its available output power. Again, multizone control solves these problems and together with opening the lockshields (see above), allows radiators to emit up to twice the power available with single zone control. This allows much more practical (and less expensive) upgrades to radiators to provide sufficient output with the lower water temperatures typical of heat pumps.
- Higher power output radiators don't inherently use more energy - but they do allow rooms to warm-up faster if the heat source can supply enough total power to the system.
- Setting a minimum valve position limit on the radiator control valves (e.g. WRVs) can allow the radiators to act as buffer to prevent problems with the heat source with sudden flow cessation or cycling when near its minimum power output (when the rooms are already warm). This method also reduces the rate of room

cooling when the heating is running giving a smoother room temperature profile, increasing WRV battery life and reducing inefficient on/off cycles of the heat source.

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 40 GW, equivalent to about 40% of its current maximum capacity[41]. Reducing this peak load would require the demand from heat pumps to be spread more evenly over the day. The next section explores the use of thermal storage to achieve this, based on the heat demand profiles generated for the houses during the pathway development.

[41] "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

7. Thermal storage to flatten energy demand profiles for domestic heat

7.1. Background

The prospect of large-scale uptake of heat pumps for domestic heating raises concerns about the demand this would place on the electricity grid, particularly if this demand occurs at similar times across many households, increases significantly during episodes of cold weather, and coincides with existing peaks in electricity usage for other purposes. Furthermore, as an increasing proportion of electricity generation comes from intermittent renewables, measures may be required to make use of electricity when the renewable resource is abundant and cut back during lulls.

Demand shifting, or spreading, at the domestic level could help meet these new supply and demand requirements by controlling the operation of heat pumps according to the availability of grid electricity, utilising some form of energy storage to ensure that the comfort of heat pump users is not compromised. Without such measures, large-scale adoption of electric heating would require major upgrade works to the electricity distribution network and investment in additional peak-load generation capacity, giving rise to high costs and disruption. Furthermore, if peak loads from heat pumps were concentrated around the start of morning and evening heating phases, additional generation to satisfy these demands would be likely to be higher carbon intensity than the base load generation. The absence of local demand shifting would also imply either a greater need for curtailment of renewable generation at times of oversupply, or increased requirements for large scale storage capacity within the generation and distribution system. Since domestic storage would occupy precious indoor space, there exists a tension between minimising costs in the system beyond the dwelling and meeting the needs of households.

IEHeat models have the capability to explore the range of possibilities for implementing demand shifting of electric heat in the domestic setting. A high-level estimate of the requirements for a thermal storage system has been produced (described in detail in **Appendix 6**) 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, it is foreseeable that new periods of peak demand would be created due to the cumulative effect of many heat pumps following the same rules. Additionally, heat pumps will tend to operate more efficiently with long, steady runs, rather than frequent cycles and power modulation, particularly if the constant low-load approach can allow installation of smaller, cheaper heat pumps. Hence the heat supply approach adopted is to run the heat pump at fixed output as steadily as possible, switching off or reducing power during peak times, and using thermal storage to buffer the output and match it to occupant demand for heat. Alternative demand profiles have also been examined to test this assumption.

If heat electrification and the penetration of renewable generation increase substantially in the future as anticipated, it may become more valuable for heat pumps to respond to the availability of renewable generation. The foundations of a study into such a dynamic response to signals from the grid are laid out in appendix section **A.6.2.3.**

7.2. Key findings

Reducing or entirely eliminating power draw from the heat pump during the evening peak demand period is possible with technically feasible quantities of storage (around 20 kWh). These exceed the capacities householders will be accustomed to in the form of hot water cylinders by a factor of around 2-3 if sized for the coldest days in winter (assuming around 9 kWh for a typical cylinder). Supporting this finding, the stakeholder group for the Newcastle Local Area Energy Planning project recommends that 500 litre tanks are most suitable for buildings with ASHPs; this is approximately 2.5 times the capacity of a typical DHW cylinder. The study concluded that an optimal quantity of storage would minimise whole system costs, but the storage required to completely avoid electricity demand during peak hours would exceed this optimum. This lends credibility to our approach of reducing but not eliminating heat pump power demand during peak hours.

7.2.1. Integrating Storage in Households

Unsurprisingly. individual days in the cold season were seen to place significantly greater demands on the system than the majority of the year (see appendix section **A.6.2.3.** Engineers are used to sizing systems for the worst-case scenario, and this first pass analysis suggests that doing so for a heat pump with storage in a typical home in the North East of UK would lead to large storage requirements – in the region of 20 kWh - even with comprehensive thermal efficiency retrofits applied. Some households are familiar with storage in the form of DHW cylinders, which would typically store around 10 kWh of heat and be around 0.6 m in diameter and 1.5 m in height[42]. However, if water tanks are to be used for the demand shifting application described, they would be likely to require greater space per kWh stored than DHW cylinders, due to a lower temperature of stored water.

It is worth considering less conservative alternatives to oversizing the system for the majority of operating conditions, so that cost and storage space requirements may be more

42 https://webapps.viessmann.com/vibooks/api/file/resources/technical_documents/GB/en/VDP/5414651VDP00008_1.PDF

palatable. Allowing the heat pump to make up energy shortfalls on occasions when storage is depleted would subject the grid to occasional, large usage spikes, since this will tend to occur en-masse during harsh weather (see Figure 7.2-1 below), implying costly reinforcement requirements. Falling back onto gas-fired heating at these times only would be technically viable, but at a national scale would require consumers to pay standing charges to maintain a gas grid which sees little usage.

Allowing indoor comfort tolerances to relax during rare extreme weather may hold the answer to an acceptable compromise between cost and performance; this would be a valuable focus for further modelling and analysis. Investigation into how this compromise could be offered in a way which is attractive to customers, while protecting their sense of control and comfort, would be an essential next step. Increasing room pre-heating times, to effectively use the materials of the building as additional storage during onerous weather conditions may also allow storage capacities to be kept within manageable limits.

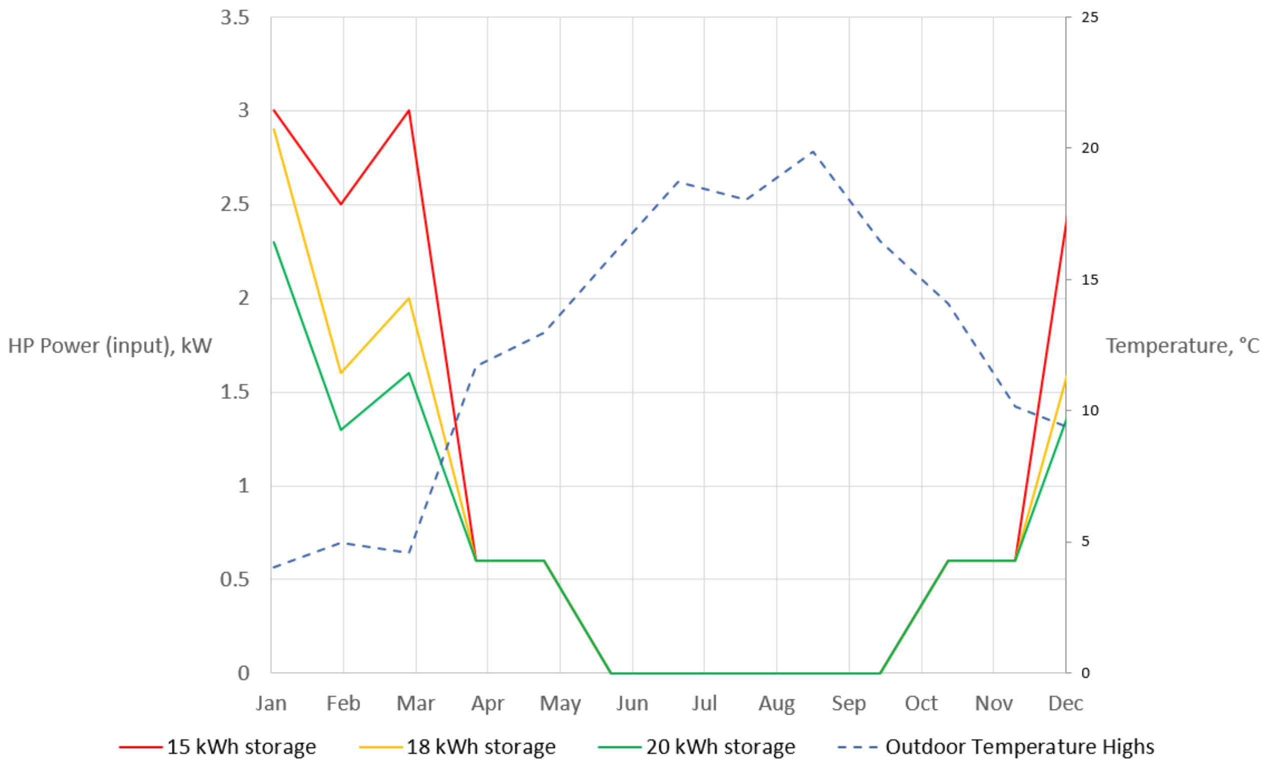

Figure 7.2-1 – Plots showing heat pump electrical power setting required with three different storage capacities, thoughout the year. Note the dramatic effect on peak grid demand in downgrading from 20 to 15 kWh storage, where it is almost doubled at times. Plots produced using data from House C with full upgrades applied and stand-alone air source heat pump.

7.2.2. Storage Technologies

Since the energy storage requirement for this case was found to be 2-3 times that which householders are used to accommodating, new technologies are likely to be required to save valuable space (see landscape review in **Annex 1.a**). The use of latent heat storage, having volumetric heat capacity of 2-3 times that of sensible heat storage (from **Annex 1.a**), appears well-aligned to this application. Latent heat storage works by changing the state of a material between solid, liquid and/or gas – a process known as phase change – whereas sensible storage simply changes the temperature of a material in an unchanging state (e.g. heating water in a tank). Some products are already sold to the domestic market which utilise phase change materials (see for example Sunamp Heat Batteries), and while they are more expensive than their sensible heat equivalents, they can deliver nearly all their stored heat at a constant temperature, unlike even well stratified water tanks. They are also expected to have longer operating lives than currently available electrochemical batteries.

Hybrid solutions are available, in which phase change material is added to the water in a tank to boost the heat capacity. This may be the most cost-effective approach for 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.[43]

Looking further ahead, thermochemical heat storage systems have been demonstrated at prototype stage, though are not currently market-ready. By employing certain types of reversible chemical reaction which absorb and release heat, energy can be stored by changing the chemical state of a material, then extracted with a subsequent reaction. Besides offering drastically higher energy storage per unit volume compared to sensible heat storage (at least ten times that of water), the material stays cool while storing energy, meaning that losses are reduced and insulation is not needed. If brought to mass market at acceptable cost, thermochemical storage could make the prospect of load shifting completely attainable without significant space implications for the household.

Electrochemical batteries attract a great deal of attention in relation to energy storage problems and future energy systems. Batteries would shift the storage of energy from the output side to the input side of the heat pump. This would 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 – an electrochemical battery aimed at the domestic market – is available at a roughly similar cost per kWh[44] to the SunAmp Heat Battery – a phase change thermal storage device for home use (not including installation costs). However, the energy density of the Powerwall is approximately three times that of the Heat Battery. Combined with the aforementioned reduction in required capacity due to COP, this makes electric storage of equal performance far more compact than thermal storage, and a strong contender for this application.

With electric storage, the heat pump would only run during times of heat demand. Consequently, more of the heat pump's operation would occur during the higher daytime outdoor temperatures than if it was run continuously to charge a thermal store (which would involve overnight operation). This will result in higher overall COPs and energy efficiency,

[43] http://www.pcmproducts.net/Solar_Heat_Storage_Recovery.htm
[44] https://www.tesla.com/en_GB/powerwall

and avoid night time noise. Thermal storage must have heat put in at a higher temperature than it can be taken out, meaning the heat pump must produce higher temperatures to charge thermal storage than to provide space heating directly, which will incur a COP penalty. By only providing direct heating as required, the heat pump supported by electric storage would avoid this penalty too. What's more, electric storage comes with the additional benefit of supplying other household appliances during periods of high electricity price, or could be charged by local generation (e.g. solar PV).

A disadvantage of using electric 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 warmup 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[45]. These relative merits and drawbacks of thermal and electric storage could be the subject of further modelling and analysis work, to identify which circumstances favour which technology.

7.2.3. 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 full details see appendix section **A.6.2.3**). 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.

[45] https://www.sunamp.com/residential/

8. Conclusions and recommendations

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 house studied, comfortable, low carbon heating was provided by a combination of targeted building fabric upgrades, minimal radiator upgrades, adoption of multizone 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 large numbers of dwellings with common features.

The study also 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 very weak for most householders. Changes to the energy market and government incentives, such as carbon pricing or low-carbon subsidies, would be required to drive the transition to comfortable low carbon heat. Indeed, current incentives, such as the Domestic Renewable Heat Incentive, have encouraged suppliers to promote use of low temperature heat pumps (to maximize seasonal coefficients of performance), necessitating more expensive radiator and insulation upgrades and struggling to provide comfortable daytime temperatures without imposing higher night time temperatures.

The process of analysis leading to the upgrade pathways has been shown to benefit from a multidisciplinary approach, in an attempt to cover all aspects of home heating by combining detailed modelling with practical knowledge of building fabric and heating systems, together with consideration of the needs and behaviour of householders.

The study has illustrated how relatively simple metrics for heating performance, relating to occupant comfort and energy use, can be powerful tools for comparing upgrade options. Further development of "comfort metrics" that can be modelled and, crucially, measured in real houses, would help identification of pathways that are attractive to consumers and may help stimulate the market for such improvements. This would require upgrades, such as those recommended by the approach reported here, to be implemented in real homes. Monitoring to compare with the predicted performance would need to be combined with recording of the householders' reactions to the changes to identify quantitative measures that relate to their experience of thermal comfort.

Modelling at the level of detail in IEHeat can also shed light on issues which may not have been widely appreciated, identifying root causes and solutions to problems that may be currently addressed in less appropriate or effective ways. Used as an investigative tool, it has also shown its potential to help develop new ways to improve domestic heating performance, such as new control approaches.

The analysis of thermal storage for spreading heat pump loads has established the relationship between storage capacity and heat pump power demand, showing that, with emerging storage technologies such as phase change materials, it should be possible both to improve comfort (through the greater power output of the storage) and to reduce the heat pump electrical power input to around 1.5 kW in cold weather for a typical three bedroom house. If this represented an average value, 15 million dwellings with heat pumps may demand a near-constant load of about 20 GW, which may influence the design and energy mix of the generation and distribution system.

However, achieving this level of uptake of heat pumps would require not only government encouragement, but also rapid development of the capacity to supply building fabric and low carbon heating system upgrades. At some point over the next ten years, the UK may need to be installing around a million heat pumps a year to meet carbon emission targets. 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. The advantages of such an increase in the size of the market include the tendency of prices to fall as economies of scale take effect and the increased availability of trained installers and service technicians, together with increased investment to develop more efficient and consumer friendly heat pumps.

There is scope for the development of innovations by the targeted use of detailed dynamic simulation of domestic heating systems. For example, the modelling experience gained in this study suggests that three temperature measurements per room and knowledge of radiator size and type could form the basis of a continuous algorithm to calculate pre-heat times. This approach could be developed and tested using IEHeat before installing in real houses, such as part of the HESG field trials. Such an algorithm could also be used to indicate where the big gains (from fabric upgrades) are to be found (i.e. which rooms are losing too much heat or which radiators are too small?).

Detailed models are often a valuable input into more simplified models: IEHeat has the potential to inform and improve models for wider local and national energy system planning.

To fulfil the potential of the approach to pathway development in this study it would be beneficial to analyse a wider range of dwellings, including in apartments. 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, investigation of criteria for successful use of under floor heating in retrofit settings, and development of more sophisticated ways to control heat pumps and hybrids (with gas boilers and with thermal storage) and to improve WRV control of room temperatures.

Appendix 1. 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. It is subdivided and ordered logically, rather than alphabetically.

General

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

OPEX: operating expenditure, in this context, energy costs for providing heating.

Building terminology

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

House: a building which forms a single dwelling, but maybe attached to other houses by a party wall (semi-detached, end-of-terrace) or two (mid-terrace).

Household: the occupants of a dwelling.

Home: combination of a dwelling, the people who live there and their possessions.

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

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

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

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

Air changes per hour: a measure of the rate of ventilation air flow in terms of the air volume of the room. For instance, 0.5 air changes per hour means that the hourly ventilation flow rate is equal to half the volume of air contained in the room.

Fractional opening (of a window or door): the fraction of the total surface area of the aperture which is effectively available to air flow (and heat transfer) when partially opened.

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.

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.

Party wall: a continuous wall shared by adjoining houses.

Rendered wall: a wall covered with an outer layer of cement or synthetic material for weather protection and aesthetic purposes.

Solid floor: a layered floor with the lowest material (usually hardcore) in direct contact with the ground, with no significant air-gaps, and usually featuring a concrete slab as the main structural element.

Suspended floor: a floor raised above the ground, often supported by timber, leaving a ventilated cavity beneath.

IWI: internal wall insulation.

EWI: external wall insulation.

CWI: cavity wall insulation.

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 floors).

MVHR: mechanical ventilation with heat recovery.

General heating system terminology

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

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

Wet heating: a central heating system which works by circulating hot water from a single heat source to heat emitters in each room via a pipe network.

Emitter: the components of heating systems that transfer heat into the rooms, such as radiators or underfloor heating.

Y-plan: a common layout of radiator networks in UK houses with tees splitting the network into two branches (usually one upstairs and one downstairs).

Lockshield: a valve at the opposite end of the radiator to the control valve (e.g. TRV) used to balance the radiators. Its name derives from the cover (shield) over the stem to prevent accidental adjustments.

Isolation valve: a valve used to disconnect part of the heating network from water flow for safety and maintenance purposes.

Flow & return (temperatures): the water leaving the boiler, heat pump or other heat source for circulation around the heating system is known as "flow". The outlet of each emitter connects into a **common "return" pipe** taking the cooler water back to the heat source.

Radiator balancing: the process of adjusting valve positions (and thus water flow rates and power outputs) of each radiator to compensate for the varying heat requirements of each room in the house. The intention is usually to achieve approximately equal rate of warm-up in each room simultaneously.

Manifold: A series of pipe fittings (tees and valves) to allow one pipe to branch into multiple pipes.

Mixing valve: a thermostatic valve which automatically maintains a flow of water at a set temperature by blending hot water with cold. Different forms of these can be used to ensure safe water temperatures are delivered by showers and taps, or are sent to underfloor heating circuits.

Circulation pump: a device driven by an electric motor used to maintain the flow of water around the heating network, through the emitters and heat source.

Heat exchanger: a device which enables the transfer of heat from one medium to another, e.g. from the hot gases of combustion to water, or from hot water to a cooler water stream.

Immersion (resistive) heater: a standard electric heater placed inside a domestic hot water cylinder (tank). These heaters transfer all the electric energy they consume to the water in which they are immersed. They can be used as a backup in case of failure of the primary water heating system, to assist the primary system by topping up the temperature, or as the primary water heating device.

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.

Gas boiler terminology

Combi boiler: A fired heater, usually burning gas, which combines provision of space heating and instantaneous water heating, without requiring a hot water cylinder (tank).

System boiler: A fired heater, often gas, which provides space heating and periodically heats a hot water cylinder to provide domestic hot water.

Combustion chamber: the part of a boiler where fuel mixes with air and burns.

Nominal power: the power output a heat source is designed to deliver, which is often its maximum power level.

Minimum firing rate/power output: the lowest amount of power a boiler can deliver, usually set by flame stability and maintaining good mixing in the combustion chamber. For most domestic gas boilers this is in the range 25-40% of nominal output. The **turn down ratio** is the ratio of nominal to minimum rate.

Latent heat of water (context: gross gas heating value): the combustion of hydrocarbons produces water vapour as part of the exhaust. Energy (known as latent heat) can be extracted from this vapour by condensing it into liquid form, thus improving the overall efficiency of the fuel use, as do condensing boilers. Heat of combustion ("calorific value") of a fuel such as natural gas can be stated as a "**gross**" (or "higher") value, or as a "**net**" (or "lower"), the difference being the latent heat of the water produced by combustion.

Flue: the pipe through which exhaust gases from combustion leave the boiler and are released outdoors.

Excess air ratio: optimal combustion requires slightly more air than would be required for stoichiometric (1:1) combustion, to allow for imperfect mixing in the combustion chamber. Typically 10-15% excess air would give the most efficient combustion. Achieving this requires the air inlet flowrate to be controlled in ratio to the fuel flow.

Damper (context: boiler combustion air flow): a moveable flap used to control the flow of air (the other method being a variable speed fan).

Heat pump terminology

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)**.

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.

Average (mean) effective 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).

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

(Scroll) compressor: a device driven by an electric motor which does work on the refrigerant in a heat pump system, consuming most of the input energy. It increases the pressure and temperature of the refrigerant gas, which then condenses into liquid in heating the delivery fluid (usually water).

Evaporator: the part of the heat pump system where liquid refrigerant turns to gas, absorbing heat from the external, low temperature, energy source.

Condenser: the part of the heat pump system where gaseous refrigerant turns to liquid, releasing heat to the delivery fluid (e.g. water to radiators).

Let-down valve: the valve between the condenser and evaporator which drops the pressure and temperature of the refrigerant below that of the external energy source.

Superheating margin: the difference in temperature between the boiling point of the refrigerant (at evaporator pressure) and the evaporator outlet temperature.

Turbo-expander: a device which can be used to provide the same function as the let-down valve but additionally converting energy otherwise lost through the expansion into rotational motion which can be used to partially drive the compressor, potentially reducing the required input power by up to 15 %.

Heating control terminology

Heating control: hardware components, software and strategy used to switch heating on and off, and in some cases vary the output power, according to time schedules of target temperatures, in response to measured temperatures and possibly other factors.

Single zone control (SZ): The common approach in UK homes, where the heating is controlled by a single thermostat, often with TRVs on most radiators to try to reduce temperature deviations (from desired values) in the rooms.

Multizone control (MZ): The house is divided into separate areas, in which the timing of heating and target temperature can be controlled independently. Each room of the house could be an independent zone.

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.

Setpoint: the desired value of a measurement given as a target to a control system. For example, in the context of heating control, the air temperature that the householders want to achieve. This can be for a room or the whole house. In domestic systems this is often defined as the upper boundary of an acceptable temperature range (a 2 °C range has been used in this study, but this varies with control device and is adjustable in IEHeat).

Warm-time/heat demand time: a time when the householders want a room to be warm.

Pre-heat: the heating system is switched on some time earlier than the start of the warm-time, in an attempt to bring it to target temperature in time. The pre-heat time in this study is fixed for each simulation. In reality it is often estimated and included in the temperature profile set by the household, but in more sophisticated control systems it may be determined by understanding the characteristics of the heating system, the building fabric, the occupants' behaviour and the present weather conditions**.**

Control band: the difference between the temperature at which the control system switches the heating on, and the temperature at which it switches it off.

Warm-up time: a result of the heating system, measured from when the heating is turned on in a room to when that room's temperature enters its control band.

Proportional-Integral-Derivative (PID) control: a ubiquitous and versatile form of continuous feedback control which adjusts a control device (e.g. the opening of a valve) to bring its measured variable (e.g. a room temperature) to the desired value (its setpoint). A simpler variant, **Proportional-only control**, is often used by mechanical controllers (where the action is provided by a lever or, in the case of TRVs, by thermal expansion of a fluid or solid such as wax); without the integral term it is more stable than PID but cannot completely remove the difference (error) between the measurement and setpoint, leaving an offset the size of which depends on the characteristics of the system and the gain of the controller.

Control algorithm: a set of logical rules and calculations used to meet the objectives of a control system.

Modelling

IEHeat: tool-kit for modelling and simulating energy performance of domestic buildings and their occupants, developed during the Integrated Electric Heat project.

Modelica® language: object oriented, equation based, acausal, simulation language (see https://modelica.org/).

Graphical interface/user interface: the means for a person to interact with software. In the case of a graphical interface, interactive images and icons are used to facilitate intuitive interaction rather than a textual format.

Dymola®: Proprietary user interface to build and run models in the Modelica language.

TIL Library: a thermodynamic and physical properties package for use in Modelica supplied by TLK-Thermo GmbH, specifically providing refrigerant properties for heat pump models.

Model: mathematical representation of a specific physical system (in this case a dwelling and it's space and water heating systems).

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.

Parameter: a model input value which defines the behaviour of part of the model which is considered invariant during the course of a simulation, but is often varied between simulations ("**cases**") to investigate the impact such changes have.

Boundary condition: a model input value which defines a boundary of the model (i.e. a value that is not calculated by the model) which may vary during a simulation, such as external air temperature or householder behaviour.

Lateral boundary condition (for underground heat transfer): the temperature of undisturbed ground at various depths to the side of a column of ground underneath a floor or above and below a horizontal heat collector for a ground source heat pump.

Solver: the numerical procedure, provided in Dymola, which solves the system of equations, of which the model is formed, on each time step.

Sample time: the simulation works by calculating the state of every component in the model at regular intervals, each one known as a sample, or **time step**. The sample time is the period of time between these samples taking place. Shorter sample times lead to greater accuracy but also longer execution time. Dymola allows the user to set a maximum sample time, which is reduced if required by the solver.

Execution time: the time required for the computer to run the simulation.

Script: a series of instructions in a programming language to automate a sequence of tasks.

Discrete elements: the sections into which a single object is divided to simplify modelling of continuous properties in the object (e.g. wall layers, layers of water in a hot water cylinder).

Hydraulic: pertaining to the flows, pressures and temperatures in a liquid-filled system.

Verification (exercise): the process of checking that the model can closely predict the behaviour of the real system it purports to represent and that it provides the fidelity and functions required to satisfy the purpose for which it has been developed.

Dynamic response: the response of a system over time to some change in conditions (e.g. an occupant adjusting the heating settings).

Base case: the state of the house as surveyed, without any upgrades to the building fabric or heating system applied.

Metric: a value calculated to quantify the performance predicted by a simulation, typically an average, total or extreme value over the duration of the simulation.

Physics

Emissivity: a measure of how much heat a material will emit through radiation when hot.

Radiative/radiant heat: the transfer of heat by electromagnetic radiation, typically infrared. This type of heat is felt when standing near an open fire.

Conductivity: a measure of how readily heat will travel through a given material.

Convective heat: the transfer of heat from an emitter to the surrounding air, though the flow of air across the emitter.

U-value – **heat transfer coefficient** (often, but not always, approximating combined conductive, convective and radiative effects, known as "**combined-mode heat transfer"**): with a U-value, U $W/m^2/K$, the heat flow over an interface area, A m^2, between two bodies at temperatures T1 and T2 K, is given by Q = U*A*(T1-T2) W.

Specific heat capacity: the amount of heat a unit mass of material will store for a unit increase in temperature – effectively the density of heat storage for a given material.

Density: the amount of mass for every unit of volume of a given material.

Lateral heat transfer: the movement of heat between an object and the material to either side (as opposed to heat transfer perpendicular to the layer of material – especially applies to ground layers below floors).

Insolation: incoming energy from the sun.

Spatial mean temperature: temperature of an enclosed space (e.g. a room) averaged over space (as opposed to over time) – temperature usually varies from one part of the room to another, such as when the windows or doors are not well insulated of draught-proofed.

Pressure drop/loss: the decrease in pressure as fluid flows through an element of the network such as a length of pipe, a valve, a radiator, etc.

Laminar flow: fluid moving smoothly in parallel layers, without disruption between layers.

Turbulent flow: chaotic fluid flow with irregular fluctuations and mixing across the average flow direction.

Stratified: segregated into layers, in the context of tall tanks of hot water or air in rooms with little convection, by hotter fluids with lower densities accumulating in higher layers.

Saturated moist air: air which contains the maximum amount of water vapour possible at a given pressure and temperature.

Relative humidity: the amount of moisture in the air, expressed as a percentage of the maximum possible at the current pressure and temperature.

Appendix 2. Modelling overview

As part of the Smart Systems and Heat Phase 1 Programme, the Integrated Electric Heat Project developed a modelling tool to evaluate the opportunities and challenges for electric heating to meet UK household requirements. To satisfy the requirements of this Upgrade Analysis Study, the tool, referred to here as "IEHeat", has been further developed to produce detailed dynamic simulation models of heat systems within dwellings, aiming to meet the following requirements:

- adaptable, without being over-complex to configure, enabling reliable and efficient building of detailed models representing a range of dwelling configurations typical of the UK housing stock
- intrinsically multizone, capable of reflecting household behaviour (room usage), heat interaction between rooms, interaction between hot water and space heating requirements
- designed to give realistic, detailed predictions of the dynamic behaviour of heating systems, including heating medium distribution, to allow evaluation of changes to heating components and control system enhancements
- flexible and easily modified to quantify changes in performance (energy usage, occupant comfort) resulting from upgrades to building fabric, heating system design, control system function and changes to household behaviour.

The IEHeat model tool-kit, built in Dymola® (a graphical interface to the Modelica® language) has been verified against test data obtained from heating trials at the Salford University "Energy House" (see **Appendix 7**). The match obtained over a 6 hour heating/cooling cycle achieved better than 0.5°C difference of mean air temperatures (within 0.25°C for over 70% of the time) and less than 1% difference in gas usage.

For the Upgrade Analysis IEHeat has been used to build models of five houses to investigate and develop upgrade pathways to low carbon, comfortable, domestic heating outcomes. Further details of the structure and components of typical IEHeat models are given below.

A.2.1. Structure and components of a typical IEHeat model

An example of the top level of an IEHeat model is shown in Figure A.2.1-1. The model graphics illustrating this section are taken from the Dymola® user interface and are included as visual references for the descriptions that follow of some of the key layers of IEHeat models.

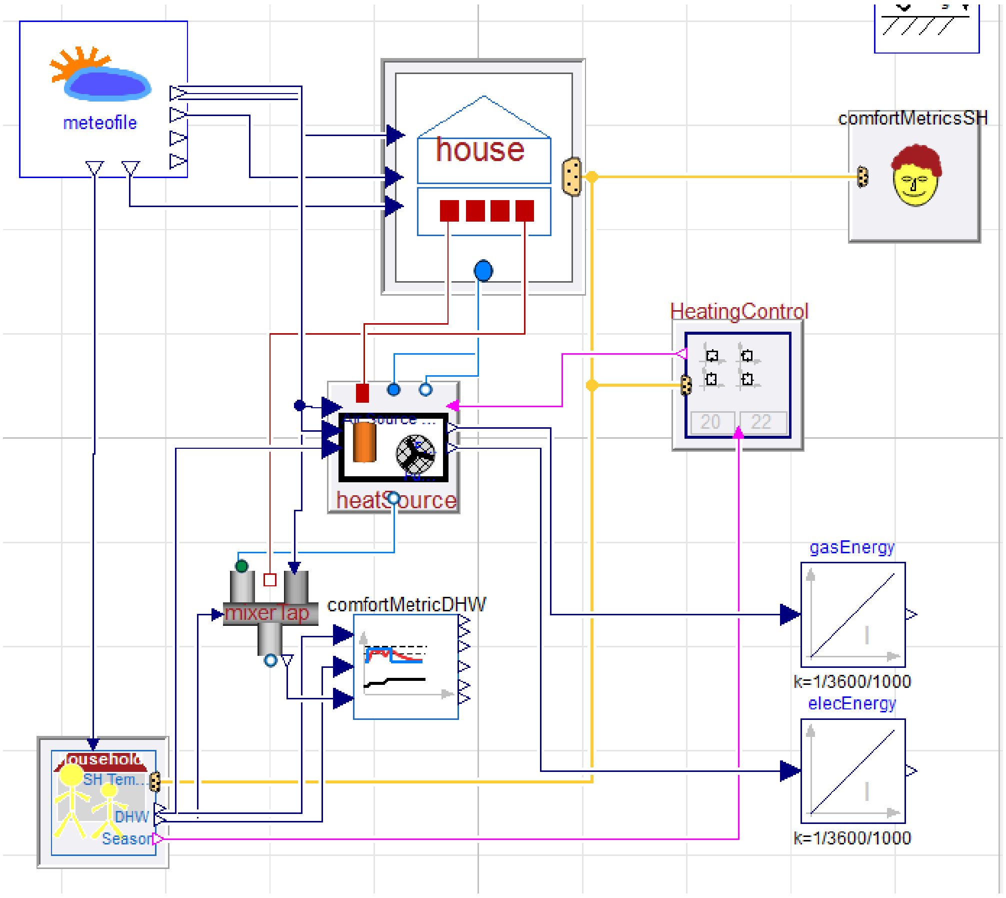

Figure A.2.1-1 Typical IEHeat top level structure

Each main component of the model is “replaceable” – a feature of Modelica® allowing a model component to be swapped for one with the same inputs and outputs but with different internal behaviour. This allows models of specific houses to be built efficiently and then easily modified to evaluate changes to the building fabric, heating system, heating control or household behaviour patterns. The base IEHeat model consists of the following main components:

- house – detailed model of the rooms and heating within the house
- household – occupant behaviour and requirements (e.g. required room temperatures, occupancy, door and window opening, hot water demand patterns)
- heat source – a model representing a heat source providing hot water for space heating and (separately) for domestic hot water – currently available are models of a combi-boiler, system boiler, air or ground source heat pump (with DHW storage or with supplementary resistive heating), hybrid heat pump/boiler and a district heating interface unit
- heating control – of a range of levels of complexity, as required – currently available are single zone (with TRVs), multizone on/off and multizone PID, currently with user-adjustable pre-heat times
- meteorological data – reading weather data at hourly intervals from a file, with data currently available for a typical mean year in various UK locations; the model can be run from any point in the file for any duration (looping if necessary), with optional offsets applied to air temperature; ground temperature estimated as average air temperature (typical for dry soil at 10m depth) with shallower ground temperatures

calculated with a thermal diffusion function based on the previous air temperature sequence; insolation also included as are wind and humidity (including from rain - but its effects are not yet fully incorporated in house model)

- a mixer tap to represent DHW demand (including heat losses and delays resulting from inlet piping)
- metrics – e.g. thermal comfort, warm-up times, deviations from target temperature range, energy consumption

A.2.2. IEHeat house model

The heart of any IEHeat model is the specific **house model** which consists of a set of interconnected cuboid rooms representing a simplified geometry of the target house (Figure A.2.2-1). House models can be constructed rapidly from survey data by placing generic room models into a template which provides the interface connections (between rooms and to the outside). Details of each room (and how it relates to other rooms) can then be configured through parameters based on the available data. Detailed interconnections between rooms are made automatically based on simple parameter settings.

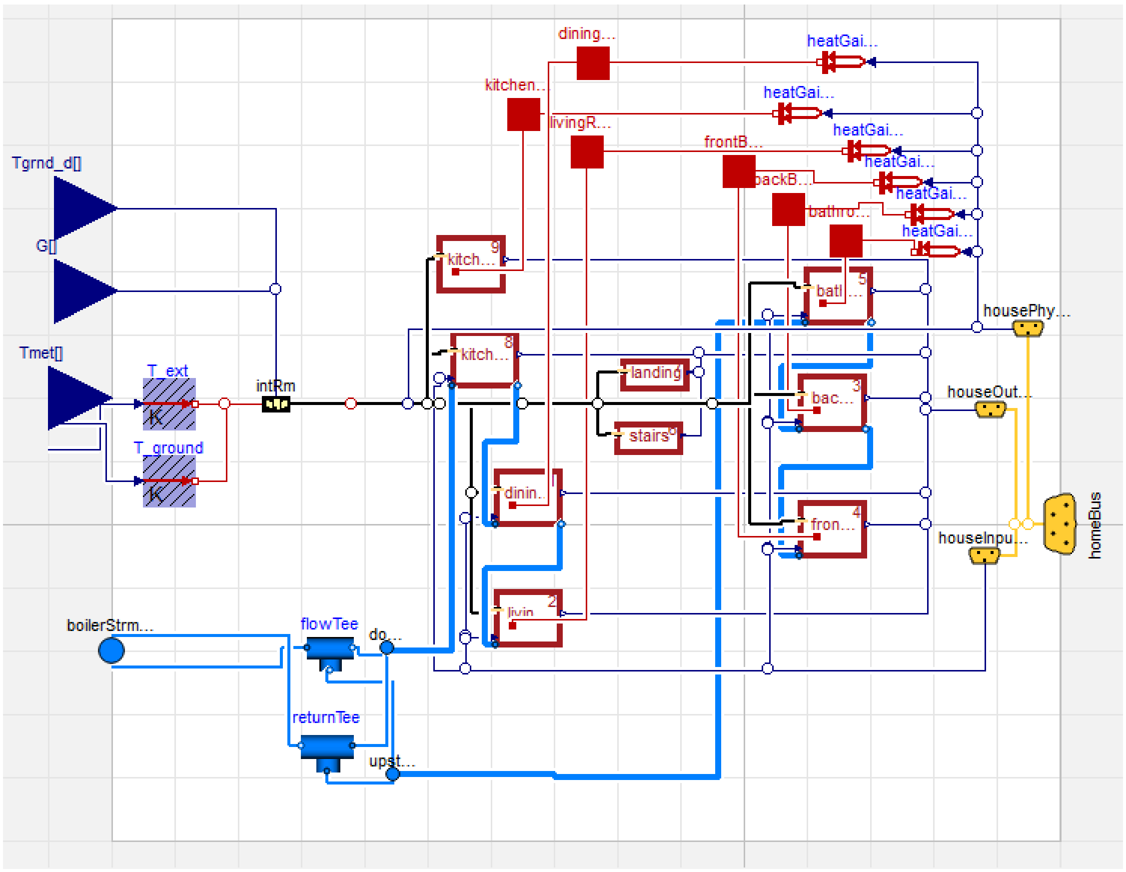

Figure A.2.2-1 Typical IEHeat house model structure

A.2.3. IEHeat generic room model

Each **room model** (Figure A.2.3-1) consists of 6 multi-layered faces (walls, ceiling, floor) each of which can be subdivided into segments to allow interfacing with more than one other room (e.g. the kitchen ceiling might exchange heat with both the bathroom and back bedroom). Windows and doors are incorporated in the walls as required, and are capable of fractional opening. The fully detailed window model includes all forms of heat transfer, including emissivity and solar radiative effects, the resulting heat flow from which is assumed to be absorbed by the floor. Rooms representing L-shaped spaces are connected by a large open door of negligible thermal mass.

A library of materials and layered **wall models** has been developed to represent the typical building materials and wall constructions used for a range of ages and styles of dwellings typical of the UK housing stock. Each layer is defined by its thickness and material thermal properties (conductivity, specific heat capacity, density) and allows heat transfer perpendicular to the face of the wall. The conductivities of air gaps in wall cavities are varied with gap width to make some allowance for radiative and convective effects. Floors also allow lateral heat transfer from the layers to allow for heat lost horizontally into the soil column around the external walls. External surfaces of walls include absorption of insolation as well as combined-mode heat transfer to ambient air. All walls (especially floors, but also ceilings and vertical walls) have the capability to include embedded electric and wet heating.

Party walls are represented using the appropriate material layers with an interface assuming either a fixed temperature or a zero heat flow (as used in this study – equivalent to assuming the adjacent house is following the same temperature profile).

Thermal effects of ventilation are defined in the room model as air changes per hour, assuming all the incoming air is from the outside (heat transfer between adjacent rooms is included in the walls and doors). The air and solid contents of each room are modelled as homogenous thermal masses with heat transfer between them governed by their spatial mean temperatures. The mass and density of the solid room contents are used to calculate its volume and reduce the air volume by the same amount. This is usually only significant in rooms such as stairs where the air volume is significantly less than the cuboid dimensions would give. The heat transfer coefficient between air and solid contents can be adjusted to allow for partial penetration of the thermal mass of the solid contents.

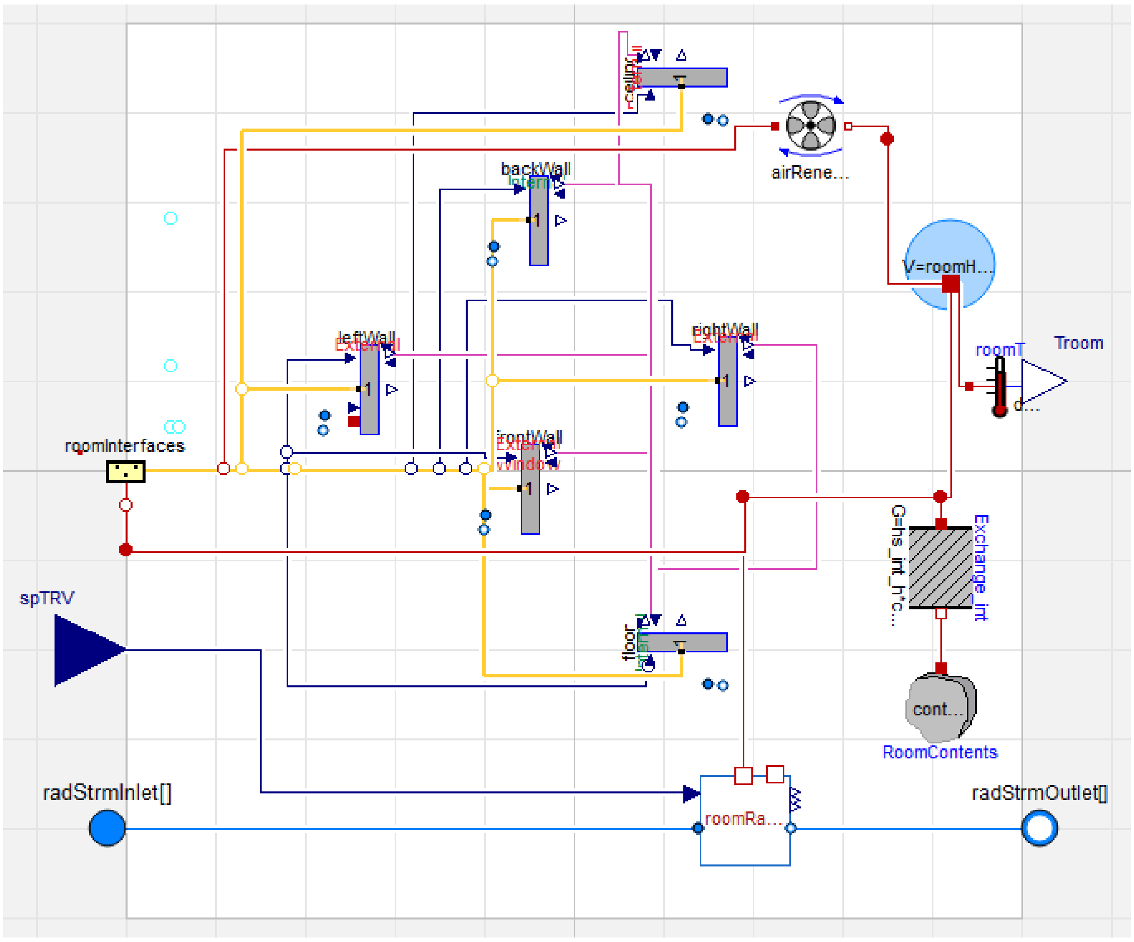

Figure A.2.3-1 IEHeat generic room model

Each room can also include detailed models of a **radiator** and the piping and valves distributing the heating water from the heat source (whose pump model forms part of the radiator piping network). The base case radiator network represents a typical Y-plan configuration but can be modified to represent any layout. The stem positions of the lockshield valves and extra piping resistances (e.g. unmodeled isolation valves) can be set to represent the radiator balancing and network behaviour. If the walls (or floor) includes wet heating, then the radiator network can be connected to this instead of to a radiator, including any manifolds, temperature controlled mixing valves and circulation pumps required.

The hydraulic modelling in IEHeat is far more detailed than a typical "building thermal model" and is designed to bring a full understanding of the influence of all the various factors that affect the behaviour and interactions of these systems. During a verification exercise it proved sufficiently detailed to identify an undocumented pressure loss in a common return line from the upstairs radiators - which was found to be caused by a partially closed isolation valve. The models of liquid flow through pipes, valves, pumps and radiators are detailed enough to give good representations of the relationships between flow and pressure drop, including laminar/turbulent flow transitions, provided reasonable input data is used (pipe diameter, estimates of pipe lengths, valve sizes, pump characteristics etc.). The radiator is modelled as a number of discrete elements which gives a realistic dynamic response for the full range of water flows.

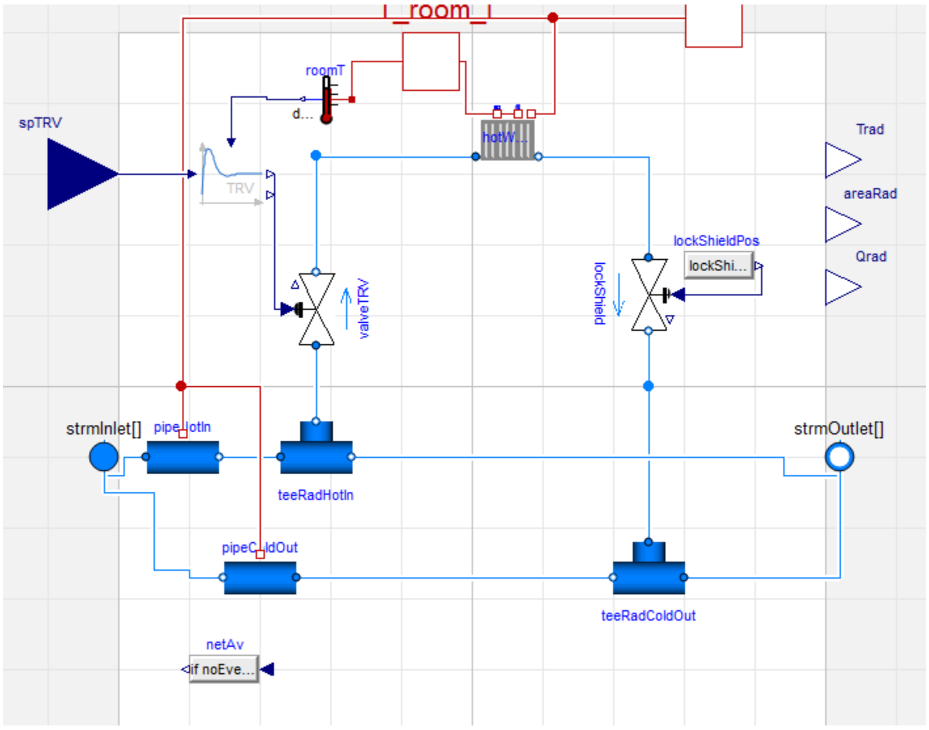

Figure A.2.3-2 IEHeat radiator model with hot water circulation piping and radiator valves

A.2.4. IEHeat heat source models

In order to evaluate changes to energy consumption and heating performance by changing to low carbon heat sources, it is necessary to model a "base case" representing the current situation. The current **heat source** for all the Upgrade Analysis houses is a gas combination ("combi") boiler providing both space heating (SH) and "on demand" domestic hot water (DHW), which has priority over space heating. A system boiler version is also available, incorporating a stratified hot water cylinder model. The IEHeat **gas boiler model** incorporates thermal masses and heat transfer representing the metal making up the combustion chamber and heat exchangers, the water being heated within the boiler and the surrounding materials in the casing and auxiliaries. The model also includes a water pump and simplified control algorithms typical of a combi-boiler of "medium age" – including control of outlet temperatures and protection against high temperatures when operating at loads below the minimum firing rate. The outlet temperature is controlled by adjusting the fraction of nominal power provided to the primary heat exchanger, which is then converted to rate of consumption of gas energy (gross – i.e. including latent heat of water in the combustion products) using boiler efficiency. The efficiency is a function of return temperature and boiler power, characterized by two operating points given on boiler data sheets – typically efficiency (or power input and output) at nominal and minimum (turn-down) power outputs. The resulting efficiency curves for a typical condensing boiler are shown in Figure A.2.4-1. Note that the efficiency increases as the return temperature falls, thanks to the increased fraction of flue gas water condensation, which typically starts with the return temperature below about 56 °C (dependent on excess air ratio, and hence nominal efficiency). The efficiency is also shown to increase at lower boiler power outputs, which relies on the assumption that the excess air ratio is maintained at all firing rates (typically with a variable speed fan or damper). This assumption will hold for all but the oldest boilers, which are typically non-condensing and are revealed on their data sheets by lower efficiencies at turn-down than at nominal output: the model also allows for the different efficiency curves of such boilers.

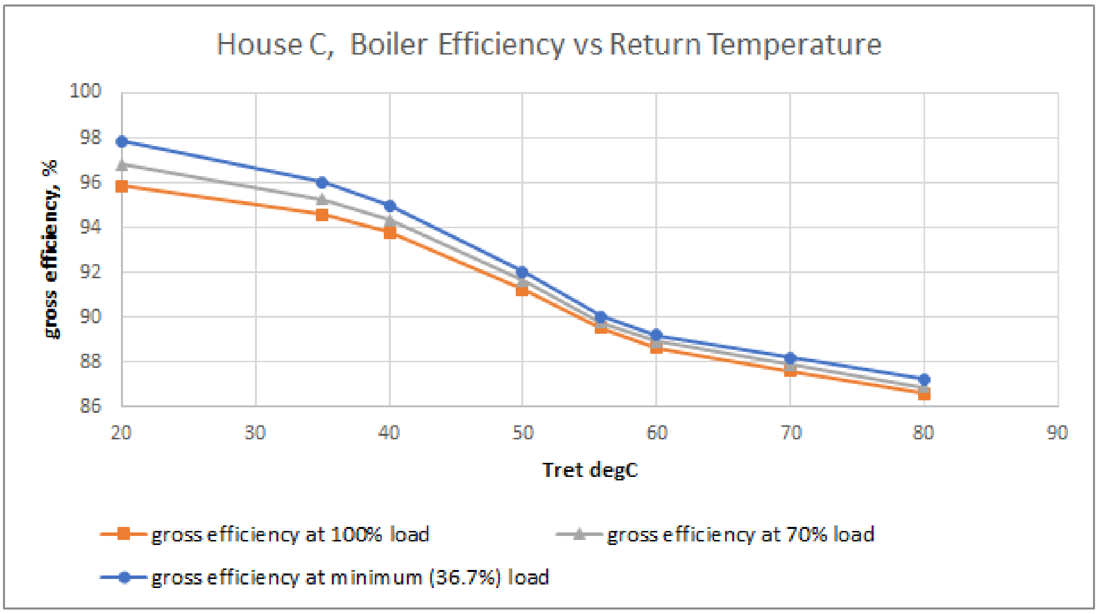

Figure A.2.4-1 IEHeat example of condensing gas boiler efficiency curves

The **heat pump models** use fluid physical and thermodynamic properties provided by the TIL-Library (version 3.5.0, from TLK-Thermo GmbH) - which allows correct representations of a range of refrigerants - with hi-fidelity compressor, heat exchanger and valve models based on their library examples. The detailed physical compressor model has been configured to represent a typical scroll compressor, but its parameters allow it to represent other types equally rigorously. The model includes typical simplified heat pump control, adjusting compressor speed to maintain water outlet temperature and let-down valve position to maintain the required superheating margin at the evaporator outlet. The air source heat pump has been matched to steady state coefficient of performance (COP) values for a typical high temperature heat pump using R410A refrigerant, with data sheet values given at inlet air temperatures of -7, +2 and +7 °C and outlet water temperatures of 35, 55 and 65 °C. The composite plot in Figure A.2.4-2 indicates a very close match except at the higher air temperature (7 °C) where the model under predicts relative to the reported COP values by about 10%. This is likely to be caused by assuming saturated moist air at the evaporator fan inlet. Further study is recommended to investigate the model performance against a wider range of heat pumps and to quantify the impact of humidity on ASHP performance. Note that the current model makes no allowance for evaporator defrost cycles.

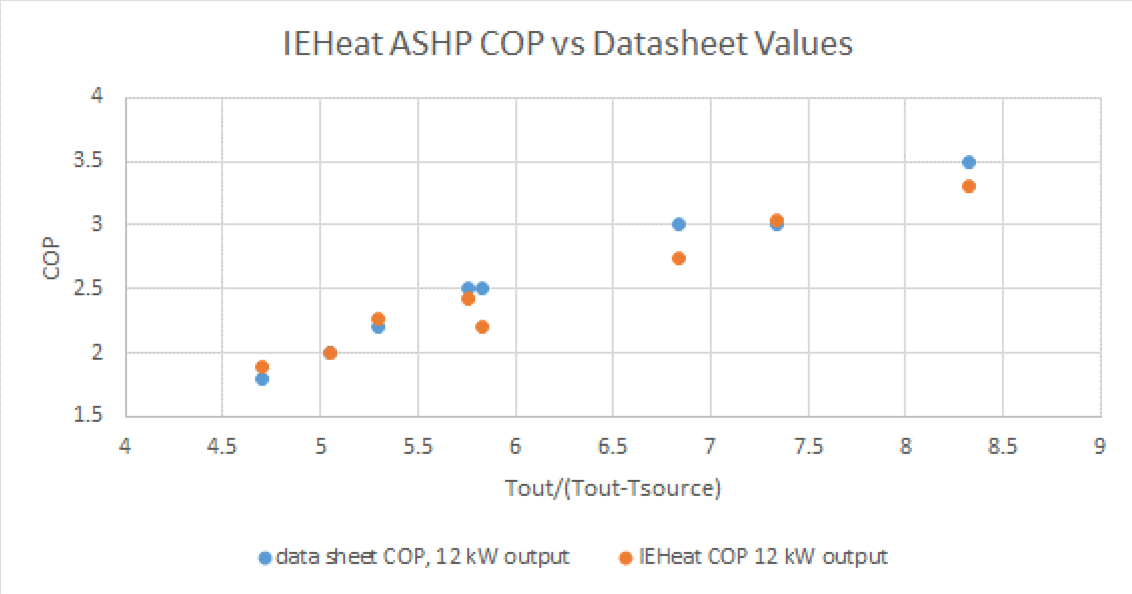

Figure A.2.4-2 Comparison of IEHeat air source heat pump COP with datasheet values

The **ground source heat pump** replaces the moist air inlet and fan on the warm-side of the evaporator with a water/mono-ethylene-glycol (anti-freeze) mix pumped through heat exchange loop(s) buried horizontally under configurable depths of ground – the material properties of which can be set to match the local soil and near-surface geology. The undisturbed ground temperature at various depths is used as a lateral boundary condition for each layer of soil or rock above, around and below the heat exchange tubing layer.

It is expected that heat pump performance will improve over the coming decades (with reduced mechanical and heat losses, use of turbo-expanders etc.) but no allowance has been made for this unknown in this study.

The heat pump is typically used in combination with a **stratified hot water tank** with optional immersion (resistive) heaters and a heat exchange coil supplied by hot water from the main heat source. The model allows for insulation around the tank, convection and conduction between discretized layers, cold water inlet near the base and outlet from the top. The default parameters are based on a popular recent model of stainless steel water cylinder, but can be adjusted to represent a wide range of storage products.

The indirect **Heat Interface Unit (HIU)** model to allow connection to a District Heat Network consists of two separate exchangers for space heating and for instantaneous DHW. The HIU model also includes a pump for the space heating water loop. The DH network tie-in point was considered to be at the street, with distribution heat loss considered only from that point to the HIU. The temperature of the DH supply can be varied as a limited linear function of external air temperature.

A.2.5. Proposed future model enhancements

It is recommended to increase the capabilities of the IEHeat modelling toolkit over time to allow more complete analysis of domestic heat transformations. Examples of features suggested for development include:

- Improve comfort metrics, adding radiative effects, mal-distribution of room air temperature and effects of humidity and air flows
- Include emerging thermal storage technology (e.g. phase-change materials)
- Model solar thermal & PV, with electric battery storage
- Include the effects of mechanical ventilation with heat recovery (MVHR)
- Include the effects of rain and wind more completely
- Include home cooling technologies

Finally, the credibility and fidelity of IEHeat should be continuously enhanced by verification against real data for installed heat pumps, hybrids and other technologies in a range of settings.

A.2.6. Upgrade Analysis modelling approach

The modelling work undertaken for the Upgrade Analysis consisted of modelling five houses representing a broad range of the UK housing stock. The data for the houses was assembled from surveys conducted with cooperative households who took part in the HEMS trial conducted as part of SSH Phase 1, over the winter of 2016/17. The Home Energy Management System (HEMS) was used to control (multizone) and monitor the heating systems in 30 houses. To facilitate efficient modelling, ensure anonymity and to provide sufficient variety for the study, some characteristics of the houses and household behaviour have been simplified, swapped and adjusted, with care being taken not to invalidate the learning and conclusions that may be achieved by modelling such "pastiches". Houses A to E do not, therefore, represent any of the individual houses in the trial, but should provide believable, realistic examples typical of the UK housing stock.

Table A.2.6-1 Upgrade Analysis houses as modelled

House	Type	Floor Area (total, heated), m^2	Number of heated spaces [1]	Current state of building fabric
A	1950s semi	97.5, 93.0	8	Inadequate insulation, old windows & doors
B	1920s mid-terrace	67.6	6	No wall or floor insulation, old windows & doors
C	1930s semi	124.5, 100.3	7	No wall or floor insulation, new windows & doors
D	1970s mid-terrace	76.1	7	No wall or floor insulation, old windows & doors
E	1980s detached	148.6, 129.8	11	Loft insulation below modern standard, old windows & doors downstairs, heated conservatory

Note 1: includes hall/stairs/landing (as a single space) if heated

Input data summaries (in **Appendix 3**) are provided for reference for each example house modelled in the Upgrade Analysis study.

Once the base case models had been built, their performance was sense-checked against the data recorded as part of the HEMS trial to ensure similar room temperature behaviour was observed. This exercise showed good agreement between the models and data, after adjusting for the changes made to houses and household behaviour, such as ensuring internal door positions were matched to those indicated in the original survey responses.

The house surveys and technology suitability assessments indicated which building fabric upgrades and heat source options were likely to work in each house. The models were run, using scripts to run multiple cases and extract a subset of results to "csv" files, to first set a base line (with single zone and multizone control options), and then to evaluate changes to the building fabric. To give a valid comparison between the options evaluated, the following approach has been taken:

- All boundary conditions (e.g. weather, household profiles) kept the same in all directly compared simulations
- a harsh mid-winter two week period in Newcastle-upon-Tyne was chosen for most cases, with typical mean annual weather data also used for selected cases
- A small set of parameters varied for each case, representing a single upgrade or a combination of two compatible changes
- Multizone control (which had demonstrated substantial benefits in its own right) also avoids changes near a single thermostat having misleading effects on comfort in other rooms (see **Appendix 4**).

For the typical 14-day simulations used in this study, a maximum sample time of 10 minutes was chosen, with the solver able to use shorter steps for consecutive events with shorter time gaps, to ensure heat source and household behaviour was captured in sufficient detail. In IEHeat it is possible to choose other sample times but the impact on accuracy, detail and execution speed need to be taken into account.

The mid-winter evaluations were checked for key cases against results from runs extended over an entire year. These were performed by running two weeks in every four (to reduce total execution time) and the energy consumption extracted from the second week of each set of results. This avoided interference from initial conditions which were estimated for each case. In most cases the changes in annual energy consumption were similar to those for the equivalent mid-winter cases.

Once the impact of individual changes had been quantified, combinations of upgrades were simulated in an attempt to achieve significant energy savings, good comfort and short warm-up times with a combi boiler, in preparation for changing to alternative heat sources. Finally investigations were made into replacing (or supplementing) the gas boiler with potentially lower carbon heat sources, primarily heat pumps.

In order to compare the performance of the upgrades, a number of **metrics** were extracted from the IEHeat results. Clearly energy consumption is important and was recorded for each case, both the gas and electricity used to provide space heating and domestic hot water, and the heat output for both of these uses. Calculations of boiler efficiency and heat pump COP were made at the boundaries of the heat source, with heat losses within (especially from DHW storage) reducing the effective values, compared to those expected from the boiler or heat pump alone.

To indicate thermal comfort, average room temperature was used as the primary indicator (see section **A.2.8**). To make the metric valid, the achieved temperature needs to be compared with the desired temperature, which is available from the multizone control temperature profiles. These profiles set a range, or temperature band, within which the system should maintain room temperature during periods of heat demand. In this study, an arbitrary (but not untypical) band of 2 °C has been used between the maximum (off) and minimum (on) temperature profiles. A comfort metric indicating an average success in achieving the desired room temperature was calculated as the fraction of time room temperature is below the lower boundary of the band when the profile requires the room to be warm, over the duration of the simulation. The fraction of time when the temperature was above the desired band was also recorded, but was not usually relevant to the evaluation of measures designed to reduce heat losses. Additional comfort metrics used when appropriate included warm-up time (measured from when the heating is turned on in a room to when that room's temperature enters the 2 °C band) and deviation from the maximum temperature setting (i.e. the top of the band). Note that rooms without heating cannot have such metrics, since they have no defined heating profile against which to compare the room temperature. The choice of metric to compare varies with the nature of the changes and results: sometimes the maximum warm-up time is more revealing than an average comfort metric, but sometimes this may be over sensitive, in unexpected ways, to small changes. For example, a small improvement in warm-up time in one room can reveal a clash of timing between DHW demand and warm-up of another room, especially if the warm-up tends to flatten-out somewhere close to the lower limit of the desired band, such that a small reduction in temperature can make a large difference to warm-up time.

A.2.7. Typical simulation results

The table below shows a summary of some of the energy consumption results from the simulations, indicating the reduction in energy used, relative to the base case, to achieve at least as good, but in most cases significantly better, thermal comfort. The differences in energy savings between "full fabric upgrades" and the ASHP cases are a combination of removing the losses from a gas boiler (typically 9-11% for a condensing boiler) and the performance of the heat pumps (typically producing about 2.5 times more useful heat than energy input). Note not all the heat source options studied are shown in the table. More detailed results for each house are included in **Appendix 5**.

Table A.2.7-1 Summary of energy consumption (typical mean Newcastle-upon-Tyne weather)

House	Annual energy consumed for heating and DHW, kWh (% saving wrt SZ base case)			
	Base case single zone	**Base case multizone**	**Full fabric upgrades[2]**	**Heat source change**
A	14668	13774 (6%)	11047 (25%)	4043 (72%) [ASHP]
B	17024	15427 (9%)	9817 (42%)	3163 (81%) [ASHP], 7917 (53%) [DH]
C	14969	13187 (12%)	9842 (34%)	3695 (75%) [ASHP]
D	14087	14897[1] (-6%)	11320 (20%)	3909 (72%) [ASHP]
E	16320	16774[1] (-3%)	14948 (8%)	4995 (69%) [ASHP]

Notes: 1 - increases in desired or achieved room temperatures can increase energy consumption with multizone control, but also provide improved comfort; 2 – includes multizone control and radiator upgrades (where recommended).

The table below indicates typical energy savings predicted by the simulations for building fabric upgrades deemed feasible for each house. Note not all these fabric upgrades were included in the final pathways, and further improvements were gained by heating system upgrades not included in the table.

Table A.2.7-2 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%

A.2.8. Using average room temperature for comfort metrics

In this work average room temperature has been used as a measurement of "comfort" in order to allow comparisons between the many simulations of various upgrade options.

It is known from experiments under controlled laboratory conditions, that thermal comfort is influenced by much more than air temperature[46]. Environmental factors include radiant heat, relative humidity and air flow, for example. Temperature distribution will also be important, especially vertical variations (people may prefer warmer floors and cooler air at head height, for example). However, there have been remarkably few experiments conducted in naturalistic environments, such as people's homes. Clearly these factors will play a role, but the actions people take to get comfortable – adjusting clothing, moving around, consuming hot food, as part of what is often called 'adaptive comfort' – will also be likely to play a significant role. People enjoy the experience of sitting by a warm fire, or hot radiator, and complain that drafts make them feel cold, but as yet it has not been possible to specify quantifiable metrics that can be included in this modelling work. They can also grow to "like what they have" and falsely justify their preferences, which complicates quantification still further.

ESC research also indicates that people use heat for various reasons other than getting comfortable[47]. For instance, to demonstrate hospitality, relieve pain and protect their property from damage. Indeed, it may be expected that households would prefer heating regimes that maintained higher ambient temperatures throughout their home if this reduced the risk of pipes freezing or damp damaging walls. Some people also use radiators to dry their laundry. There are qualitative reports that some people dislike losing this ability if their radiators are removed when installing a new heating system. Alternatives would have to be found, for instance hanging laundry above baths, or on electrically heated clothes horses. It should be noted that this study does not include significant analysis of these issues, nor the impact of wet clothing on heat transfer to rooms. Further study, combining data gathering from real homes with detailed modelling, is recommended to better characterise meaningful measures of domestic comfort.

[46] Haines, Lawton, Spencer (Loughborough University), 2014, "Domestic Thermal Comfort Literature Review, Findings Report", Rev C, for ETI.

[47] Lipson, 2017, http://www.eti.co.uk/smart-systems-and-heat-consumer-challenges-for-low-carbon-heat/

Appendix 3. Input data summaries for Upgrade Analysis example houses

The following tables show the principle input data used for the base case of each example house modelled in the Upgrade Analysis. Layout sketches can be found in results summaries for each house.

A.3.1. Notes and abbreviations:

Azimuth: angle the front of the house faces, relative to south, e.g. 90° = west facing, 180° = north facing etc.

Windows: "DG" = double glazed, "SG" = single glazed, "old" = pre-2002 regulations change, "new" = post-2002

Doors: for internal doors, to avoid duplication, these are defined in rooms where they appear in left and front walls or ceilings.

Wall identifiers: "left" and "right" are as seen when facing the front of the house, square brackets (e.g. "[1]") are used to indicate the segment of a wall in which a window or door is located.

Radiators: "DPDC" = double panel, double convector, "SPSC" = single panel, single convector, etc., TR= towel rail.

A.3.2. House A: 1950s semi-detached

Table A.3.2-1 House A general data

Wall insulation	cavity wall insulation only in right wall of main house and in extension walls
Floors (ground floor)	solid, no insulation
Loft insulation	75 mm
Azimuth	33°

Table A.3.2-2 House A room data

Parameter		**Living Room**	**Dining Room**	**Hall**	**Kitchen**[1]	**Porch**	**Utility**	**Landing**	**Front Bedroom**	**Back Bedroom**	**Spare Bedroom**	**Bathroom**
Height, m		2.327	2.327	2.327	2.327	2.19	2.19	2.392	2.392	2.392	2.392	2.392
Length, m (front to back)		4.054	3.064	2.222	4.0085	1.744	1.475	3.048	3.814	4.055	2.575	2.126
Width, m (left to right)		5.39	4.501	2.888	2.418	1.246	1.562	2.438	2.838	2.838	2.438	2.446
Windows	Wall	Right	Right		Front	Front			Front	Back	Back	Front
	Type	DG, old	SG		DG, old	SG			DG, old	DG, old	DG, old	DG, old
	Height, m	0.979	0.429		1.161	2.1			1.12	1.12	1.12	1.12
	Width, m	1.51	1.5		1.901	0.33			1.895	1.894	1.895	1.898
Door 1	Wall	Front [1]	Front[2]	Front[4]		Front[4]		Front [1]	Left	Left	Front	
	Height, m	0.65	2.095	2.186		2.1		2.1	2.1	2.1	2.1	
	Width, m	1	3.166	0.85		0.841		0.78	0.78	0.78	0.78	
Door 2	Wall	Front [2]	Back[3]	Left		Left[5]		Front [2]				
	Height, m	2.1	2.114	2.1		2.1		2.1				
	Width, m	0.78	3.082	0.78		0.78		0.78				
Door 3	Wall			Ceiling[6]								
	Height, m			1.244								
	Width, m			1.06								
Radiators	Type	DPSC	DPSC	DPDC					SPSC	DPDC	DPSC	TR
	Wall	Front [1]	Left	Left [2]					Front	right	back	left
	TRV present?	Y	Y	Y					Y	Y	Y	N
	Length, m	1.7	1.4	0.6					1.2	1	0.6	0.6
	Height, m	0.6	0.6	0.6					0.6	0.7	0.6	1.2
	Nominal power, W	3494	2877	1651					1577	3210	1233	540
Flow (hot) pipe from boiler or previous radiator	Length, m	7.4265	7.454	4.351					2.99	7.814	6.093	2.726
	Elevation change, m	0	0	0					2.19	0	0	0
	Internal Diameter, mm	13.6	13.6	13.6					13.6	13.6	13.6	13.6
	Insulation, mm	0	0	0					0	0	0	0
	Length, m	9.1265	6.054	3.751					4.19	5.614	4.493	2.126

Parameter		**Living Room**	**Dining Room**	**Hall**	**Kitchen**[1]	**Porch**	**Utility**	**Landing**	**Front Bedroom**	**Back Bedroom**	**Spare Bedroom**	**Bathroom**
Return (cold) pipe to boiler or next radiator	Elevation change, m	0	0	0					-2.19	0	0	0
	Internal Diameter, mm	13.6	13.6	13.6					13.6	13.6	13.6	13.6
	Insulation, mm	0	0	0					0	0	0	0

Notes: 1 – although not containing a radiator, the kitchen has an opening above the living room radiator and so is counted as a heated room; 2 -sliding glazed doors; 3 – aluminium framed double-glazed sliding doors; 4 – half glazed (single), wooden; 5 – half glazed (single), wooden, always closed; 6 – always open (stairs to landing).

Table A.3.2-3 House A gas boiler data

Type	Condensing gas combi boiler
Gross efficiency at 100% load, max outlet T	87.8%
Gross efficiency at 100% load, min outlet T	93.9%
Maximum load (gross input power)	27.33 kW
Minimum load (gross input power)	8.2 kW (30%)
Mass (dry)	39.5 kg
Water volume, SH path	2.9 litres
Water volume, DHW path	1 litre
Max pump head (after allowing for losses in the boiler)	2 m
Nominal flow	8 litres/min
Head at nominal flow	1.8 m

A.3.3. House B: 1920s mid-terrace

Table A.3.3-1 House B general data

Wall insulation	None
Floors (ground floor)	Suspended timber (living/dining), solid (kitchen), no insulation
Loft insulation	100 mm (main), 50 mm (kitchen extension)
Azimuth	225°

Table A.3.3-2 House B room data

Parameter		Living Room	Dining Room	Kitchen 1	Kitchen 2	Stairs	Landing	Front Bedroom	Back Bedroom	Bathroom
Height, m		2.734	2.734	2.319	2.241	5.669	2.735	2.735	2.735	2.43
Length, m (front to back)		3.295	3.328	3.198	2.692	0.786	3.628	3.295	3.328	2.692
Width, m (left to right)		3.622	3.622	1.961	1.961	3.622	0.875	3.622	2.647	1.961
Windows	Wall	Front	Back	Right	Right			Front	Back	Back
	Type	DG, old	DG, old	DG, old	DG, old			DG, old	DG, old	DG, old
	Height, m	1.98	1.65	1.11	0.74			1.6	1.52	1.13
	Width, m	2.446[1]	1.05	1.025	0.868			1.14	1.08	0.706
Door 1	Wall	Front	Front[2]	Front[2]	Front[3]	Front GF[2]	Front[3]		Left	Front
	Height, m	2.56	2.1	2.1	2	2.1	2.735		2.1	2.1
	Width, m	0.9	0.78	0.78	1.26	0.78	0.875		0.78	0.78
Door 2	Wall			Right		Front 1F				
	Height, m			2.01		2				
	Width, m			0.87		0.78				
Radiators	Type	DPDC	DPDC[4]	DPDC				DPDC	SPSC	DPNC[5]
	Wall	Left	Left	Left				Front	back	left
	TRV present?	Y	Y	Y				Y	Y	Y
	Length, m	1.3	1.3	1				1.3	1.6	0.6

Parameter		**Living Room**	**Dining Room**	**Kitchen 1**	**Kitchen 2**	**Stairs**	**Landing**	**Front Bedroom**	**Back Bedroom**	**Bathroom**
	Height, m	0.6	0.6	0.6				0.5	0.5	0.7
	Nominal power, W	3576	3576	2751				2980	1752	1012
Flow (hot) pipe from boiler or previous radiator	Length, m	4.114	4.198	0.742				8.734	3.222	2.561
	Elevation change, m	0	0	-2.319				0	0	0
	Internal Diameter, mm	13.6	13.6	13.6				13.6	13.6	13.6
	Insulation, mm	0	0	0				0	0	0
Return (cold) pipe to boiler or next radiator	Length, m	5.414	5.498	1.742				10.034	4.222	3.161
	Elevation change, m	0	0	2.319				0	0	0
	Internal Diameter, mm	13.6	13.6	13.6				13.6	13.6	13.6
	Insulation, mm	0	0	0				0	0	0

Notes: 1 – including bay; 2 – half-glazed; 3 – archway (open); 4 – surrounded by wooden box/shelf; 5 - shelf over, blocking convection path.

Table A.3.3-3 House B gas boiler data

Type	Non-condensing gas combi boiler
Gross efficiency at 100% load, nominal outlet T	81.7%
Gross efficiency at 42% load, min outlet T	78.9%
Maximum load (output)	30 kW
Minimum load (output)	12.7 kW (42%)
Mass (dry)	48 kg
Water volume, SH path	1.5 litres
Water volume, DHW path	0.8 litres
Max pump head (after allowing for losses in the boiler)	5 m
Nominal flow	18 litres/min
Head at nominal flow	2.45 m

A.3.4. House C: 1930s semi-detached

Table A.3.4-1 House C general data

Wall insulation	Original house: solid wall (uninsulated) upstairs rendered; Extension & conservatory: cavity wall insulation
Floors (ground floor)	Suspended timber, no insulation, wooden floor coverings
Loft insulation	Main house: 75 mm, no roof felt. Extension: flat roof (uninsulated)
Azimuth	45°

Table A.3.4-2 House C room data

Parameter		Living Room	Kitchen	Hall	Utility	Garage	Conserva-tory	Front Bedroom	Back Bedroom	Spare Bedroom	Bathroom	Landing
Height, m		2.578	2.578	2.578	2.578	2.578	2.578	2.556	2.556	2.556	2.556	2.556
Length, m (front to back)		6.828	2.439	4.289	2.7	1.519	3.209	3.271	3.457	2.439	1.637	2.582
Width, m (left to right)		4.092	5.493	2.326	2.867	2.867	3.771	4.092	4.092	2.326	2.326	2.326
Windows 1	Wall	Back	Back	Front			Back	Front	Back	Back	Front	Left
	Type	DG door, new	DG, new	DG, new			Patio door, DG	DG, new	DG, new	DG, new	DG, new	DG, new
	Height, m	2.05	1.187	1.2			1.96	1.49	1.14	1.113	0.95	1.15
	Width, m	3.07[1]	1.368	1.24			1.5	2.188	1.74	1.17	1.16	0.61
Windows 2	Wall	Front					All external					
	Type	DG, old					DG, old					
	Height, m	1.49					1.337					
	Width, m	2.188					full length					
Door 1	Wall	Left [1]	Front [1]	Front	Front	Front	Front	Left	Left	Front		Front
	Height, m	2.1336	2.1336	2.226	2.1336	2.226	1.96	2.1336	2.1336	2.1336		2.1336
	Width, m	0.83	0.83	0.83	0.83	2.5	0.83	0.83	0.83	0.83		0.83
Door 2	Wall		Front [2]	Ceiling[2]								
	Height, m		2.1336	2.2								
	Width, m		0.83	0.9								

Parameter		Living Room	Kitchen	Hall	Utility	Garage	Conserva-tory	Front Bedroom	Back Bedroom	Spare Bedroom	Bathroom	Landing
Radiators	Type	DPDC	DPDC	SPSC				DPSC	SPSC	SPSC	TR	
	Wall	Left [2]	Front [1]	Right				Front	Back	Back	Back	
	TRV present?	Y	Y	Y				Y	Y	Y	N	
	Length, m	1.6	0.9	1.6				1.1	1.1	1	0.5	
	Height, m	0.6	0.6	0.6				0.6	0.6	0.6	1.2	
	Nominal power, W	4402	2476	2102				2261	1445	1314	450	
Flow (hot) pipe from boiler or previous radiator	Length, m	2.6445	2.867	7.638				10.82	3.372	6.017	4.683	
	Elevation change, m	0	0	0				0	0	2.578	0	
	Internal Diameter, mm	13.6	19.6	13.6				13.6	19.6	19.6	13.6	
	Insulation, mm	0	0	0				0	0	0	0	
Return (cold) pipe to boiler or next radiator	Length, m	4.2445	1.967	9.238				11.92	4.472	7.017	5.183	
	Elevation change, m	0	0	0				0	0	-2.578	0	
	Internal Diameter, mm	13.6	19.6	13.6				13.6	19.6	19.6	13.6	
	Insulation, mm	0	0	0				0	0	0	0	

Notes: 1 – includes bay; 2 – always open (stairs to landing).

Table A.3.4-3 House C gas boiler data

Type	Condensing gas combi boiler
Gross efficiency at 100% load, max outlet T	87.6%
Gross efficiency at 40% load, min outlet T	96.0%
Maximum load (output)	24 kW
Minimum load (output)	9.6 kW (40%)
Mass (dry)	44.2 kg
Water volume, SH path	2.5 litres
Water volume, DHW path	1 litre
Max pump head (after allowing for losses in the boiler)	5.25 m
Nominal flow	13.3 litres/min
Head at nominal flow	3.5 m

A.3.5. House D: 1970s mid-terrace

Table A.3.5-1 House D general data

Wall insulation	Uninsulated cavity walls
Floors (ground floor)	Solid floors, no insulation
Loft insulation	100 mm
Azimuth	225°

Table A.3.5-2 House D room data

Parameter		**Living Room**	**Kitchen**	**Hall**	**Back Bedroom**	**Front Bedroom**	**Side Bedroom**	**Bathroom**	**Landing**
Height, m		2.242	2.242	2.242	2.318	2.318	2.318	2.318	2.318
Length, m (front to back)		4.437	2.713	4.437	3.827	3.396	3.323	2.328	1.426
Width, m (left to right)		3.463	5.367	1.804	2.708	2.923	2.424	2.624	2.624
Windows 1	Wall	Front	Back [2]	Front	Back	Front	Front	Back	
	Type	DG, old	DG, old	DG, old	DG, old	DG, old	DG, old	DG, old	
	Height, m	1.5	0.899	1.1	1.309	1.232	1.232	0.823	
	Width, m	2.403	2.1	0.63	1.818	1.24	1.24	1.627	
Windows 2	Wall		Back [1]						
	Type		DG, old[1]						
	Height, m		2						
	Width, m		1.47						
Door 1	Wall	Left	Front	Front	Front [1]			Front	Front [1]
	Height, m	2	2	2	2			2	2
	Width, m	0.8	0.8	0.8	0.8			0.8	0.8
Door 2	Wall			Ceiling[2]					Front [2]
	Height, m			2					2
	Width, m			0.9					0.8
Radiators	Type	DPDC	DPDC	DPDC	DPDC	DPDC	DPDC	DPDC	
	Wall	Back	Left	Right	Back	Front	Front	Front	

Parameter		**Living Room**	**Kitchen**	**Hall**	**Back Bedroom**	**Front Bedroom**	**Side Bedroom**	**Bathroom**	**Landing**
	TRV present?	Y	Y	N	Y	Y	Y	Y	
	Length, m	0.9	0.7	0.7	0.7	0.6	0.6	0.5	
	Height, m	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
	Nominal power, W	2063	1605	1605	1605	1376	1376	1146	
Flow (hot) pipe from boiler or previous radiator	Length, m	5.2485	6.367	3.442	3.796	3.3855	10.092	6.306	
	Elevation change, m	0	0	-2.442	2.442	0	2.442	0	
	Internal Diameter, mm	13.6	13.6	13.6	13.6	13.6	13.6	13.6	
	Insulation, mm	0	0	0	0	0	0	0	
Return (cold) pipe to boiler or next radiator	Length, m	5.4485	7.067	4.742	4.496	3.3855	10.692	6.106	
	Elevation change, m	0	0	2.442	-2.442	0	-2.442	0	
	Internal Diameter, mm	13.6	13.6	13.6	13.6	13.6	13.6	13.6	
	Insulation, mm	0	0	0	0	0	0	0	

Notes: 1 – fully glazed patio doors; 2 – always open (stairs to landing).

Table A.3.5-3 House D gas boiler data

Type	Condensing gas combi boiler
Gross efficiency at 100% load, max outlet T	89.6%
Gross efficiency at 25% load, min outlet T	94.8%
Maximum load (output)	25.6 kW
Minimum load (output)	6.4 kW (25%)
Mass (dry)	29kg
Water volume, SH path	1.2 litres
Water volume, DHW path	0.5 litres
Max pump head (after allowing for losses in the boiler)	3.4 m
Nominal flow	17.3 litres/min
Head at nominal flow	2.7 m

A.3.6. House E: 1980s detached

Table A.3.6-1 House E general data

Wall insulation	cavity wall insulation
Floors (ground floor)	Solid floors, uninsulated in original house
Loft insulation	Main house and single storey extension: 100 mm; New extension: 250 mm
Azimuth	90°

Table A.3.6-2 House E room data

Parameter		Living Room	Kitchen	Hall	Extension	Utility	Garage	Conserva-tory	Front Bedroom	Side Bedroom	Back Bedroom	Study	Bathroom	Ensuite	Landing
Height, m		2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.326	2.326	2.326	2.326	2.326	2.326	2.326
Length, m (front to back)		4.5	3.256	4.5	7.856	3.256	4.5	3.475	5.396	4.5	3.256	2.97	2.3	2.36	2.386
Width, m (left to right)		3.42	4.887	1.367	2.92	2.419	2.419	3.954	2.419	2.811	2.82	1.976	1.967	2.419	1.967
Windows 1	Wall	Front	Back [2]		Front	Back [2]		Left [2]	Front	Front	Back	Front	Back	Back	
	Type	DG, old	DG, old		DG, old	DG, old		DG old[2]	DG, new	DG, new	DG, new	DG, new	DG, new	DG, new	
	Height, m	1.4	1.17		1.01	1.05		2.08	1.2	1.21	1.21	1.21	1.09	1.18	
	Width, m	2.195	1.2		1.8	1.19		1.737	1.8	1.8	1.74	0.88	1.17	1.12	
Windows 2	Wall		Back [1]			Back [1]		All extern.							
	Type		DG old[1]			DG old[2]		DG old							
	Height, m		2.08			2.01		1.362							
	Width, m		1.73			0.79		full wall							
Door 1	Wall	Left	Left	Front	Left [2]	Front	Front	Front		Left [2]	Left [1]		Front	Front	Left
	Height, m	2	2	2.08	2	2	2.1	2.14		2	2		2	2	2
	Width, m	0.8	0.8	0.86	0.8	0.8	1.987	1.8		0.8	0.8		0.8	0.8	0.8
Door 2	Wall		Front [2]	ceiling[3]											Front
	Height, m		2	2											2
	Width, m		0.8	0.9											0.8

Parameter		**Living Room**	**Kitchen**	**Hall**	**Extension**	**Utility**	**Garage**	**Conserva-tory**	**Front Bedroom**	**Side Bedroom**	**Back Bedroom**	**Study**	**Bathroom**	**Ensuite**	**Landing**
Radiators	Type	DPDC	DPDC	DPDC	DPDC			SPSC	SPSC	DPDC	SPSC	SPSC	TR	TR	
	Wall	Back	Front [2]	Left	Front			Back	Front	Front	Back	Front	Right	Front	
	TRV present?	Y	Y	N	Y			Y	Y	Y	Y	Y	N	N	
	Length, m	1.8	1.4	0.7	1.6			1.7	1.8	1.6	1.8	0.9	0.6	0.45	
	Height, m	0.6	0.6	0.6	0.6			0.3	0.6	0.6	0.6	0.6	1.1	0.8	
	Nominal power, W	4952	3851	1926	4402			1117	2365	4402	2365	1183	495	270	
Flow (hot) pipe from boiler or previous radiator	Length, m	0.5	6.534	7.037	15.285			7.731	6.396	5.652	2.02	2.811	3.57	6.349	0.5
	Elevation change, m	0	0	0	0			0	0	0	0	0	2.57	2.57	0
	Internal Diameter, mm	13.6	13.6	13.6	13.6			13.6	13.6	13.6	13.6	13.6	13.6	13.6	13.6
	Insulation, mm	0	0	0	0			0	0	0	0	0	0	0	0
Return (cold) pipe to boiler or next radiator	Length, m	2.3	7.934	7.737	15.185			9.431	8.196	7.252	3.82	2.111	4.17	6.799	
	Elevation change, m	0	0	0	0			0	0	0	0	0	-2.57	-2.57	
	Internal Diameter, mm	13.6	13.6	13.6	13.6			13.6	13.6	13.6	13.6	13.6	13.6	13.6	
	Insulation, mm	0	0	0	0			0	0	0	0	0	0	0	

Notes: 1 – patio door (sliding); 2 – fully glazed door; 3 - always open (stairs to landing).

Table A.3.6-3 House E gas boiler data

Type	Condensing gas combi boiler
Gross efficiency at 100% load, max outlet T	87.9%
Gross efficiency at 40% load, min outlet T	95.4%
Maximum load (output)	30.7 kW
Minimum load (output)	13.2 kW (43%)
Mass (dry)	44.5 kg
Water volume, SH path	2.2 litres
Water volume, DHW path	1 litre
Max pump head (after allowing for losses in the boiler)	5 m
Nominal flow	16.7 litres/min
Head at nominal flow	2.55 m

A.3.7. Desired room temperature profiles

Charts shown in Figure A.3.7-1 to Figure A.3.7-10 show the base case temperature profiles used for each house in the Upgrade Analysis modelling, approximated from combined sets of HEMS-trial data. The profiles represent the upper temperature limit of the control band desired for each room in each house for a 7-day cycle (the multizone control attempts to achieve room temperatures within a 2 °C band below this temperature, and has pre-heat times defined to allow the rooms to reach their desired range by the beginning of the "warm-times" defined by these profiles).

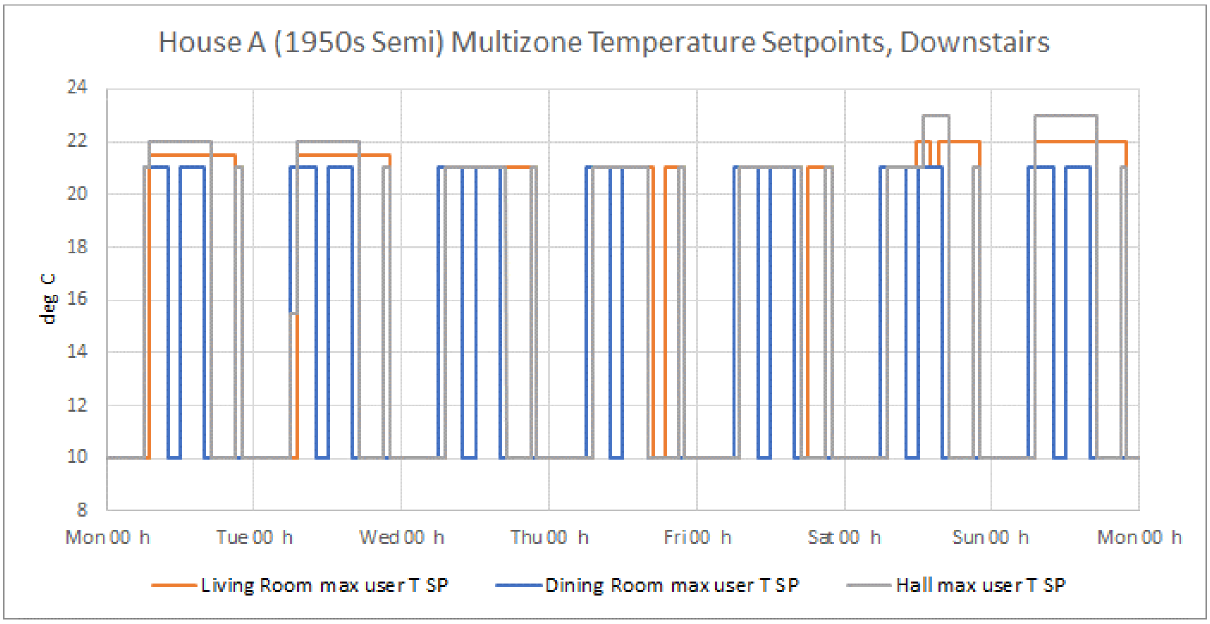

Figure A.3.7-1 House A temperature demand profile (top of control range) for a representative winter week for downstairs rooms

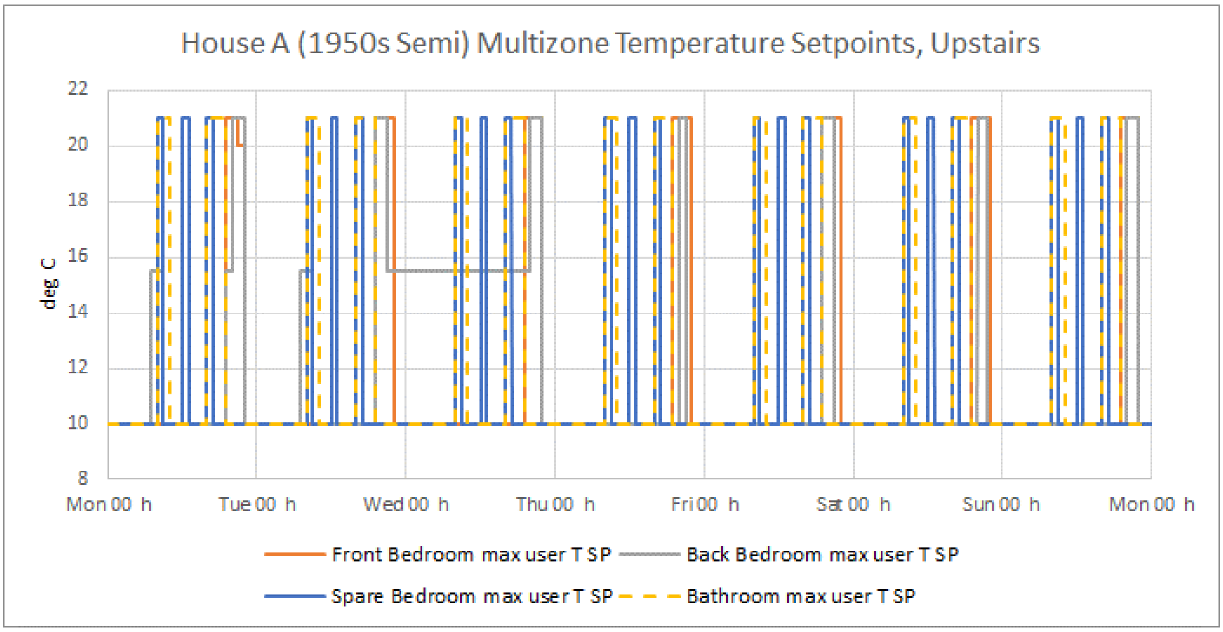

Figure A.3.7-2 House A temperature demand profile (top of control range) for a representative winter week for upstairs rooms

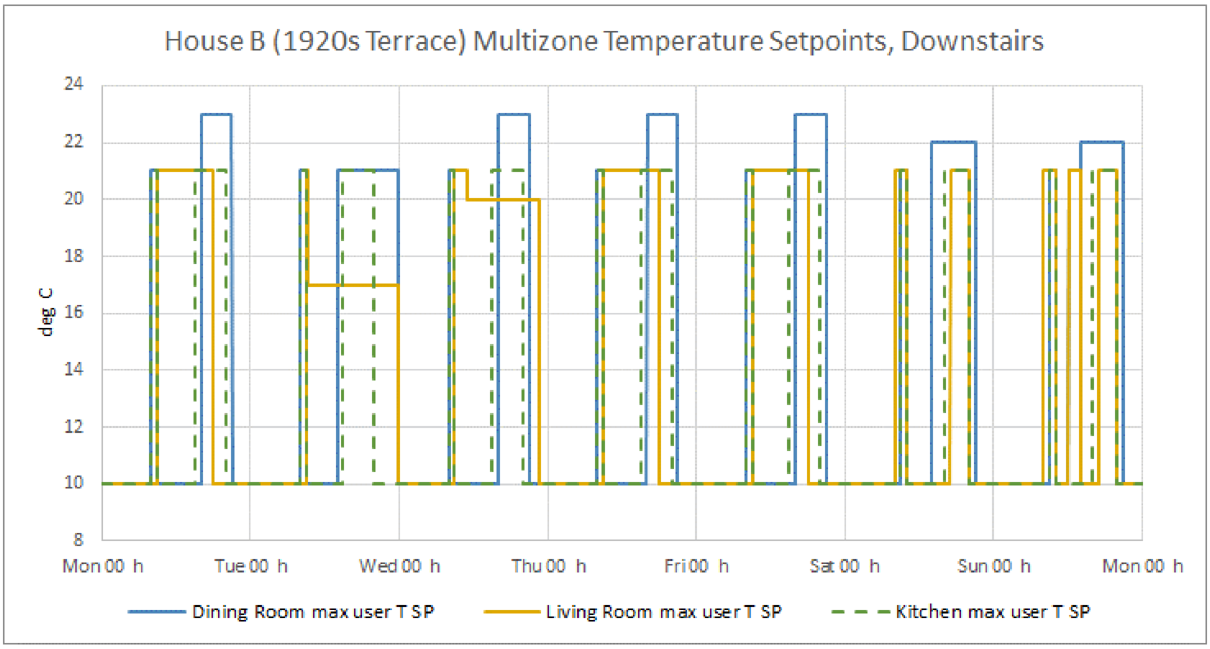

Figure A.3.7-3 House B temperature demand profile (top of control range) for a representative winter week for downstairs rooms

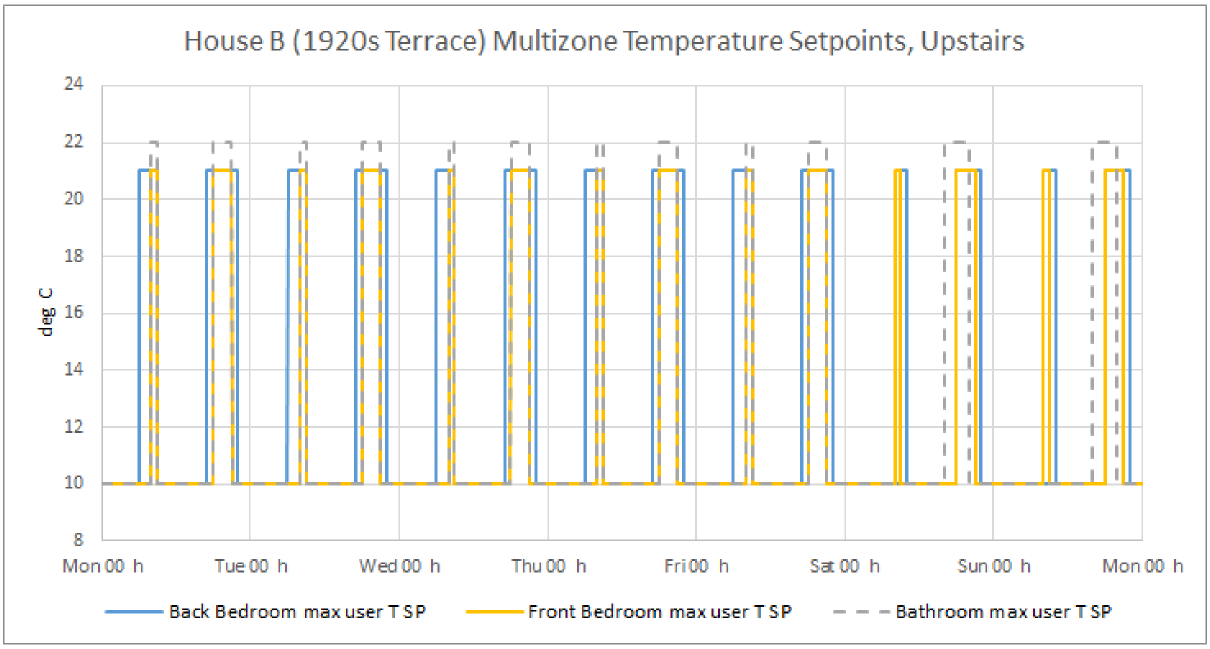

Figure A.3.7-4 House B temperature demand profile (top of control range) for a representative winter week for upstairs rooms

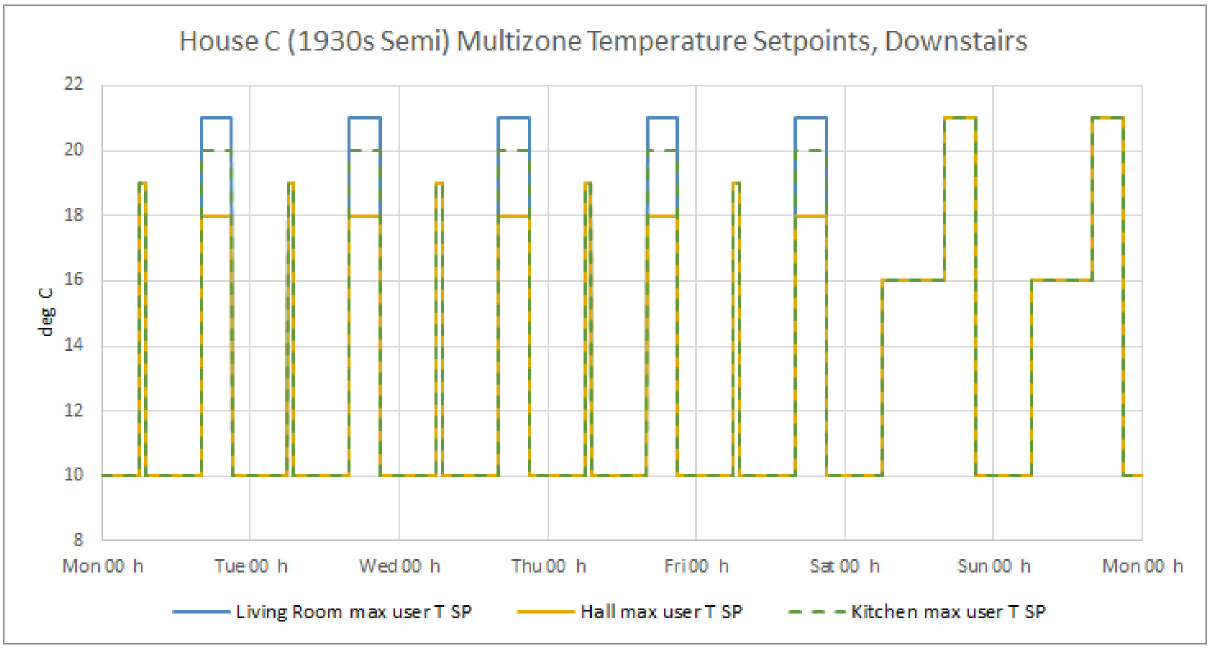

Figure A.3.7-5 House C temperature demand profile (top of control range) for a representative winter week for downstairs rooms

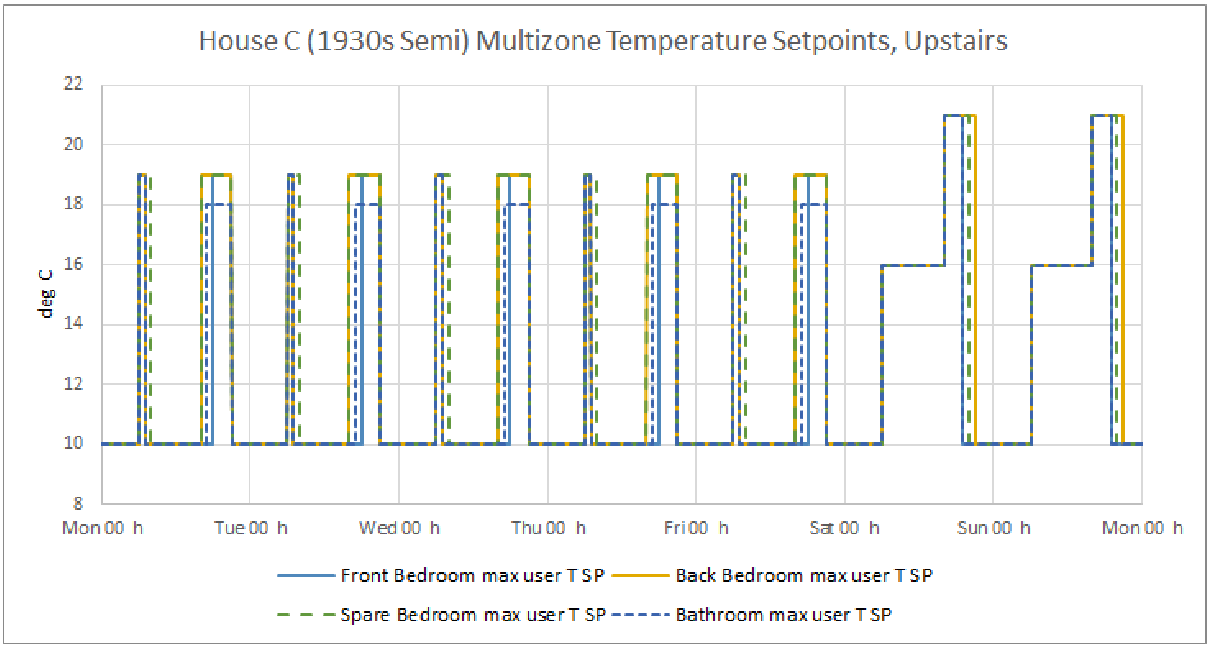

Figure A.3.7-6 House C temperature demand profile (top of control range) for a representative winter week for upstairs rooms

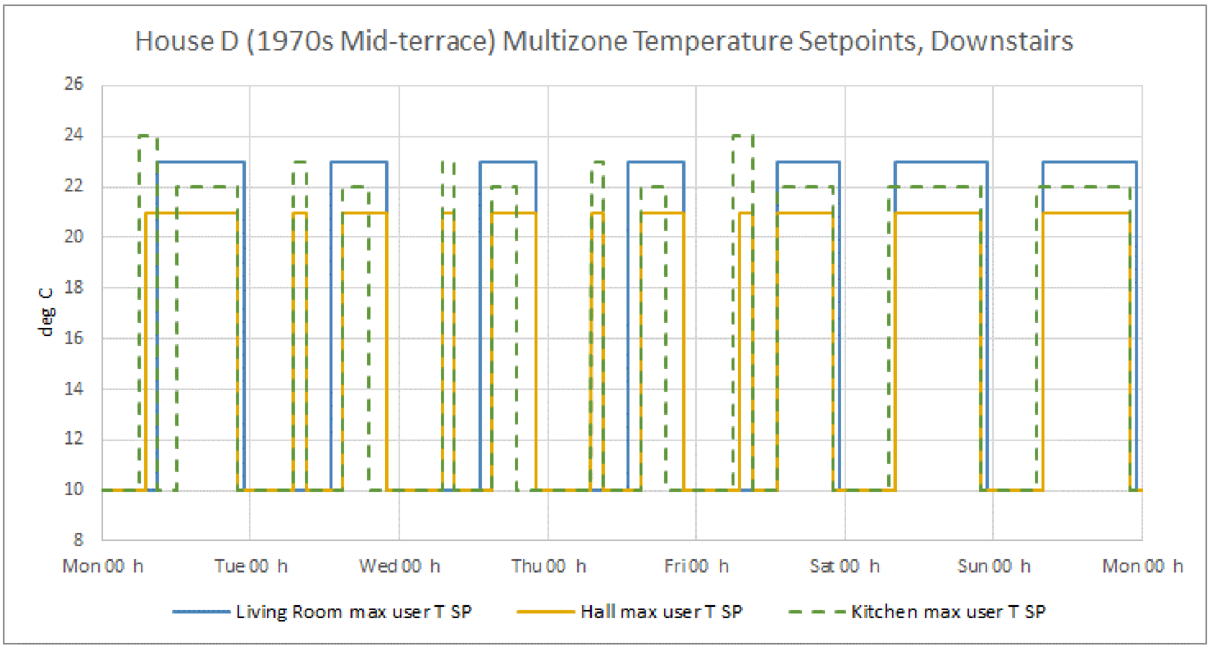

Figure A.3.7-7 House D temperature demand profile (top of control range) for a representative winter week for downstairs rooms

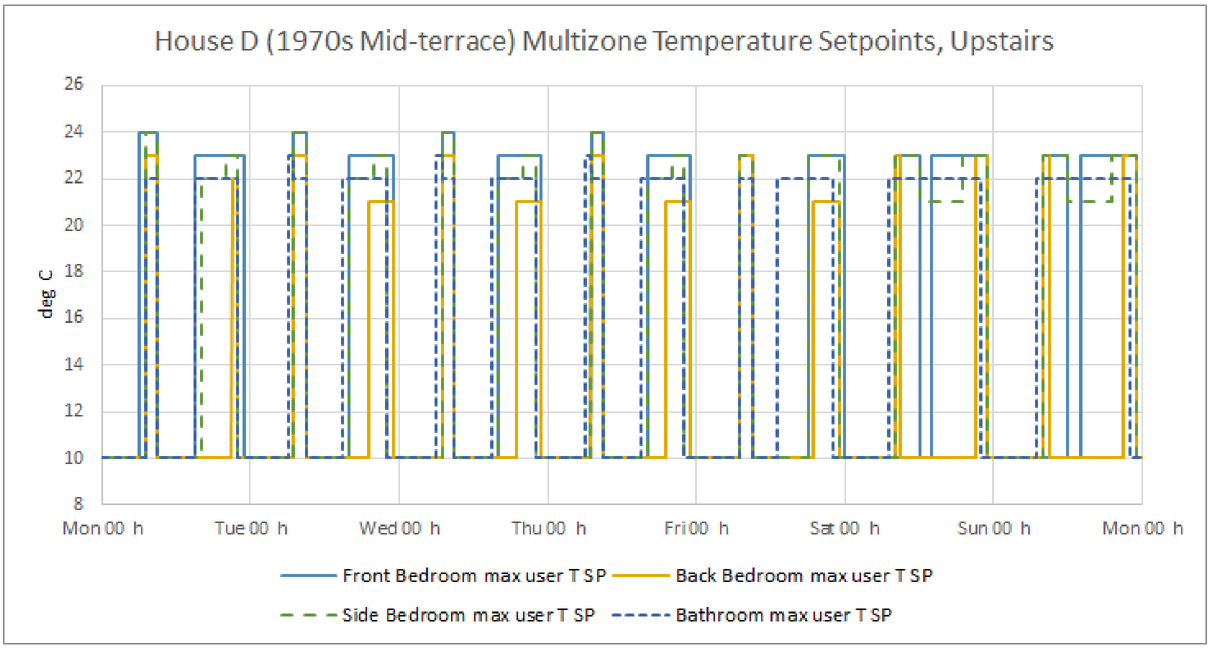

Figure A.3.7-8 House D temperature demand profile (top of control range) for a representative winter week for upstairs rooms

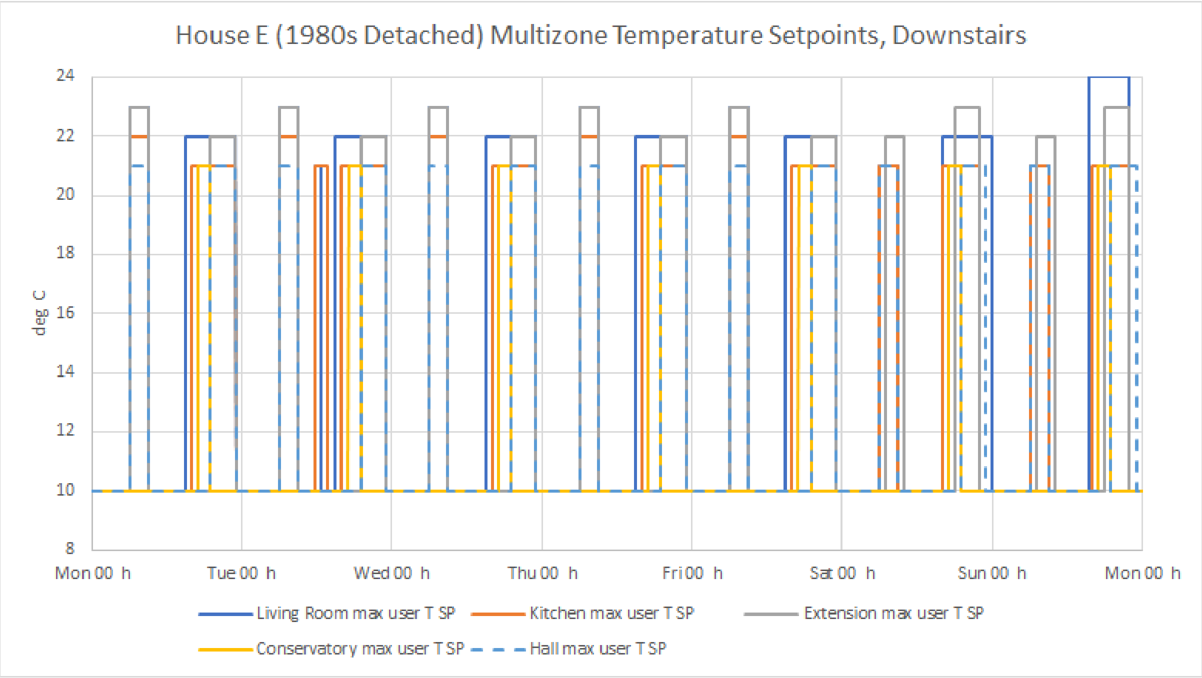

Figure A.3.7-9 House E temperature demand profile (top of control range) for a representative winter week for downstairs rooms

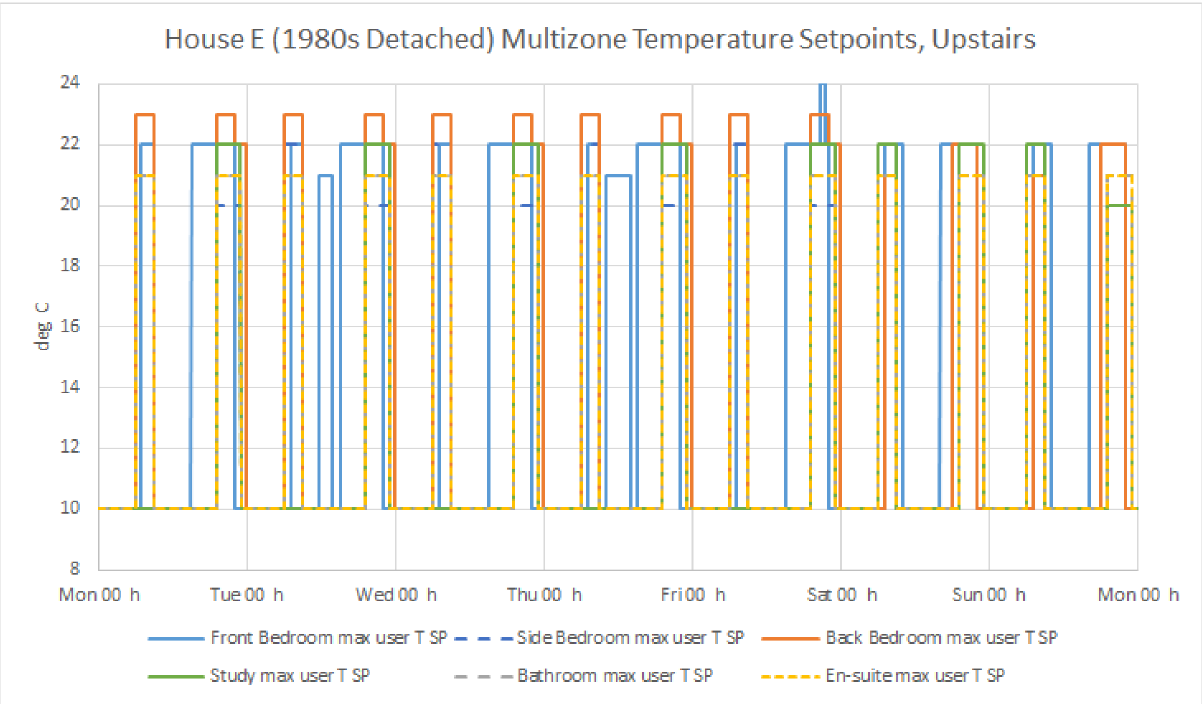

Figure A.3.7-10 House E temperature demand profile (top of control range) for a representative winter week for upstairs rooms

A.3.8. Air temperature data used (typical mean year in Newcastle-upon-Tyne)

Figure A.3.8-1 and Figure A.3.8-2 show the dry bulb air temperature used in the simulations. The weather data files used also include insolation, wind direction and velocity, and humidity.

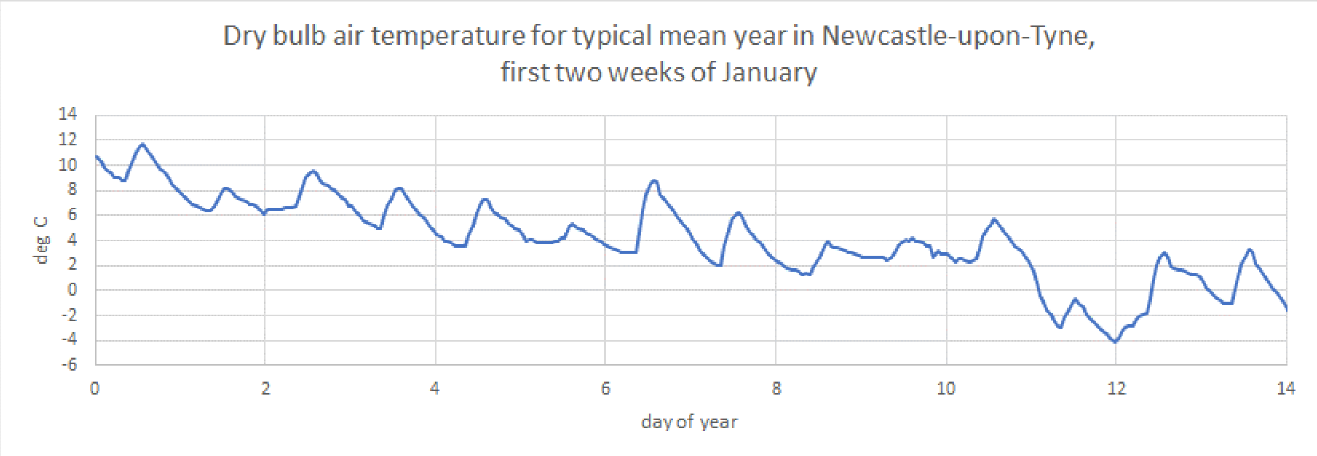

Figure A.3.8-1 - Two weeks' mid-winter external temperature data

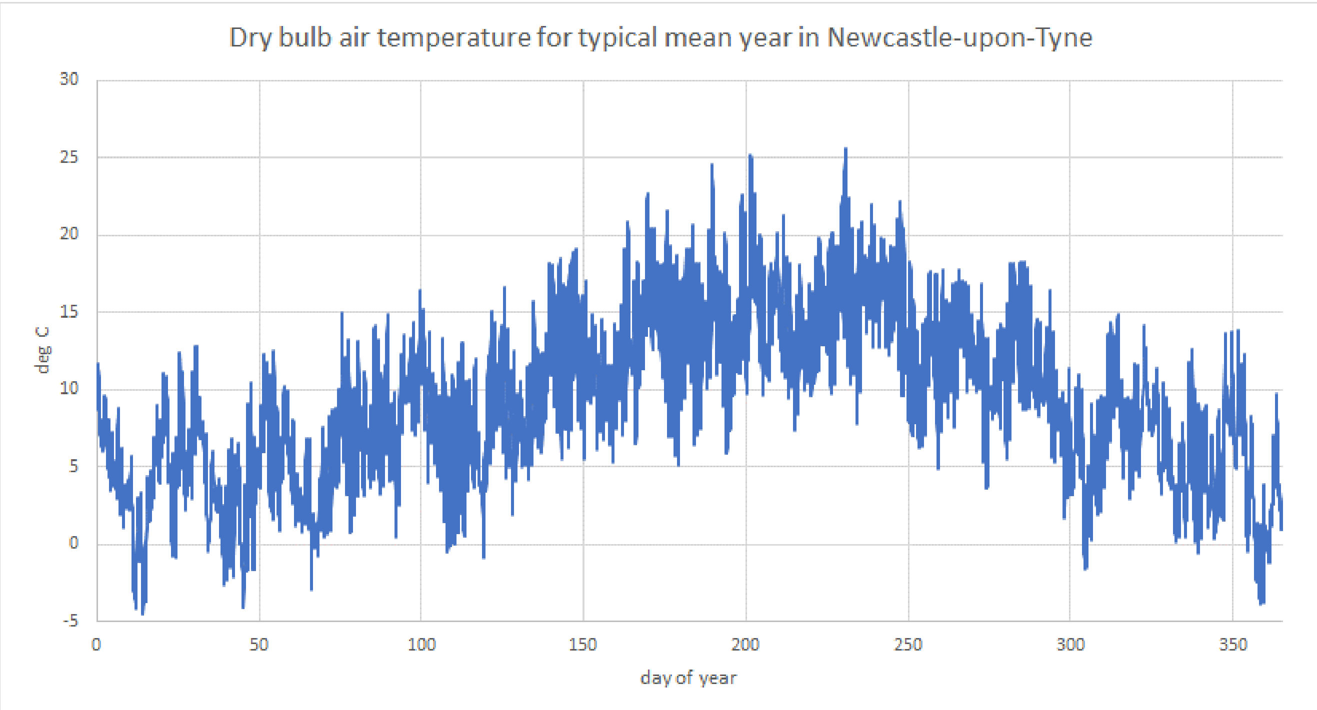

Figure A.3.8-2 – One year's external temperature data

Appendix 4. Technical note: comparison of single thermostat with TRVs versus multizone on/off control for upgrade evaluations

The following note explains some of the insights gained using IEHeat within the Upgrade Analysis work, regarding the comparison between typical single zone control and simple multizone control. Some discussion is also included of practical aspects of installing multizone control.

A.4.1. Definitions

The following terms are defined below in detail to aid understanding of how they are used in the context of this technical note and the Upgrade Analysis Report:

TRV: thermostatic radiator valves are very common on wet radiators to adjust the flow to the radiator to influence the impact of the radiator on room temperature. They are inherently proportional-only control devices since they work by the expansion of a plug of wax (or equivalent) acting to deflect the valve position from an adjustable "zero point" in response to the temperature around the valve head. As such they do not control to an exact temperature: the settings are often numbered (e.g. 1-5) and the offset from the "data sheet" temperature relating to this setting will depend on radiator size, balancing, inlet temperature, room characteristics etc. To have an effect on room temperature, TRVs rely on being able to reduce radiator power output as the flow rate is adjusted.

Single zone control: is shorthand for the standard approach used in many UK homes with gas boilers, using a single room thermostat (e.g. in the hall or living room) which decides whether the boiler space heating is on or off, with TRVs on most radiators (usually not the one near the room thermostat). If the thermostat includes a "programmer" the householder is able to set a single time series of temperature setpoints (which may allow different time series for different days of the week). Each TRV has its own setting (adjusted by the occupant) which is assumed to be fixed during each simulation being discussed here.

WRV: wireless radiator valves, currently available from several suppliers, can be used with multizone control to dramatically reduce control signal wiring throughout the house.

Multizone control: is shorthand for on/off control of each radiator separately, using a thermostat in each room, each with a separate time series of temperature setpoints, to actuate a WRV on that room's radiator. Note that alternatives exist, such as incorporating the radiator valve and room thermostat and timer in a single device. This has equivalent behaviour provided the heat source is set to turn on when any of the radiator valves will be operating, and can automatically turn itself off when no heat is demanded (e.g. based on return temperature).

Control band: in the current modelling work, both control approaches use a 2 °C gap between switching the heating on or off. When people discuss the required temperature (setpoint) they are often implicitly referring to the maximum temperature of a range (the "off temperature") but sometimes a temperature setting will be in the middle of the control band. In IEHeat the bounds of the range are separately defined – i.e. the maximum ("off") and minimum ("on") temperatures. The gap on typical home heating thermostats ranges from 1 to 2 °C (US manufacturers often use a control band of +/- 1°F, which gives a total width of 1.1 °C). The gap can be adjusted in the model to match user or equipment requirements, but its size is not critical to the insights discussed in this technical note, or indeed to the conclusions of the Upgrade Analysis.

Upgrade evaluation cases: a series of simulations run under identical conditions save for one parameter (or a combination of a small number of parameters) which are changed to show the impact of these changes on energy consumption and comfort in a house.

A.4.2. Impact of control approach on upgrade evaluation simulation results

To quantify the effects of various possible changes to the example houses modelled for this study, evaluation cases have been run with room temperatures and energy usage results being recorded. Simple metrics were included to allow a summary table of results to be produced for each set of cases, allowing quick and reliable comparisons to be made. For example, it is straightforward to calculate the total energy consumption (in kWh) over a two-week winter period for each case and compare the impact of each change. Quantifying "comfort" is more complicated, but the main approach being used at present in IEHeat is to report the fraction of time when a room temperature is outside its control band (relative to the time the profile requires the room to be warm). Often the "too cold" fraction (fraction of time below the minimum temperature of the control band) is more useful for comparing measures to reduce heat losses and improve warm-up times, and especially when using lower temperature heat sources. Furthermore, the "too hot" fraction is of less relevance when using multizone control since over-heating by the heating system is almost eliminated (see below) and no cooling system (or temperature-dependant window opening) is modelled to combat over-heating in hot weather.

When looking at the results of evaluation cases using single zone control, comparing simple comfort metrics can give unexpected results which reinforce the case for using multizone control, but also may be misleading when trying to quantify the benefits of building fabric upgrades. An example is taken from a 1950s semi-detached house with a single thermostat in the hall, old/thin doors from hall to porch and from porch to outside. If the front doors of this house were updated then the single thermostat would turn the heating off in response to the significantly warmer hall, before other rooms were heated to their target temperatures. This is clearly not an issue with multizone control –Figure and Figure A.4.2-2, show the single zone control gives colder living room temperatures for the cases with upgraded doors. This would result in a larger than expected energy saving from the door upgrade with the existing control, thanks to the lower temperatures (and poorer comfort) in the rest of the house. Conversely extra insulation away from the single thermostat (for example) could lead to some rooms being over-heated by single zone control, perhaps even resulting in an increase in energy consumption (especially if the occupants open windows to compensate). This problem would be largely eliminated by multizone control, as would the other obvious issue with single control of heating some rooms even when not required.

As a result of these observations, evaluation cases comparing building fabric upgrades used multizone control, to ensure the results could be directly related to the long-term benefits of the upgrade. Moreover, the upgrade to multizone control has been recommended in all pathways.

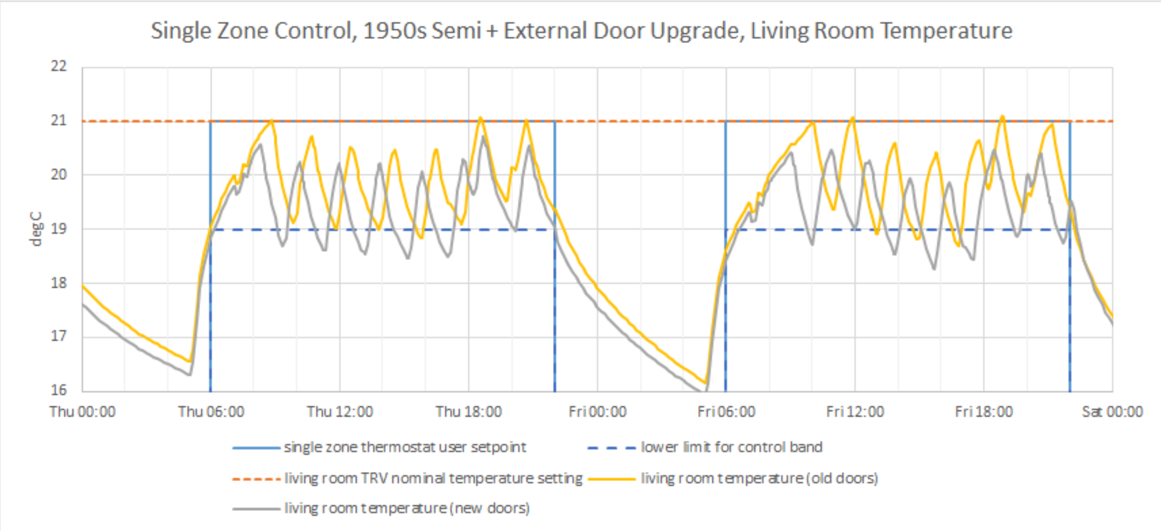

Figure A.4.2-1 – single zone control (thermostat in hall) gives colder living room temperature with new front door

Note: chart variables labelled "...user setpoint" represent the periods during which the householder wants the room to be warm, whereas the heating control pre-empts the start of these periods by a "pre-heat time".

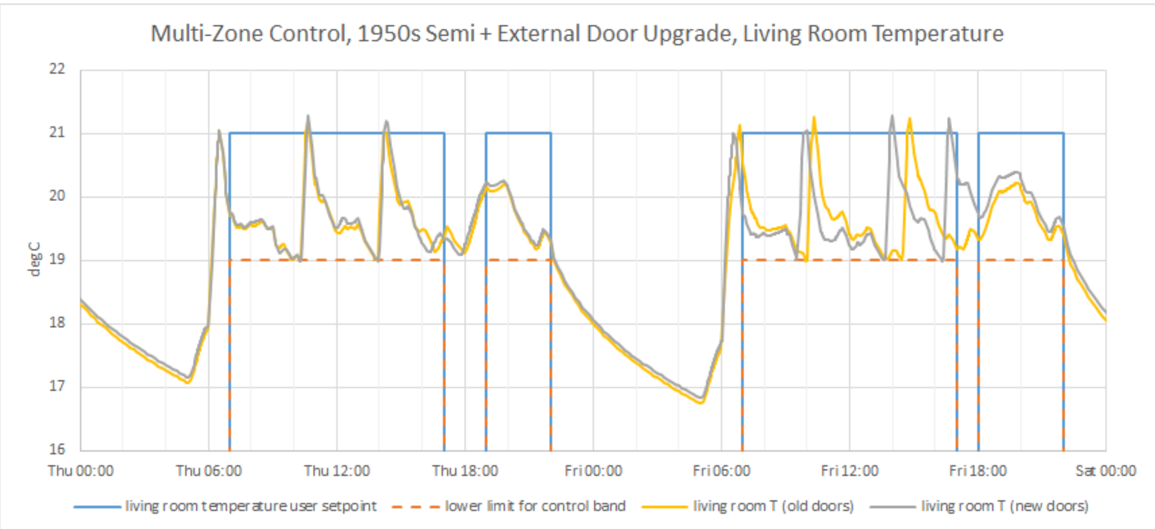

Figure A.4.2-2 - multizone control keeps living room temperatures inside control band with and without front door upgrade

A.4.3. Influence of TRVs (thermostatic radiator valves)

Another finding of note regarding multizone direct control of radiator valves is that it reduces the onerous task of balancing the radiator network – something which single zone control requires in order to get all rooms warming at roughly the same time (and hence not over or under heating any rooms).

While TRVs offer the possibility for occupants to adjust the power delivered to each radiator, they do not completely remove the risk of under- and over-heating (see definitions above) and can actually reduce the performance of the heating system - since some radiators in a house (particularly when not all radiators are appropriately sized) will have to operate on the relatively steep part of the radiator power curve much of the time (see Figure A.4.3-1), reducing the potential power output of the radiators.

Radiator balancing will always be a compromise between different objectives, and will only achieve synchronised warm up for one set of TRV settings, room thermostat setting and weather conditions.

Again, using multizone control avoids these issues by allowing use of higher radiator water flows (by fully opening the WRV) when warming a room and turning it off at a point specific to only that room, thus maximizing the power emitted by each radiator when it is required to provide heating. The elimination of the sensitivity to balancing is a significant benefit for multizone control over single zone, especially considering the difficulty in balancing radiator networks, and the impossibility of finding a criterion for achieving a balance that covers all requirements (the standard advice to heating engineers, based on radiator temperature difference during warm-up, works well only if all radiators are correctly sized).

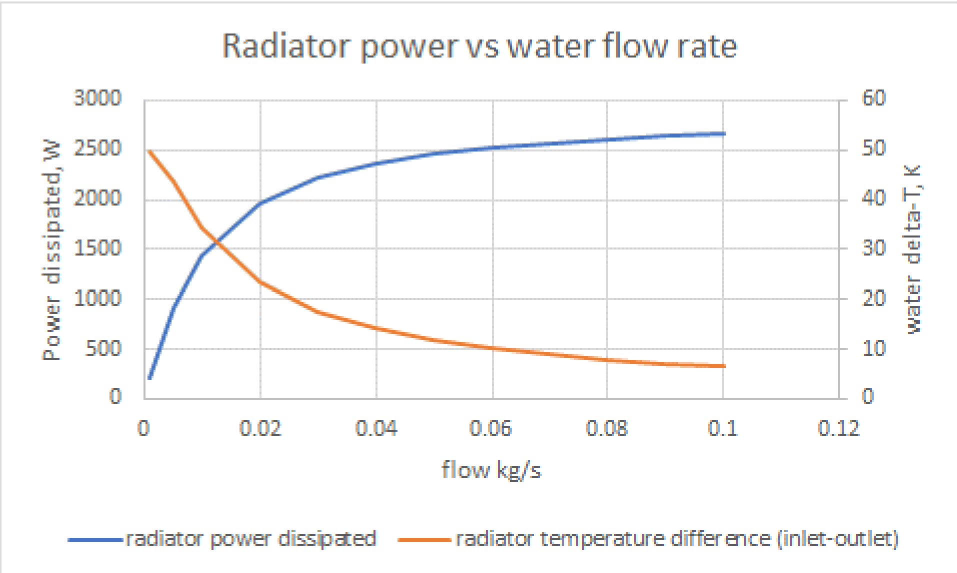

Figure A.4.3-1 – Typical radiator operating curves, using fixed water inlet and room air temperatures

Clearly there is scope for improving the on/off approach discussed above, but it is clear that to make valid comparisons between the possible upgrades to houses, it is necessary to use multizone control for evaluation simulations. It should also be apparent that use of multizone control in practice will be key to maximizing the benefits of building fabric upgrades, and may even prove an enabling factor for electric heating technology such as heat pumps.

A.4.4. Effect of minimum WRV opening

During modelling of heat pumps and sensitivity cases investigating impacts of high minimum rates of gas boilers, it was noticed that a significant improvement in thermal comfort and heat source efficiency could be achieved by setting a minimum valve position for each radiator – i.e. when a room has warmed-up, instead of fully closing the valves they are left slightly open. Openings between 1-5% of flow capacity were found to be suitable, and the key results (e.g. energy usage, comfort metrics) were found to be relatively insensitive to the values used provided they were in this range. Heating systems, especially those using heat pumps, often use a buffer tank or bypass loop to achieve a similar function to that provided by the radiators in this approach. Keeping a flow path open reduces shocks to the heat source (and its pump) caused by the flow suddenly stopping. Using a buffer tank, or radiators acting in the same way, reduces the times when the heat source needs to operate at, or below, its minimum output. Keeping a well-insulated dwelling warm may only take 2-3 kW of heating power, but to warm it up from cold in a reasonable time may require a peak power many times this. Most heat sources have limits on their minimum rates (e.g. resulting from water pump characteristics, from flame stability for gas boilers, or from compressor operation and heat exchanger efficiency in heat pumps). Often these limits are higher than the power required to maintain a warm temperature, resulting in the familiar cycles of heating and cooling experienced in most UK homes. Frequent cycling (turning off and on again) reduces the overall efficiency of most heat sources. Allowing a small flow through a radiator when its room is warm reduces the rate at which that room cools (by dissipating some heat into the room – unlike a buffer tank), which helps prolong the time before the radiator next needs to turn on fully (assuming the heating is still circulating to warm up other rooms). This reduces the frequency of cycling of the heat source (after initial warm-up) by maintaining the flow rate around the system for longer durations above the minimum limit. It can sometimes lead to some rooms staying warm when their warm-time finishes, but in most cases there is a significant improvement in meeting room temperature targets.

This finding suggests that, taking it to its extreme conclusion, there may be benefit in abandoning the "on/off" WRV control approach in favour of continuous control of radiator valve positions, which when combined with improved turn-down performance of heat sources (perhaps utilizing thermal storage) could avoid on/off cycling of heat sources altogether during periods of heating demand. Further work would be required to investigate this approach, to quantify the benefits both in terms of energy usage and comfort. Investigations into valve power consumption (battery life) and behaviour at low openings (e.g. noise) would also be required. However this is a potential area for innovation which could bring significant benefits.

A.4.5. Other practical issues with multizone control

The benefits of multizone control indicated above suggest that any innovations which allow such a system to be reliably "DIY" installed at a reasonable cost would greatly assist uptake of such an approach.

Installing multizone control as described above requires WRVs to be fitted to all radiators in a dwelling. Many existing radiators have TRVs whose heads can easily be swapped for WRV heads. However some TRVs and fixed valves may require plumbing work to remove and replace with a full WRV body and head. WRVs are typically larger than TRVs which can be problematic where the existing radiator is very tight to a wall, especially if the piping is concealed in the wall. Being wireless devices, WRVs rely on batteries for operating power, which means battery life and ease of replacement can be a significant issue for the householders. Considering frequency and size of WRV position changes in the design of the heating control is therefore important, and innovations would also be beneficial in areas such as battery technology, reduced valve power consumption or self-charging technology.

Locations of the room temperature measurements should be considered carefully, both from an aesthetics point of view, and to ensure the temperature to which the heating responds is representative of how the occupants experience the room – mal-distribution of temperature within rooms can have a large influence of perceived comfort. In bathrooms, the WRV and room thermostat must be suitable for use in wet environments and located away from the possibility of direct contact with water from a shower, for example.

Once installed, the WRVs and room thermostats must be wirelessly connected to each other and to the heat source control (to provide at least a demand signal to the heat source, based on any room that requires heat). Setting up wireless networks is not always straightforward: ESC has gained experience with Z-Wave mesh networks (an increasingly widespread standard for domestic automation devices) which indicates careful attention is required to network installation in each dwelling. For example, correctly choosing numbers and locations of mains-powered network devices acting as "repeaters" can be necessary to avoid signals being blocked by building fabric, interference with other transmitters etc. Improvements are also suggested in network security and responses to failures (such loss of device power at end of battery life). Further investigation of these issues, with the latest version of Z-Wave, is planned.

Appendix 5. IEHeat results summaries for Upgrade Analyses

The following sections describe key findings and results extracted from the many simulations conducted on five models of houses as part of the Upgrade Analysis, as discussed above.

In each case most of the comparative evaluation cases use hourly weather data from the first two weeks in January of a typical mean year in Newcastle-upon-Tyne (to ensure challenging conditions). These are extended to annual comparisons for selected cases, estimating results by running the model for two weeks in every four weeks throughout the year, with weekly energy consumption taken from the second week in each case (to minimize the influence of initial conditions). Summing and multiplying by four gave the total annual consumption. Note these annual estimates are for use only in comparing the impact of upgrades, not for predicting annual consumption more generally (due to the fixed choice of weather data). For some building fabric upgrades annual energy consumption was estimated from winter results and base case annual results. Most building fabric upgrades improve the effective U-value, giving the same proportional reduction to overall heat loss at any time of year (provided multizone control is preventing over or under heating), such that the ratio of heat required for space heating with or without the upgrade is nearly constant over the whole heating season (although reducing heat loss may slightly shorten the duration of the heating season). Assuming heat for DHW is not changed significantly by fabric upgrades then allows the total energy consumption to be estimated.

The quantified comparisons of results use energy consumption at the input boundary to the house (gas energy stated using the gross, or higher, heat of combustion – i.e. including the latent heat of the water in the combustion products) and thermal comfort metrics based on room temperatures (see section **A.2.8**). For selected rooms, a comfort metric is tabulated, calculated as described in section **A.2.6 above**. Additional metrics used when appropriate include warm-up time and deviation from the maximum temperature setting (i.e. the top of the control band). Note that rooms without heating (such as the kitchen in House A) do not have such metrics, since they have no defined heating profile.

Metrics for the heat source performance are effective efficiency or coefficient of performance (i.e. based on usable heat) rather than purely looking at the device itself. These are calculated as the sum of the heat flow to the radiator network and the heat flow delivered to the domestic hot water users divided by the power supplied to the heater, over the time span of the simulation in question. The primary difference between effective and device performance metrics arises from heat losses from the domestic hot water tank and the piping from the heat source to this tank.

Each set of results presents house details, as modelled, and metrics for the base case (current situation) and the existing house fabric with multizone control. Then a set of feasible building fabric evaluations are reported, individually and with likely combinations. Finally results for options for heating system changes are reported, including the combined fabric upgrades selected for the pathways.

A.5.1. Summary of IEHeat results for House A (1950s semi-detached)

A.5.1.1. House and household description

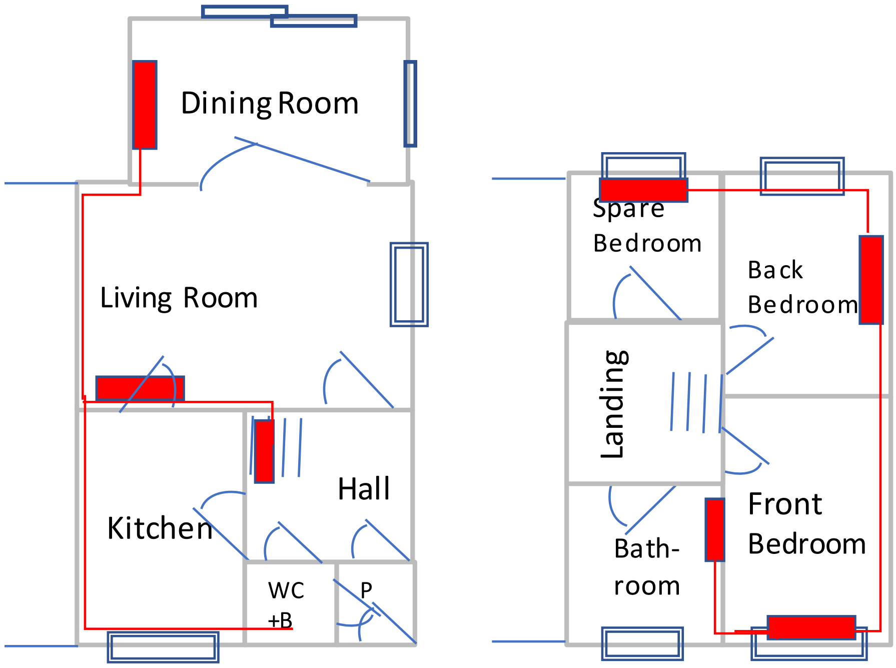

Figure A.5.1-1 House A schematic (simplified for modelling)

The house has cavity walls which are insulated only on the right side (as seen from the front), possibly not fully effectively. The windows are mostly pre-2002 double glazing, including the sliding door at the rear but excluding a single glazed window in the dining room. The front doors (internal and external porch doors) are aging, part-single glazed, wooden doors.

The heating system comprises a combi-boiler with a mix of radiators (DPDCs in hall and back bedroom, lower specifications in other rooms) + towel rail, controlled by a single thermostat and timer (in hall) with TRVs on all radiators except the hall. For comparison with the upgrade evaluation cases (below) multizone on/off control was also modelled. Note that for the single zone case the radiators are roughly balanced to allow the TRVs to warm up the rooms together. For the multizone case this is not so necessary (as no room should over heat) so the lockshield valves have been opened wider to improve warm-up times.

The following data was used to define the household requirements and behaviour: 7 day temperature profiles have been approximated from combined sets of HEMS data (which is per-room and varies over time) – for the single zone case this has been merged to give a boiler heat demand whenever any room requires heating; occupancy heat gains have also been estimated from sets of HEMS data; the doors and windows are normally closed, with some brief opening (for morning/midday/evening activity); DHW demands simulate morning and evening usage (totalling about 200 litres per day at 38-40 °C).

A.5.1.2. Base case results, winter

Note the poor comfort metrics for the single zone case result from the long warm-up time in cold weather owing, in part, to the sub-optimal radiator balancing (the single thermostat turns the heating off before all the rooms are warm, which is avoided by multizone control). The warm-up times for all but the living room remain unacceptably long on the coldest days (over 2 hours for the front bedroom). The multizone case has been used for comparison with building fabric upgrade options.

Table A.5.1-1 - Base case results summary (mid-winter, two weeks)

Case	Energy Used, kWh[1]	Fraction of Demand Time Below T Range, %			
		Living Rm	Dining Rm	Front Bedroom	Back Bedroom
Base (single zone control)	1044	3.2	40.3	63.7	32.5
Base (multizone control)	1010	0.0	2.5	10.7	0.8

Note 1: Gas energy stated is gross (i.e. including latent heat of water)

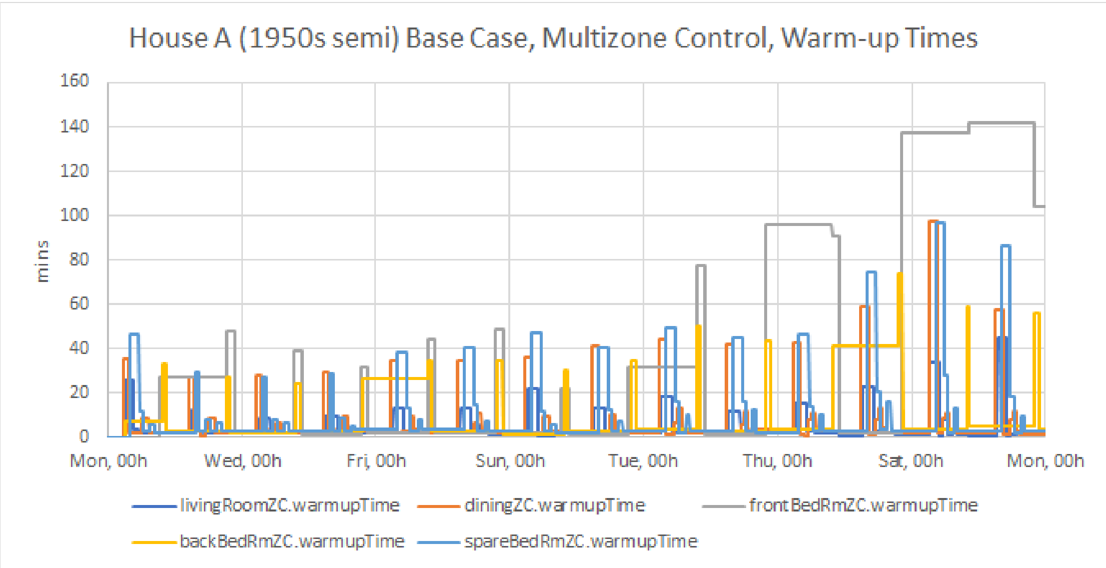

Figure A.5.1-2 – warm-up times, multizone base case

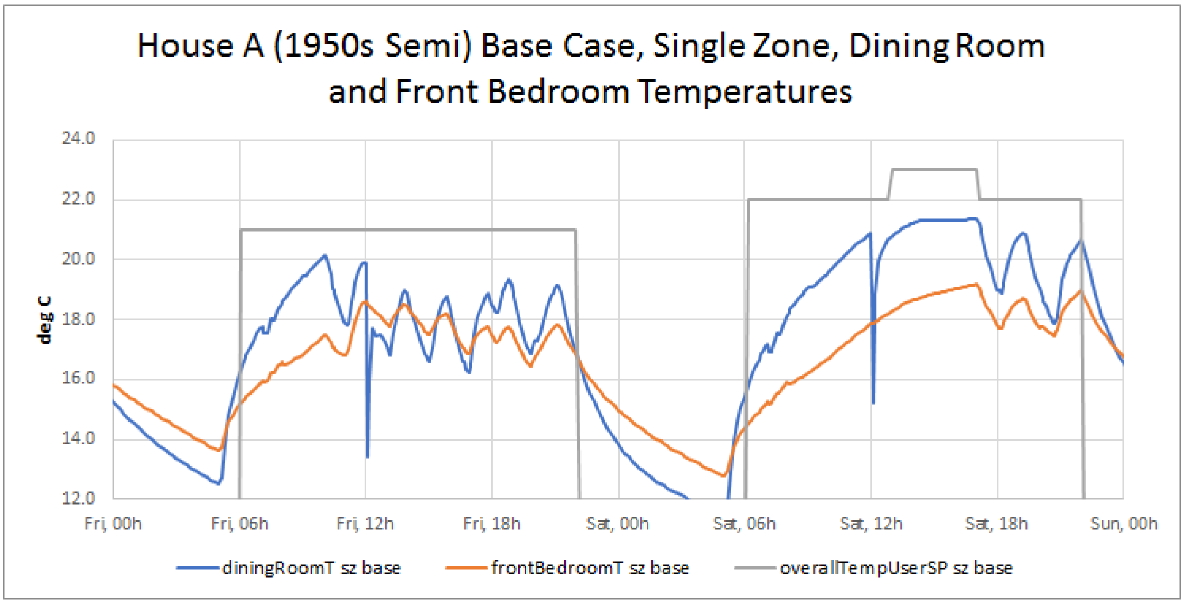

Figure A.5.1-3 – temperatures of rooms providing least comfort, single zone base case

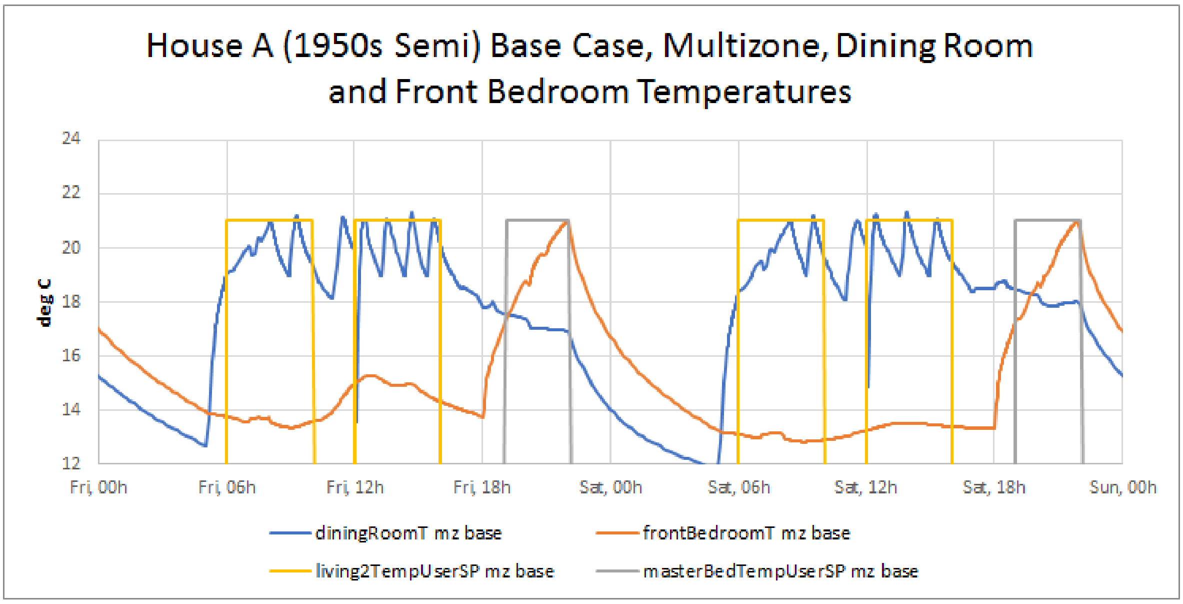

Figure A.5.1-4 – temperatures of rooms providing least comfort, multizone base case

A.5.1.3. Base case annual energy consumption

The annual energy consumption has been estimated as described in the introduction to the results summaries. The multizone case uses about 6% less energy as some rooms are heated for only a fraction of the overall demand period used in the single zone case.

Table A.5.1-2 - Base case estimated annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	Annual Energy Consumption, kWh	Energy Output for DHW, kWh[1]	Energy Output for SH, kWh
Base (single zone control)	14668	2463	10795
Base (multizone control)	13774	2483	9562

Note 1 – energy to DHW varies between cases due to interaction with space heating causing varying boiler temperatures at the beginning of DHW demand events.

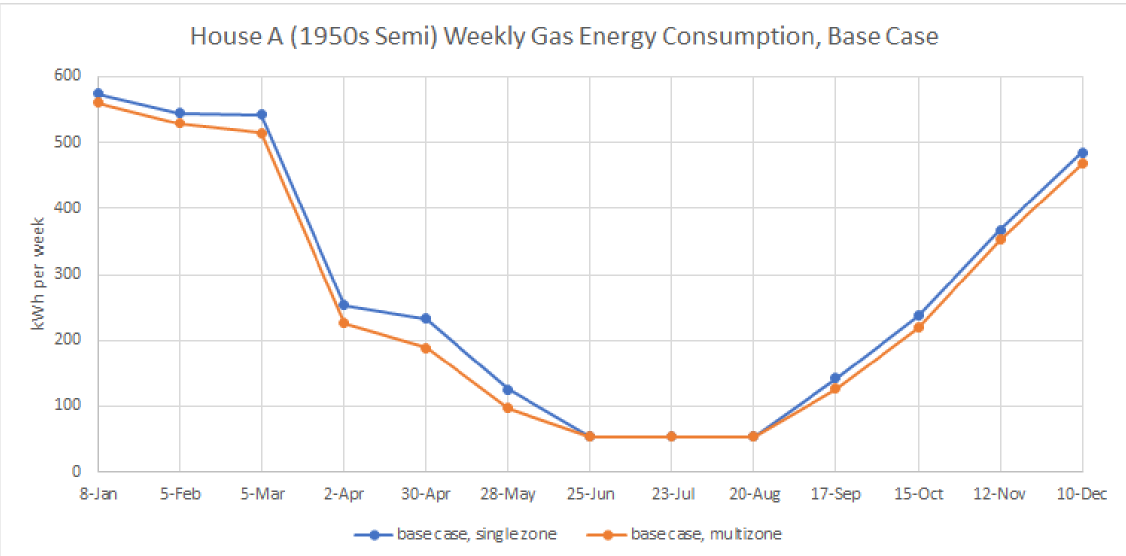

Figure A.5.1-5 - weekly energy consumption, base case

A.5.1.4. Building fabric upgrade evaluation cases

A summary of results of evaluation cases are presented below, investigating the impact of building fabric upgrades, to enable energy and comfort gains to be incorporated with practical and household issues in the decision process to choose upgrades to recommend.

A.5.1.4.1. Evaluation cases: windows, doors, cavity wall, external wall, floor and loft insulation

Replacing all windows with modern double glazing with U-values of 2 W/m2/K (previously 2.8 W/m2/K and one single glazed with 4.8 W/m2K assumed) gave a 5% saving in energy used in winter.

Upgrading the front porch doors to thicker, better insulated/draft-proofed (modern standard, external U=2 W/m2/K, internal U=3 W/m2/K) and the rear patio door to a modern double glazed door with U=2 W/m2/K increased the saving to 9% in winter conditions.

Table A.5.1-3 – Windows and doors upgrade results summary (mid-winter, two weeks)

Case	**Energy Used, kWh**	**Fraction of Demand Time Below T Range, %**			
		Living Rm	**Dining Rm**	**Front Bedroom**	**Back Bedroom**
New windows	959	0.0	2.3	7.6	0.6
New windows and doors	918	0.0	1.9	6.9	0.5

A number of cases were run to evaluate the impact of insulation. As there is a suspicion that the cavity wall insulation may be incomplete or deteriorated, cases from full to no CWI were run, indicating a +/- 10% variation in energy consumption relative to the base case (CWI on right wall only). A series of cases with varying thickness of external wall insulation indicated that up to 20% energy saving could be achieved with 100 mm EWI on all external walls.

Increasing the loft insulation to 150 mm achieved an energy saving of just over 1%, while adding 50 mm of floor insulation (above the concrete slab) in the living and dining rooms saved just over 2% relative to the base case.

Table A.5.1-4 – wall, floor & loft insulation upgrade results summary (two weeks, mid-winter)

Case	Energy Used, kWh	Fraction of Demand Time Below T Range, %			
		Living Rm	Dining Rm	Front Bed	Back Bed
no CWI on any wall	1120	0.3	2.5	28.3	9.2
possible actual (no CWI upstairs)	1061	0.0	2.4	27.2	9.1
Base case (right wall fully CWI)	1010	0.0	2.5	10.7	0.8
all walls fully CWI	912	0.0	2.7	1.6	2.5
actual (no CWI upstairs) with 5mm EWI[1]	1024	0.0	2.5	19.5	6.2
actual (no CWI upstairs) with 10mm EWI	994	0.0	2.5	14.5	5.0
actual (no CWI upstairs) with 20mm EWI	952	0.0	2.4	8.2	1.3
actual (no CWI upstairs) with 30mm EWI	925	0.0	2.3	4.3	0.7
actual (no CWI upstairs) with 50mm EWI	891	0.0	2.2	1.6	0.0
actual (no CWI upstairs) with 100mm EWI	848	0.0	2.1	0.1	0.0
Base case + 50 mm floor insulation in living & dining rooms	989	0.0	2.8	10.6	0.6
Base case + 150mm loft insulation	998	0.0	2.6	9.0	0.9

Note 1: range of thicknesses evaluated deliberately extends below practical range for model consistency checking.

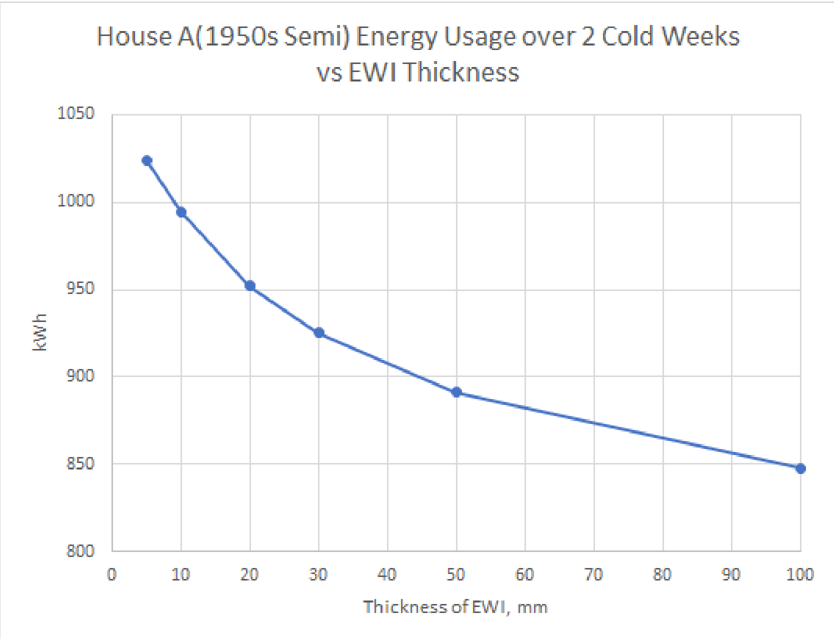

Figure A.5.1-6 – energy consumed vs external wall insulation thickness

A.5.1.4.2. Possible combinations of upgrades

If energy saving is a priority of the upgrade pathway (likely if a heat pump is proposed) then the results suggest that a saving of about 21% can be achieved (relative to the single zone base case) by upgrading the heating control to multizone, upgrading the windows and doors, and completely insulating all the walls (either by fully insulating the wall cavities, or by adding 20-50mm of external wall insulation). This set of upgrades reduces the warm-up times to less than 30 minutes for all but the coldest days, when the front bedroom can take about 70 minutes to reach its target temperature range.

Noting that the radiators in the dining room and all bedrooms are on external walls it would be beneficial to reduce the fraction of radiator power output transferred to the walls. This would be the equivalent of fitting an insulated foil sheet on the wall behind the radiator. This is a relatively cheap and easily fitted upgrade. However it is difficult to quantify the reduction in heat flow to the wall achieved by radiator reflector foil. In the case reported here the fraction of radiator power output transferred to the wall is reduced by 60% (e.g. from 25% to 10% for a single panel single convector radiator). This reduces the warm up times in all modified rooms, bringing the front bedroom below 60 minutes even on the coldest days. The energy saving is modest thanks to the addition of full CWI. Note that this upgrade has not been included in pathway due to the uncertainty of the magnitude of the effect – this would benefit from further investigation in real houses.

Table A.5.1-5 - upgraded building fabric, results summary (two weeks, mid-winter)

Case	**Energy Used, kWh**	**Fraction of Demand Time Below T Range, %**			
		Living Rm	**Dining Rm**[1]	**Front Bed**	**Back Bed**
all walls fully CWI, new windows and doors	825	0.0	2.0	0.3	0.0
all upgrades above + radiator reflector foil	820	0.0	2.2	0.0	0.0

Note 1: the anomalous dining room metrics are due to opening the back door to access the garden.

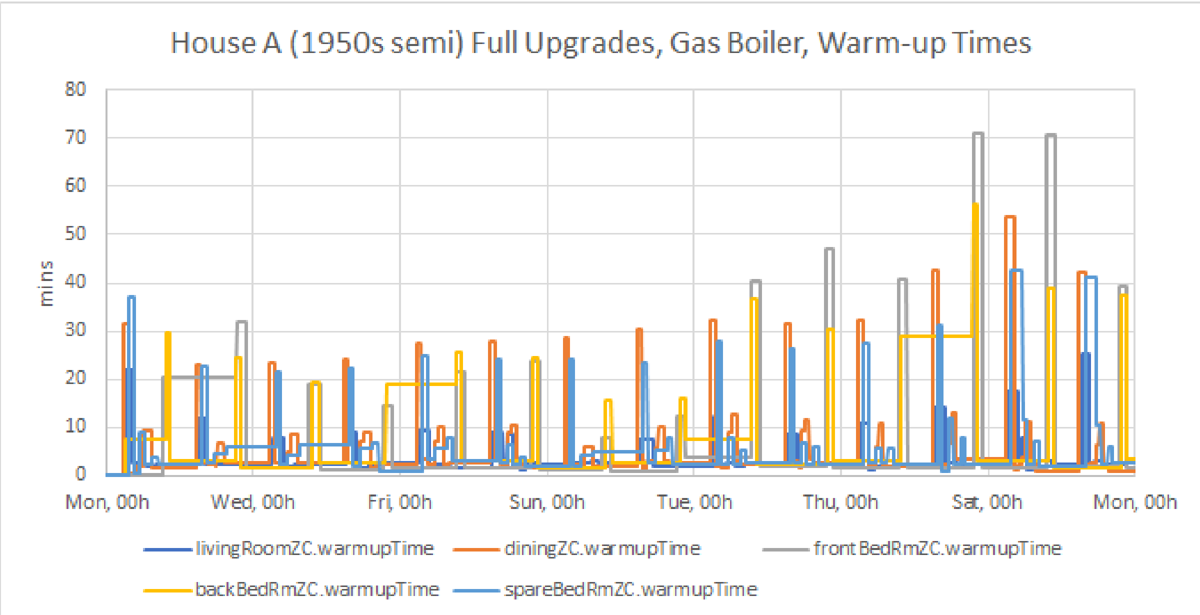

Figure A.5.1-7 – warm-up times in winter, upgraded building fabric, gas boiler

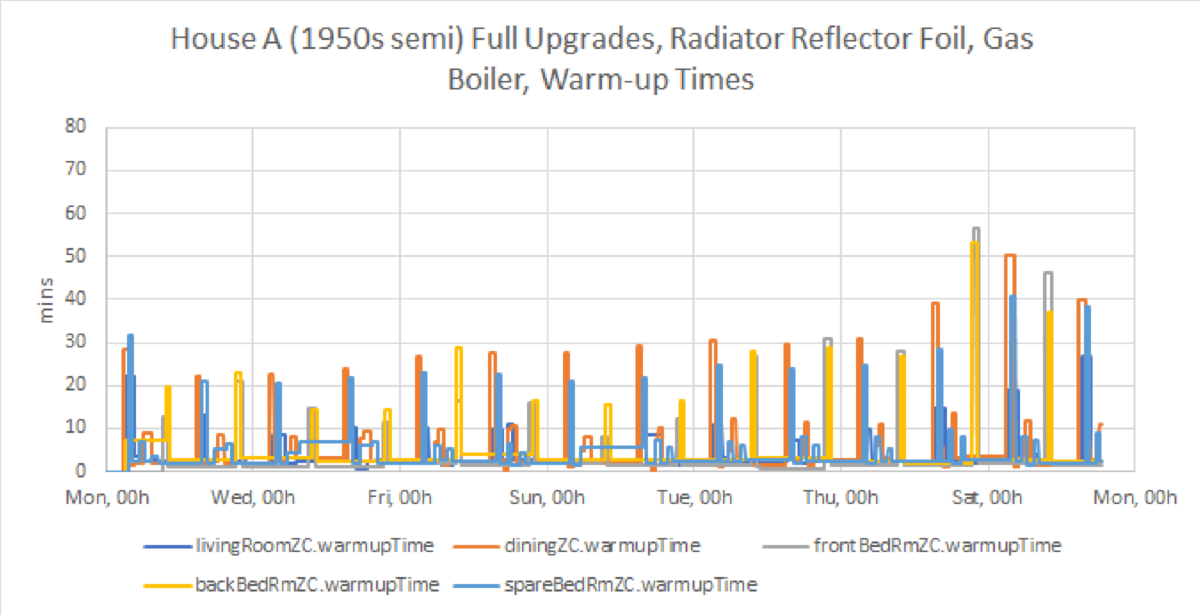

Figure A.5.1-8 – warm-up times in winter, upgraded building fabric with radiator reflector foil, gas boiler

Annual consumption for the suggested upgraded building fabric case was estimated in the same way as for the base case.

Table A.5.1-6 - Upgraded case estimated annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	**Annual Energy Consumption, kWh**	**Energy Output for DHW, kWh**	**Energy Output for SH, kWh**
all walls fully CWI, new windows and doors	11047	2475	7274

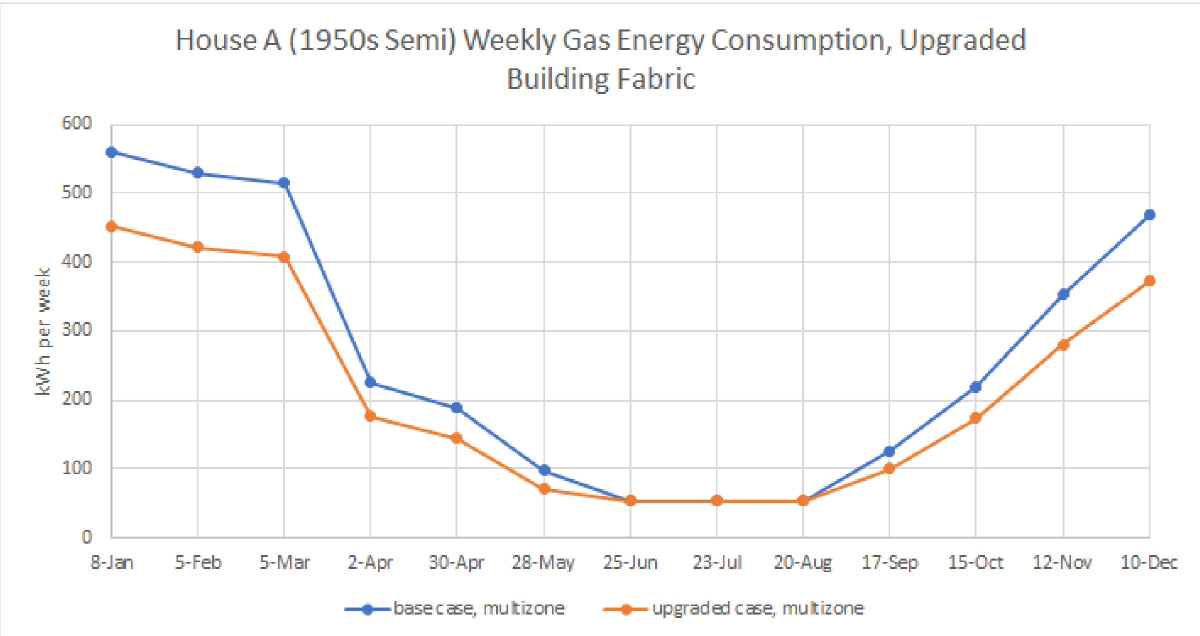

Figure A.5.1-9 - weekly energy consumption, building fabric and radiator upgrades

A.5.1.5. Air source heat pump cases

Using an Air-Source Heat Pump as a heat source was considered technically feasible for this house. From preliminary tests and base case simulations it was clear that using a lower heating medium temperature with no other changes would give unacceptably long warm-up times, based on trying to achieve the occupants' desired heating profile (as opposed to trying to keep the house warm continuously – an approach that requires further study and consideration of occupant comfort, particularly regarding overheating and noise levels during the night). Therefore some heating system upgrades were considered for all cases using the heat pump. Also, this house has space to reinstate a DHW cylinder, which would facilitate use of a heat pump without a supplementary water heater (other than a 3 kW immersion heater).

A.5.1.5.1. Base case – single zone, upgraded radiators with marginally increased flows

For comparison, a "base case" with heat pump was simulated, as follows:

i. Combi boiler replaced with a 12 kW (nominal output) Air-Source Heat Pump (with a fixed SH outlet temperature of 40 °C) and a 200 litre insulated DHW cylinder (requiring bursts of 3kW immersion heater to achieve 60 °C for 1 hour each morning to guard against legionella)
ii. all the radiators not already double panel double convectors (DPDC) increased in power by upgrading to DPDC
iii. using standard single thermostat on/off control with TRVs (allowing an increased pre-heat time of 120 mins)
iv. lockshield valves slightly further open (especially bedrooms) but still required to balance (due to TRVs+single zone control), but note ASHP water circulation rate is typically higher than that of gas boilers
v. two mid-winter weeks as per base case above.

Table A.5.1-7 – 12 kW output ASHP with upgraded radiators, results summary (two weeks, mid-winter)

Case	Energy Used, kWh	Peak Electricity Demand, kW	Fraction of Demand Time Below Range, %			
			Living Rm	Dining Rm	Front Bed	Back Bed
ASHP base (single zone control)	386	4.96	50.5	89	55	49

The comfort metrics indicate very poor performance with respect to the desired warm times, as can be seen in the charts for selected rooms in Figure A.5.1-10 and Figure A.5.1-11.

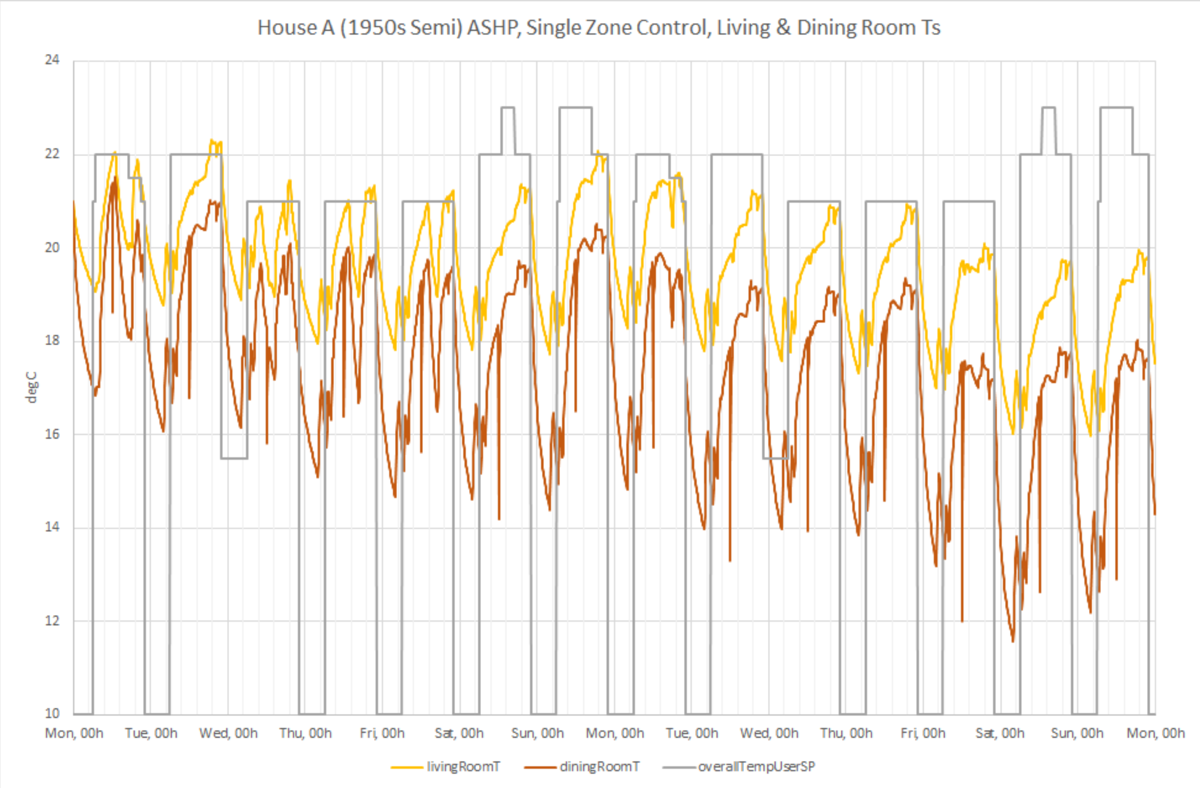

Figure A.5.1-10 – downstairs room temperatures, air source heat pump with upgraded radiators

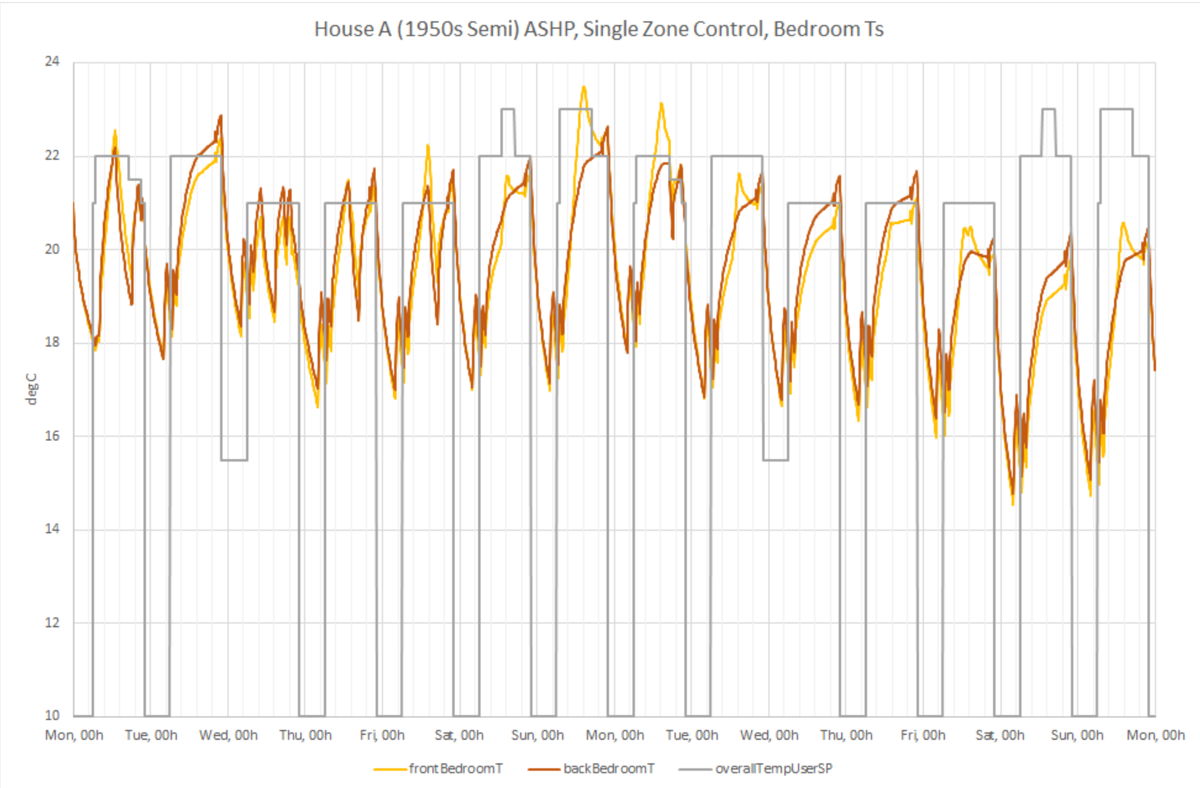

Figure A.5.1-11 – bedroom temperatures, air source heat pump with upgraded radiators

A.5.1.5.2. Multizone Cases

Preliminary cases were run using multizone on/off control with the 12 kW heat pump, with and without upgrades to the CWI, windows and doors as suggested by the building fabric evaluation cases. These cases used pre-heat times of 60 minutes for all rooms except bedrooms, which used 120 minutes.

Table A.5.1-8 – 12 kW output ASHP with multizone control, results summary (two weeks, mid-winter)

Case	Energy Used, kWh	Peak Electricity Demand, W	Fraction of Demand Time Outside Range			
			Living Rm	Dining Rm	Front Bed	Back Bed
12kW ASHP multizone (on/off) control	407	7108	0.9%	3.1%	3%	1%
12kW ASHP multizone (on/off) control + upgrades	361	7100	0.7%	1.9%	0	0.5%

Further investigation of heat pump performance with multizone control indicated the importance of turndown (minimum power output) and reducing cycling using a fluid buffer within the heating system. Scroll compressor data indicated a 6:1 turndown was typical (allowing operation at 17% nominal speed). This was incorporated in the model and had the effect of reducing COP after warm-up with a 12 kW heat pump, since the compressor was running at minimum speed and the outlet temperature increased above its setpoint. Therefore a 6 kW (nominal output) heat pump was simulated, which rarely needed to operate at its minimum.

To avoid frequent cycling of the heat pump, the radiators (and DHW storage tank when present) provide a fluid buffer by allowing the heat pump outlet to flow at low rates, rather than zero, at periods of low heat demand. This is achieved by setting a minimum opening on each radiator valve (e.g. 1-5% depending on the relative size of radiator). This had the added effect of making deviations below the desired temperatures very infrequent, although occasionally some rooms had brief periods slightly warmer than the desired range.

The peak electricity demand from the 12 kW (output) heat pump was often around 7-8 kW which would exceed the current capacity of the electricity distribution infrastructure should heat pumps be installed in most homes. To test heat pump performance with a more reasonable peak demand, a power input limit was added to the heat pump model, and the cases with the 6 kW (output) heat pump were limited to a maximum input power of 2.5 kW.

The following further heating system upgrades relative to the ASHP base case above were found to be beneficial to occupant comfort:

i. Further opening the lockshields (especially bedrooms where they were almost fully open), to maximize the power output of the radiators
ii. setting the heat pump outlet temperature for SH as a linear function of outside air temperature (rising to 55 °C at or below 5 °C outside)

iii. the above changes, together with the building fabric upgrades, allowed use of pre-heat times of 40 min downstairs, 60min in bedrooms,
iv. increasing the heat pump outlet temperature for DHW to 65 °C when the tank required heating to 60 °C (to reduce use of immersion heater)

The following cases were simulated using the above improvements and with the building fabric upgrades:

Table A.5.1-9 – ASHP with upgraded building fabric and radiators, results summary (two weeks, mid-winter)

Case	Energy Used, kWh	Average effective COP	Peak Electricity Demand, W	Fraction of Demand Time Outside Range			
				Living Rm	Dining Rm	Front Bed	Back Bed
12 kW ASHP MZ (with min opening)	319	2.26	10017	5.7% (too warm)	2.5% (2% too warm)	0%	0%
6 kW output ASHP with 2.5 kW input limit, MZ (with min opening)	286	2.52	2540 (+brief periods of 3 kW immersion)	5.9% (too warm)	3.1% (2.1% too warm)	0%	0%

These heat pump cases, using multizone control to extract the maximum performance from the radiators, and elevated outlet temperatures in particularly cold weather, show that good comfort can be achieved (based on room temperature during desired warm times), even with a 2.5 kW electricity demand limit. The importance of correct sizing of heat pump is demonstrated by noticing the reduction in average effective COP (see glossary, **Appendix 1**) with the 12 kW machine due to turndown limitations. Some optimization of DHW heating would be needed to avoid simultaneous immersion heating and running of the heat pump at maximum power. Improvements in control could be made to reduce over-heating some rooms. Charts for selected room temperatures are shown in Figure A.5.1-12 to Figure A.5.1-15 for the 6kW (limited to 2.5kW input) air source heat pump. Note variables labelled "...user max T target" represent the periods during which the householder wants the room to be warm, whereas the heating control pre-empts the start of these periods by the "pre-heat time". The charts indicate that these pre-heat times were sometimes longer than the actual warm-up times achieved, indicating that it may be possible to use shorter pre-heat times or lower heat pump outlet temperatures at these times. An effective automatic adjustment of pre-heat times would improve comfort and system robustness.

The energy consumption for this severe mid-winter case, when including building fabric upgrades, is about 28% that of the equivalent house using a gas boiler, and about 27% of the consumption in the existing house with single zone control. The COP for space heating will increase during warmer weather (but the increased proportion of heat used for hot water may offset this), but it may be worth considering retaining the existing gas boiler for use if the heat pump operating costs in cold weather are unacceptable. Use of solar PV to heat DHW tank during times of excess generation and to provide power to the heat pump during the day should also be considered as ways to reduce electricity consumption.

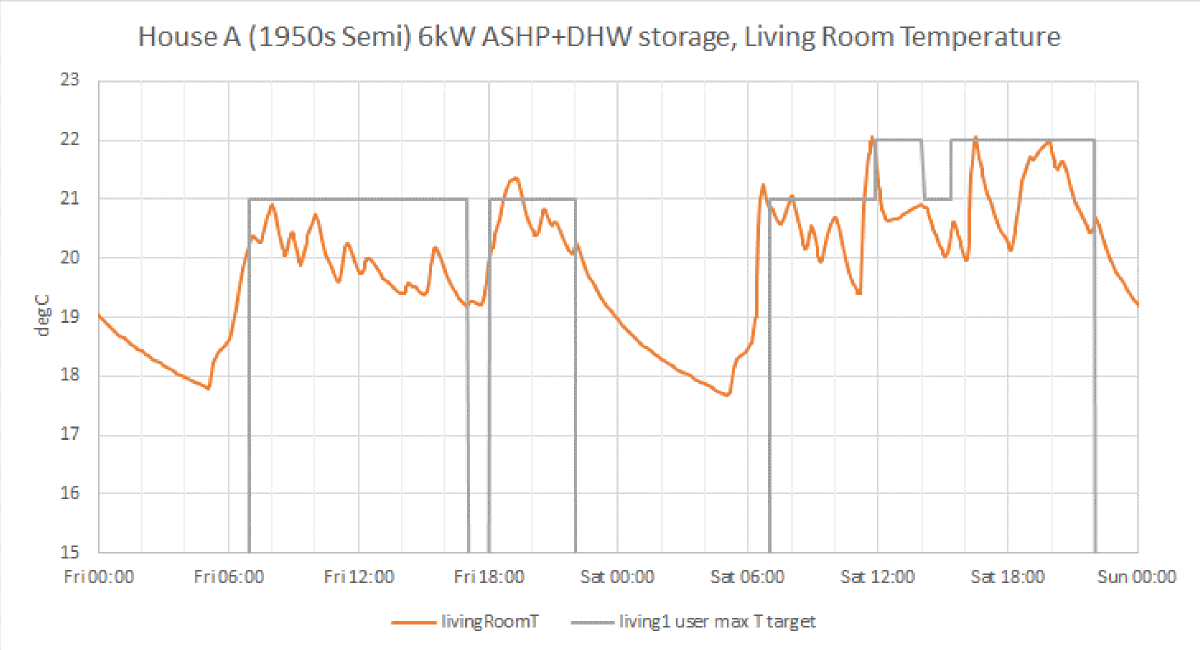

Figure A.5.1-12 – living room temperature, 6kW air source heat pump (2.5 kW input limit) with full upgrades

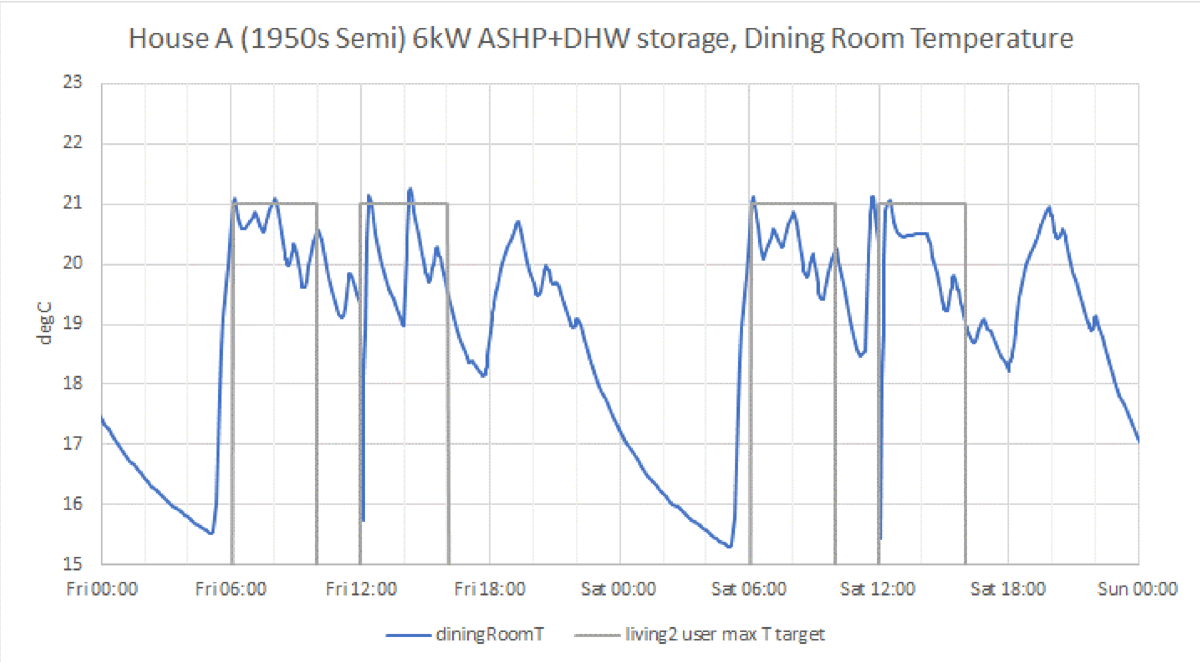

Figure A.5.1-13 – dining room temperature, 6kW air source heat pump (2.5 kW input limit) with full upgrades

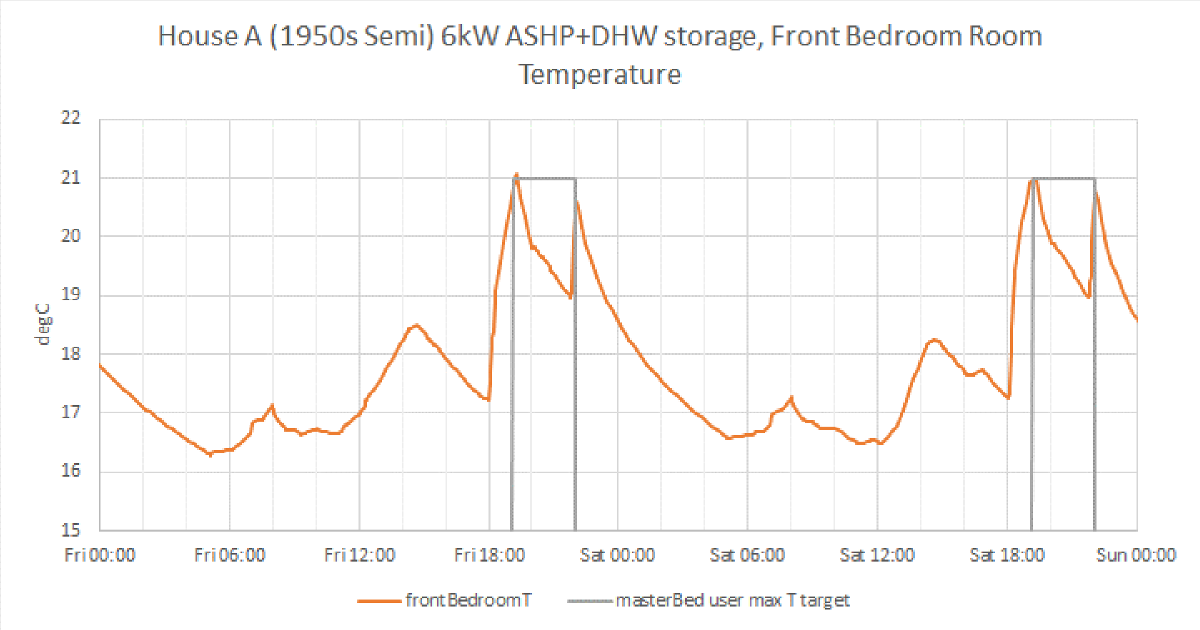

Figure A.5.1-14 – front bedroom temperature, 6kW air source heat pump (2.5 kW input limit) with full upgrades

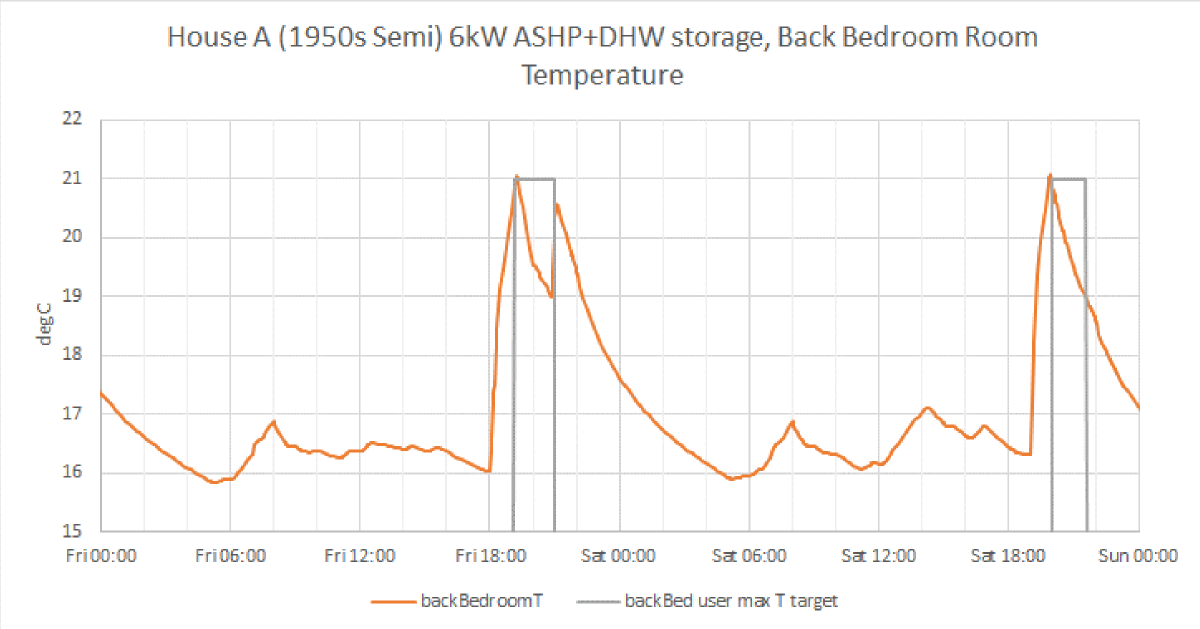

Figure A.5.1-15 – back bedroom temperature, 6kW air source heat pump (2.5 kW input limit) with full upgrades

A.5.1.5.3. Multizone + upgrades annual energy consumption & peak electricity demand

The final (6kW) upgraded heat pump case above was run for half a year, from which the annual consumption has been estimated. It is apparent from the results that the function of external temperature used to adjust the heat pump outlet temperature could be improved: the energy usage at intermediate temperatures could probably be reduced with a more physical calculation of pre-heat time and outlet temperature, including considering reducing outlet temperature after the initial warm-up.

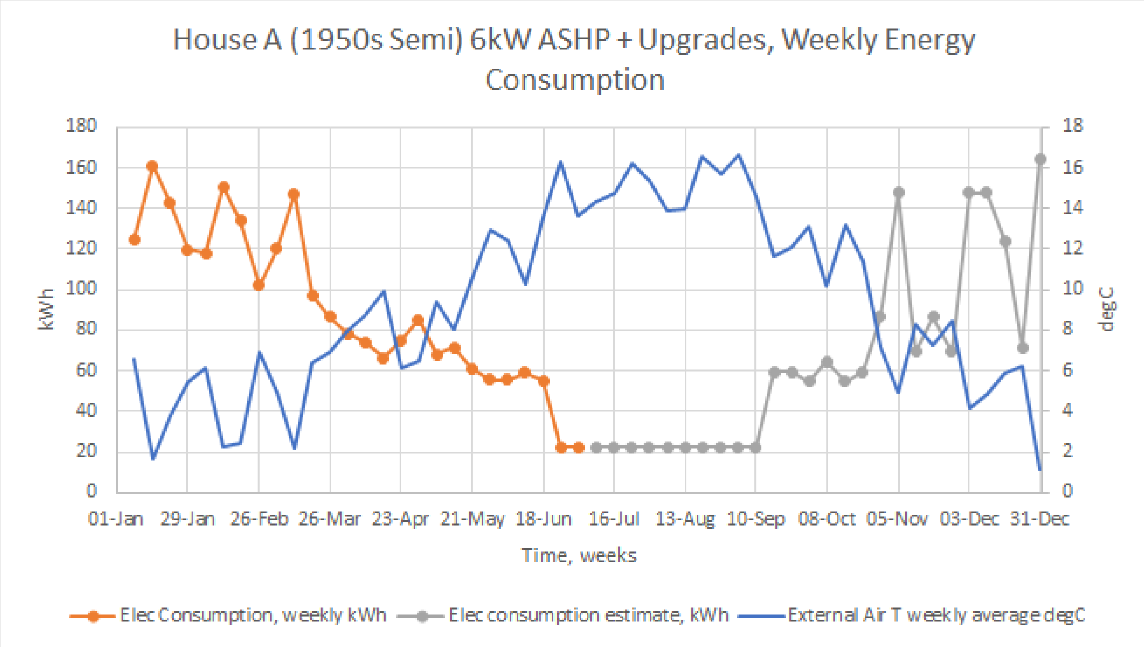

Figure A.5.1-16 – weekly energy consumption, 6kW air source heat pump (2.5 kW input limit) with full upgrades

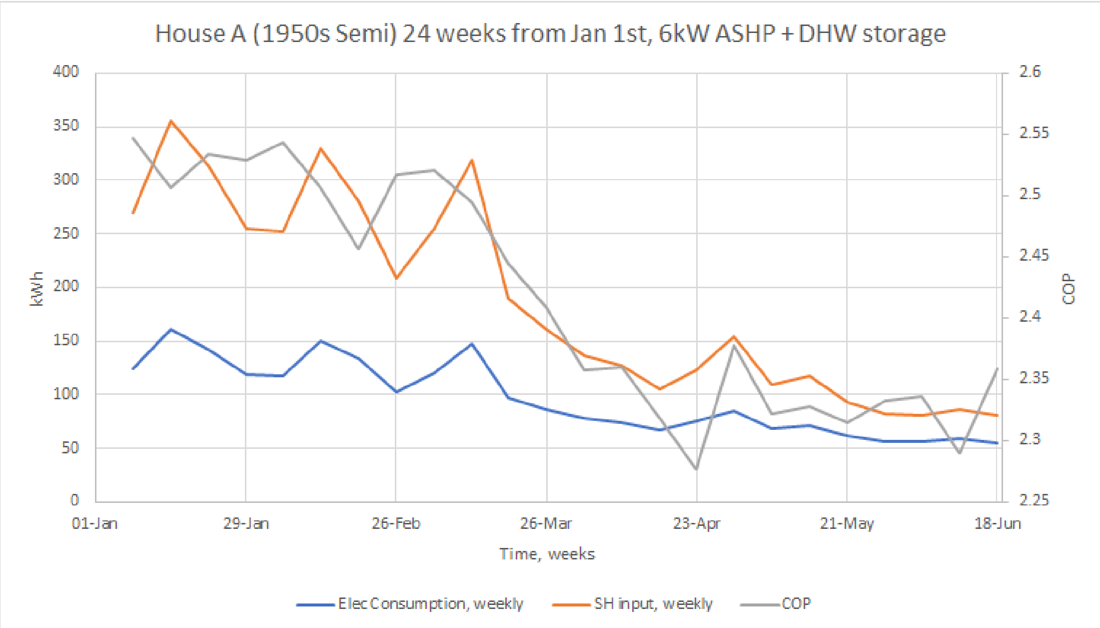

Figure A.5.1-17 – weekly energy input to space heating and COP, 6kW air source heat pump (2.5 kW input limit) with full upgrades

Note that the requirement to heat the DHW tank to 60°C each morning (using a heat pump outlet temperature at 65°C, rather than the maximum for space heating of 55°C) results in a lower average COP as the external temperature increases, due to increased proportion of time heating the DHW tank and increased proportion of heat lost via the DHW tank (the COP quoted is the effective COP, including heat losses around the tank).

The overall energy consumption with a simple linear outlet temperature adjustment is only 27.5% of the base-line case (single zone control, no upgrades). The savings from changes to building fabric, control and heat source are nearly independent of each other, such that their effects can be characterized as energy reduction factors which can be multiplied together to give the overall reduced consumption. In this case, multizone control reduces annual energy consumption by a factor of 0.94, building fabric by 0.8 and the change from a condensing boiler (effective efficiency of 0.88) to a heat pump with an average effective COP of about 2.4, gives a reduction factor for heat source change of 0.37. Just under 10% of the energy used to provide DHW is lost through the insulation of the storage tank (averaging about 45W, based on a comparison with the combi-boiler energy usage for DHW in an earlier case). This suggests that using solar PV to heat the water during periods of excess generation (e.g. early afternoons) would give a significant saving. As a temporary step in the pathway, retaining the gas boiler for DHW (and potentially SH on cold days) is worth considering.

Table A.5.1-10 – ASHP with upgraded building fabric and radiators, annual consumption estimates

Case	**Annual Energy Consumption, kWh**	**Energy Output to DHW, kWh**	**Energy Output to SH, kWh**
6kW ASHP 2.5kW input limit, multizone control + fabric upgrades	4043	2497	7270

A.5.1.6. Hybrid of gas boiler + air source heat pump

A number of configurations are possible when combining a heat pump with a gas boiler. There exist some packaged products combining the two technologies, but it is seen as a potential consumer benefit to enable existing gas boilers to be retained with a heat pump added to reduce gas consumption at low risk to the householders. This could be a transitional arrangement hoping to move to fully electric heat sometime in the future.

Preliminary investigations confirmed that there was little benefit in operating the two heat sources separately, switching based on external air temperature, for example. However, operating the heat pump in series with the gas boiler has been found to work well, provided the gas boiler outlet temperature is set to the same target as that of the heat pump – such that the boiler only operates when the heat pump is unable to meet its target (i.e. it is at its input power limit) during warm-up. Access to the boiler's target setpoint from an external signal may not always be possible, in which case a fixed outlet target for both heat sources may be satisfactory. In the simulation case the external temperature was rarely high enough to reduce the outlet temperature below 55 °C. In practical terms installing this arrangement would require modifications to the control and piping: the overall heat demand from the combined room controllers would turn on the heat pump (provided the external temperature is not too low), with the boiler also turned on if the heat pump outlet temperature was too far (e.g. > 2 °C) below its target; it is likely that bypasses would be necessary for use when either heat source was operating individually, unless their pumps are capable of allowing forward flow without excess pressure loss when at zero speed.

It is recognised that many other approaches to hybrid heat pump control, including use of room temperature deviations to switch on the gas boiler, or using electricity and gas prices or carbon intensity to decide which energy source to use. This study has chosen to evaluate the performance of the approach described above as it is simple to implement, without relying on assumptions about external factors such as prices and generation mix, and focuses on occupant comfort.

It is assumed here that the gas boiler's DHW function is retained, thus eliminating the need for a storage tank. The results indicate a possible 71% reduction in gas consumption relative to the combi-boiler case with the same building fabric upgrades. The electricity energy consumed for space heating is equivalent to about 30% of the savings in gas consumption.

Table A.5.1-11 – ASHP/gas boiler hybrid with upgraded building fabric and radiators, results summary (two weeks, mid-winter)

Case	**Energy Used by HP, kWh**	**Average COP**	**Peak Electricity Demand, W**	**Energy Used by Boiler, kWh**	**Fraction of Demand Time Outside Range**			
					Living Rm	**Dining Rm**	**Front Bed**	**Back Bed**
6kW ASHP 2.5kW input limit MZ (with min opening) + gas boiler in series	176	2.8	2675	242	4.0% (too warm)[1]	2.1%	0%	0%

Note 1 – the pre-heat time for the living room could be reduced to correct this.

Figure A.5.1-18 to Figure A.5.1-22 show the performance of the hybrid heat pump/gas boiler as described above. The power trends illustrate the brief uses of the boiler for warm-up operation (the power to the SH is seen to exceed the output of the heat pump). This has the effect of reducing the warm-up times to those expected with a constant flow temperature (as shown on the charts of room temperature below).

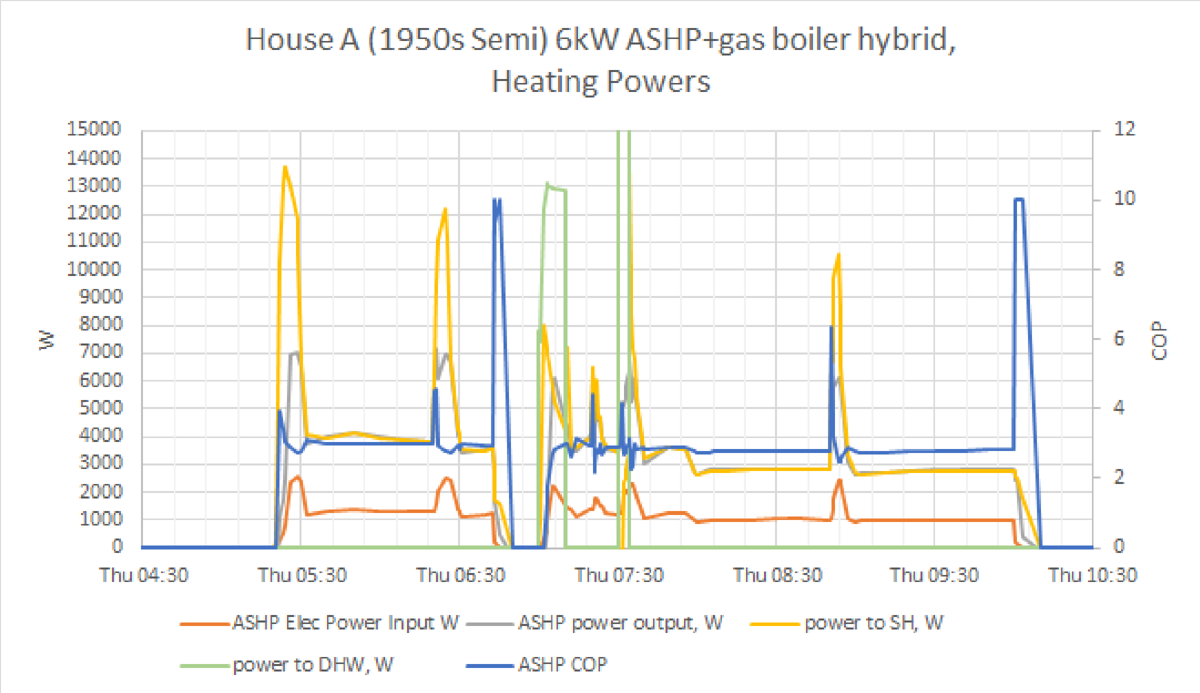

Figure A.5.1-18 –heating power and effective COP, 6kW air source heat pump (2.5 kW input limit) plus gas boiler with full upgrades

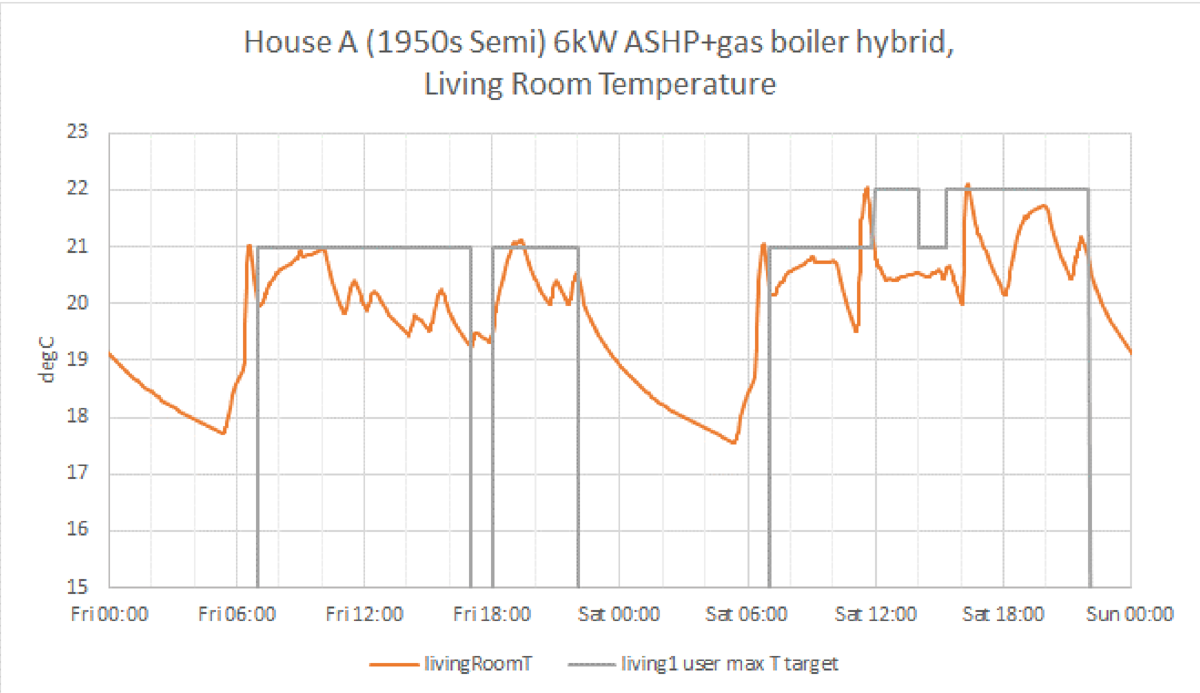

Figure A.5.1-19 –living room temperature, 6kW air source heat pump (2.5 kW input limit) plus gas boiler with full upgrades

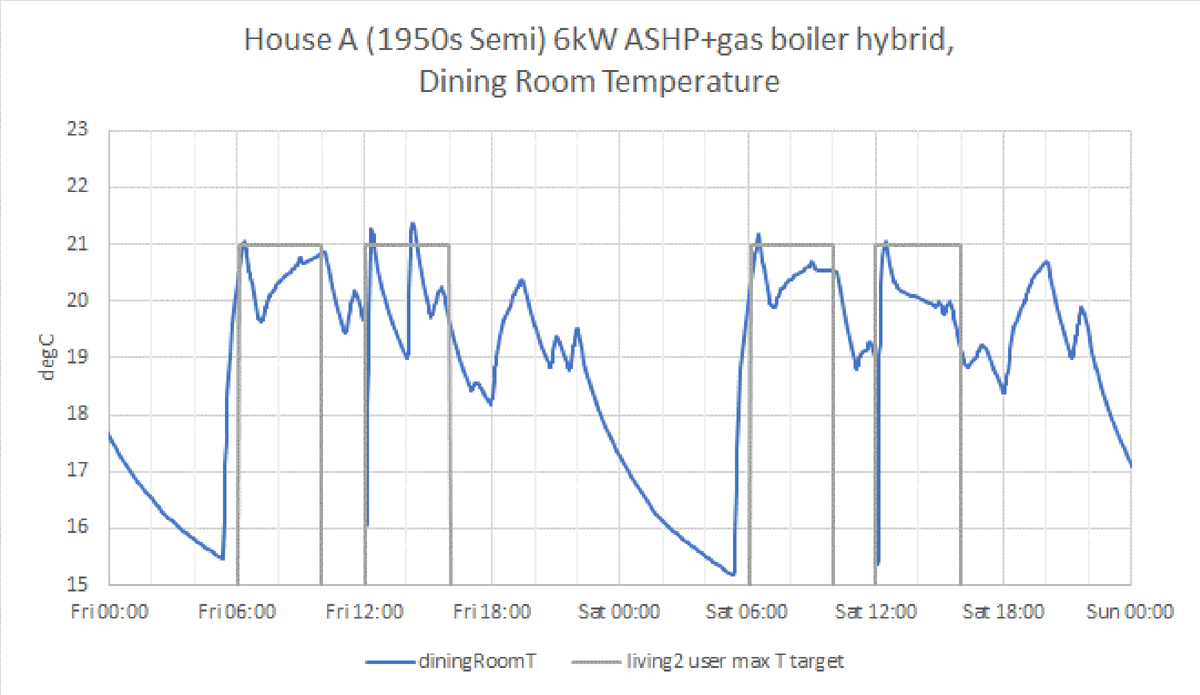

Figure A.5.1-20 – dining room temperature, 6kW air source heat pump (2.5 kW input limit) plus gas boiler with full upgrades

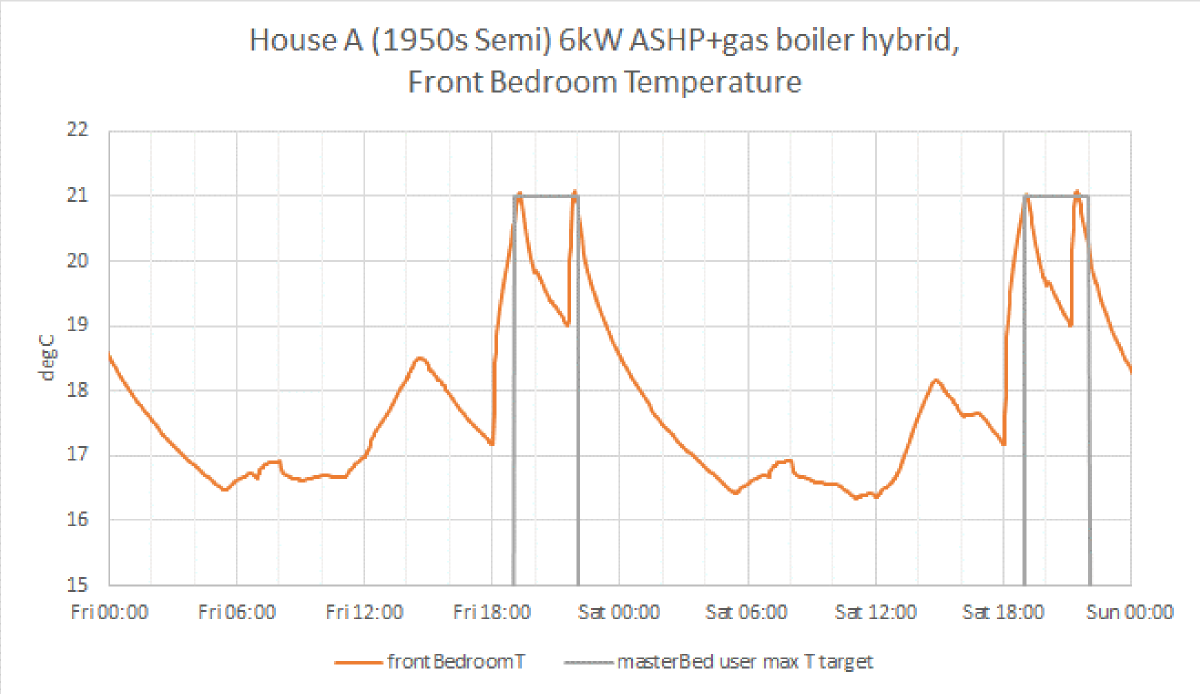

Figure A.5.1-21 – front bedroom temperature, 6kW air source heat pump (2.5 kW input limit) plus gas boiler with full upgrades

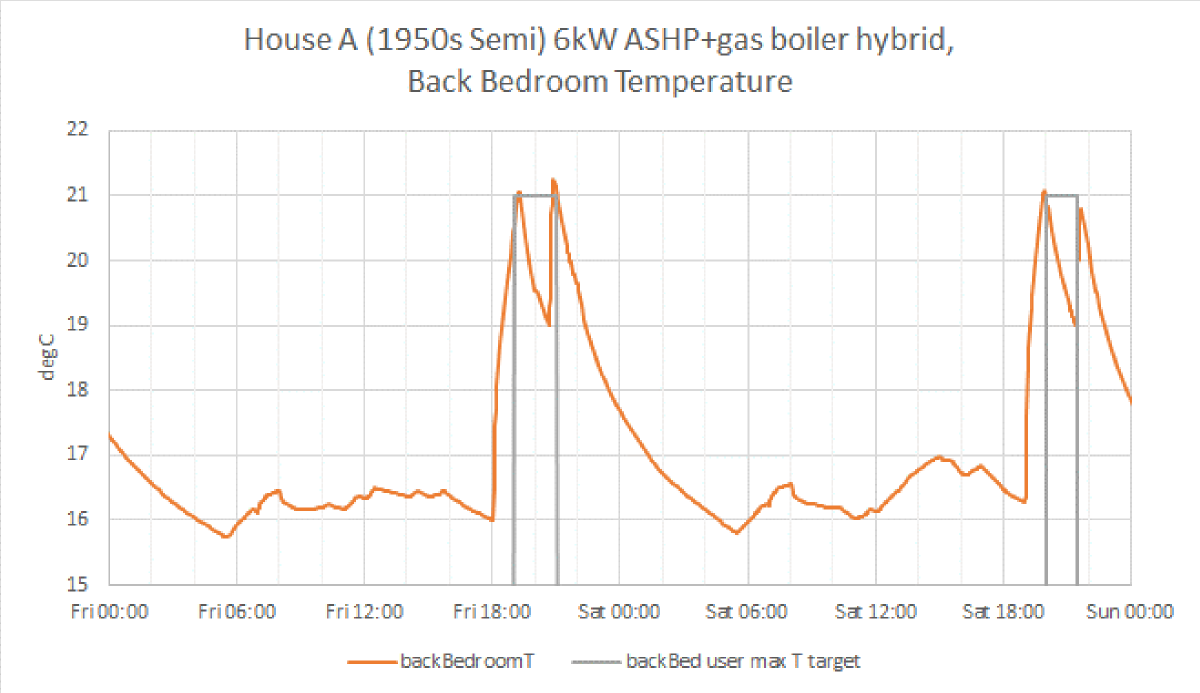

Figure A.5.1-22 – back bedroom temperature, 6kW air source heat pump (2.5 kW input limit) plus gas boiler with full upgrades

A.5.1.6.1. ASHP/gas boiler hybrid + upgrades: annual energy consumption

The upgraded case with a hybrid heat pump above was run for two weeks in every four for a year, with weekly energy consumption taken from the second week in each case to give an estimate of annual consumption for comparison with the combi-boiler results above. The overall energy consumption is less than 45% of the base-line case (single zone control, no upgrades). The weekly average effective COP is ranges from 2.8 to 3.6 thanks to using the gas boiler for warm-up and DHW, with an annual average overall COP (including the gas boiler) of about 1.5. Note that, in contrast to the stand-alone ASHP case, where losses from the DHW tank reduced the COP in summer, the effective COP increases in warmer weather when the heat pump is used only for space heating. The overall COP (including the boiler) does, however, fall to the boiler efficiency during the summer when the heat pump is not used.

Table A.5.1-12 – Air source heat pump with upgraded building fabric: annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	**Annual Energy Consumption, kWh**	**Energy Output for DHW, kWh**	**Energy Output for SH, kWh**
6kW ASHP 2.5kW input limit + gas boiler in series, full upgrades	4462 (gas), 2108 (elec.)	2449	7600

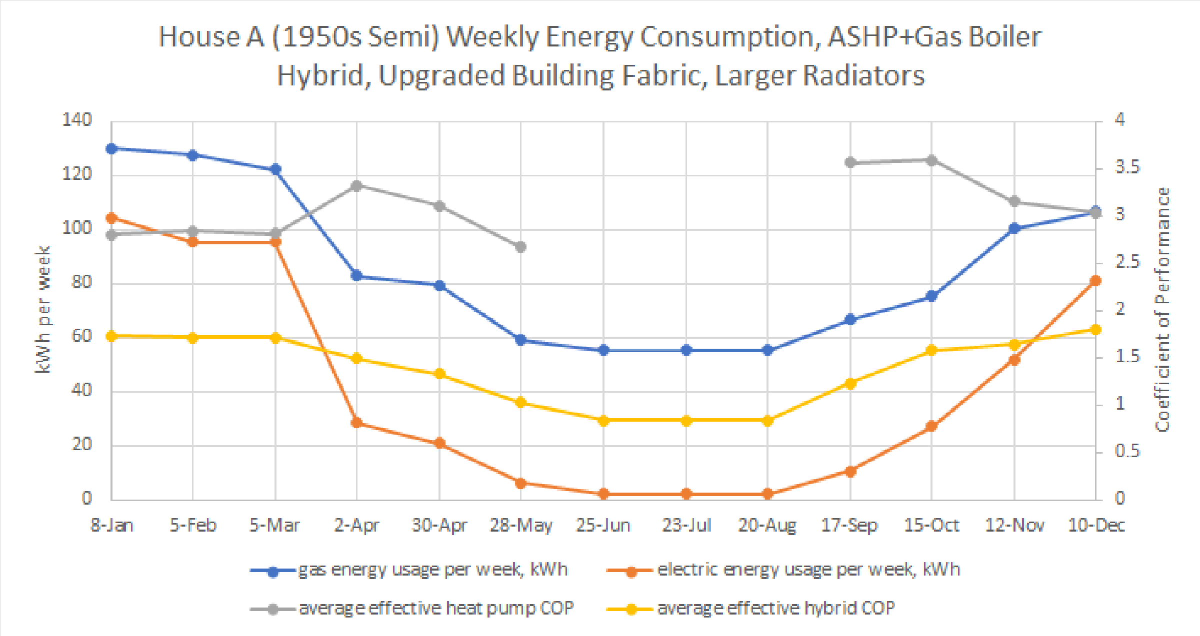

Figure A.5.1-23 – weekly energy consumption, air source heat pump/gas boiler hybrid, with building fabric upgrades

A.5.1.7. Upgrade pathway stages

The following stages in the pathway to fully upgraded building fabric and heat source have been identified (including considerations of practicalities, disruption and benefits to the householders):

Stage 1: multizone control + complete cavity wall insulation

Stage 2: replace windows and doors + upgrade radiators

Stage 3A (optional): 6 kW ASHP in series with existing gas boiler

Stage 3B: 6 kW ASHP + 200 litre DHW cylinder

The summary of the results for each stage in the pathway are shown in Table A.5.1-13 and Table A.5.1-14.

Table A.5.1-13 – pathway stages, summary (two weeks, mid-winter)

Case	**Energy Used, kWh**	**Fraction of Demand Time Below T Range, %**			
		Living Rm	**Dining Rm**	**Front Bedroom**	**Back Bedroom**
Base (single zone control)	1044	3.2	40.3	63.7	32.5
Stage 1 (MZ + CWI)	912	0.0	2.7	1.6	2.5
Stage 2 (+ windows + doors + rads)	820	0.0	2.2	0.0	0.0
Stage 3A (+ASHP/boiler)	418	0.0	2.1	0.0	0.0
Stage 3B (+ ASHP)	286	0.0	2.1	0.0	0.0

Table A.5.1-14 – pathway stages, estimated annual consumption for heating and hot water (Newcastle-upon-Tyne, typical mean year)

Case	Annual Energy Consumption, kWh	Energy Saving, %	Energy Output for DHW, kWh	Energy Output for SH, kWh
Base (single zone control)	14668		2463	10795
Stage 1 (MZ + CWI)[1]	12194	16.9	2480	8494
Stage 2 (+ windows + doors + rads)	11047	24.7	2475	7274
Stage 3A (+ASHP/boiler)	4462 (gas), 2108 (elec)	55	2449	7600
Stage 3B (+ ASHP)	4043	72.4	2497	7270

Note 1: estimated from results from winter stage 1 and annual and winter base case (MZ) and stage 2.

A.5.2. Summary of IEHeat Results for House B (1920s mid-terrace)

A.5.2.1. House and household description

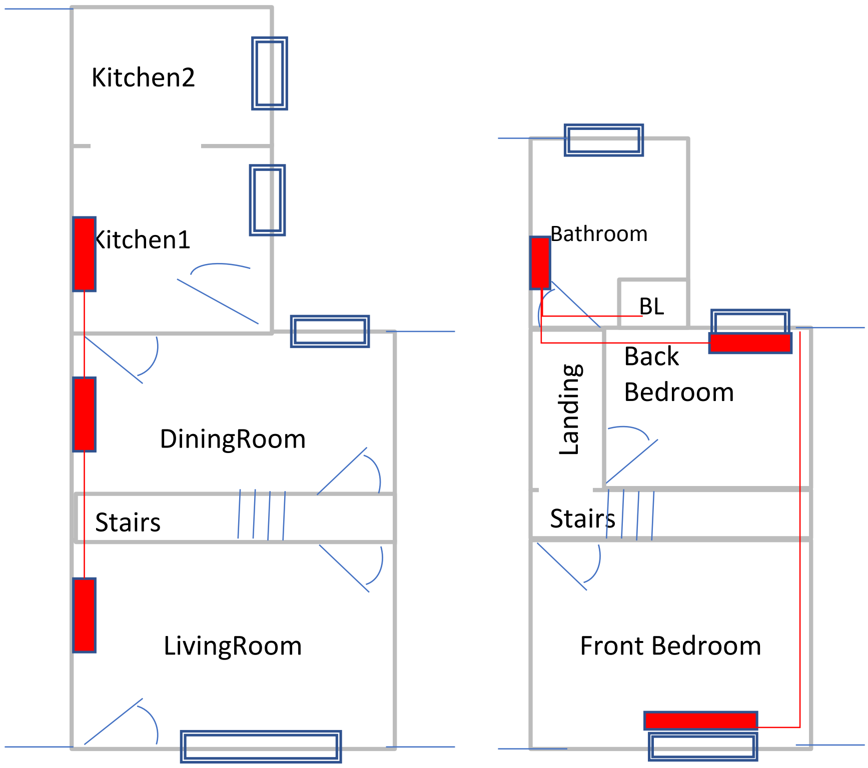

Figure A.5.2-1 House B schematic (simplified for modelling)

The house has solid double-skinned walls which are uninsulated. The living room and dining room floors are suspended with vent bricks, while the kitchen has a solid floor. The windows are pre-2002 double glazing; the front and rear doors are also of aging uPVC construction, the rear door being half glazed.

The heating system comprises a non-condensing combi-boiler with mostly modern radiators – all double panel double convectors (DPDC) except in the back bedroom and bathroom, controlled by a single thermostat and timer (in dining room) with TRVs on all radiators. For comparison with the upgrade evaluation cases (below) multizone on/off control was used, with minimum valve openings set to use the radiators as a buffer (see section **A.4.4**). For the single zone case the radiators are roughly balanced to allow the TRVs to warm up the rooms together. For the multizone case this is not so necessary (as no room should over heat) so the lockshield valves have been opened wider to improve warm-up times.

The following data was used to define the household requirements and behaviour: 7 day temperature profiles have been approximated from combined sets of HEMS-trial data (which is per-room and varies over time) – for the single zone case this has been merged to give a boiler heat demand whenever any room requires heating; occupancy heat gains have also been estimated from sets of HEMS data; the doors and windows are normally closed, with the exception of the kitchen (internal door closed and window open only when cooking) bathroom (door closed and window open only when showering) and some brief opening (for morning/midday/evening activity); DHW demands simulate morning and evening usage (totalling about 180 litres per day at 40°C).

A.5.2.2. Base case results, winter

Results with the existing building fabric and heat source are tabulated below. Note the poor comfort metrics for the single zone case result from the long warm-up time in cold weather resulting from the sub-optimal radiator balancing (the single thermostat in the dining room turns the heating off before all the rooms are warm). The multizone case, which gives a reduction in energy usage of about 9%, will be used for comparison with building fabric upgrade options.

Table A.5.2-1 Base case results summary (mid-winter, two weeks)

Case	**Energy Used, kWh[1,2]**	**Fraction of Demand Time Below T Range, %**				
		Living Rm	**Kitchen**	**Front Bed**	**Back Bed**	**Dining Rm**
Base (single zone control)	1124	41.8	15.9	7.1	0.5	1.4
Base (multizone control)	1018	1.4	1.2	0.5	2.0	0.5

Notes: 1 - Gas energy stated is gross (i.e. including latent heat of water); 2 - These results relate to a mid-winter two week period in Newcastle-upon-Tyne.

A.5.2.3. Base case annual energy consumption

The annual energy consumption has been estimated as described in the introduction to the results summaries. The multizone case is again shown to use about 9% less energy as some rooms are heated for only a fraction of the overall demand period used in the single zone case.

Table A.5.2-2 - Base case estimated annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	**Annual Energy Consumption, kWh[1]**	**Energy Output for DHW[2], kWh**	**Energy Output for SH, kWh**
Base (single zone control)	17024	2335	11242
Base (multizone control)	15427	2341	9904

Notes: 1 - Gas energy consumption stated is gross (i.e. including latent heat of water); 2 – energy to DHW varies between cases due to interaction with space heating causing varying boiler temperatures at the beginning of DHW demand events.

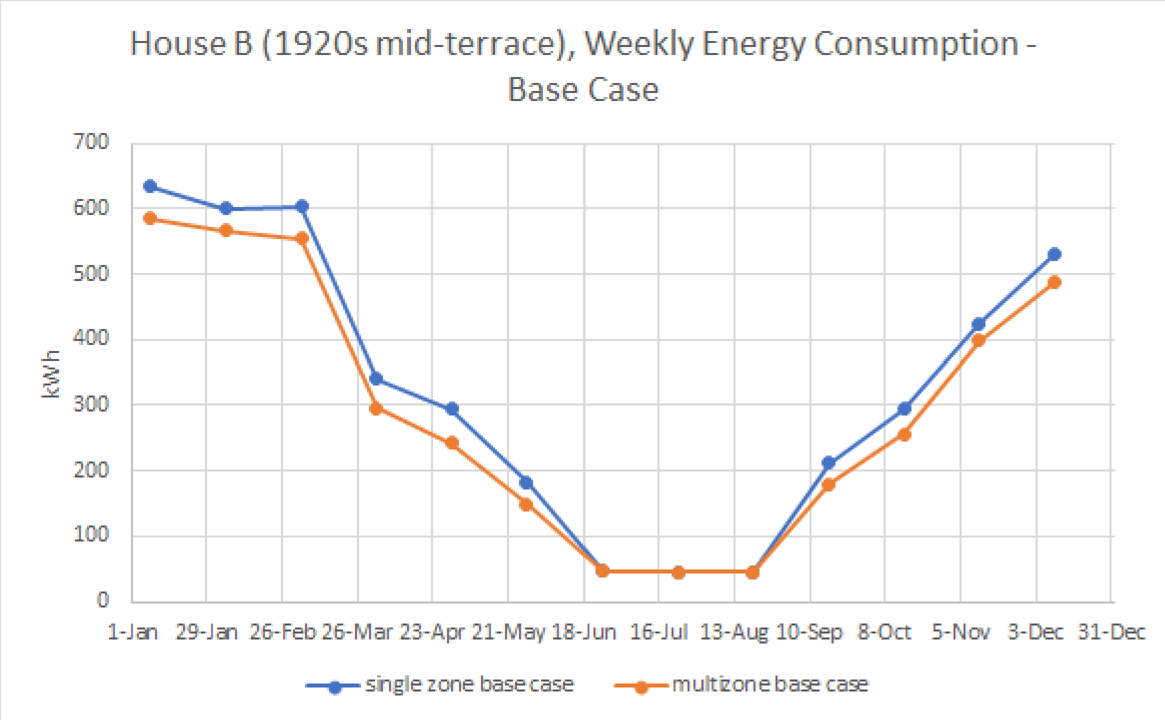

Figure A.5.2-2 - weekly energy consumption, base case

A.5.2.4. Building fabric upgrade evaluation cases

A summary of results of evaluation cases are presented below, investigating the impact of building fabric upgrades, to enable energy and comfort gains to be incorporated with practical and household issues in the decision process to choose upgrades to recommend.

A.5.2.4.1. Evaluation cases: windows, doors, floor, loft and wall insulation

Reducing all window U-values from 2.8 to 2 W/m2/K gave a 4.3% saving in energy used in winter. Updating external doors to thicker, better insulated/draft-proofed (modern standard, external U=1.8-2.2) had a smaller impact of about 1.6% saving.

Table A.5.2-3 – Windows and doors upgrade results summary (mid-winter, two weeks)

Case	**Energy Used, kWh**	**Energy saving w.r.t. MZ base case**	**Fraction of Demand Time Below T Range, %**				
			Living Rm	**Kitchen**	**Front Bed**	**Back Bed**	**Dining Rm**
New windows	976	4.3%	1.1	0.9	0.3	1.1	0.4
New doors	1004	1.6%	1.1	0.9	0.4	1.4	0.5
New windows and doors	961	5.8%	0.6	0.6	0.3	1.0	0.6

Floor and roof insulation evaluation cases are summarized below:

Table A.5.2-4 – Floor and roof insulation upgrade results summary (mid-winter, two weeks)

Loft insulation (total), mm	Kitchen extension roof insulation, mm	Suspended floor insulation, mm	Energy used, kWh	Energy saving, %	Fraction of Demand Time Below T Range, %				
					Living Rm	Kitchen	Front Bed	Back Bed	Dining Rm
100	50	0	1020		1.5	1.1	0.4	1.4	0.6
150	50	0	1014	0.7	1.4	1.1	0.4	1.2	0.7
250	50	0	1007	1.3	1.4	1.1	0.3	0.9	0.5
100	150	0	1018	0.2	1.5	1.1	0.4	1.5	0.6
150	150	0	1011	0.9	1.5	1.0	0.4	1.3	0.7
100	50	50	970	5.0	0.9	0.7	0.5	1.4	0.6
100	50	75	963	5.6	0.8	0.7	0.4	1.3	0.6
100	50	100	958	6.1	0.9	0.6	0.4	1.1	0.6
150	150	100	949	7.0	0.9	0.6	0.4	1.2	0.6

Loft insulation upgrades have only a small effect (< 1.5%), kitchen roof insulation has very little effect (< 1%), although these savings may be achieved at low cost, depending on ease of access to the roof spaces. Although significantly more disruptive and costly, insulating the suspended floors in the living and dining rooms makes a significant difference to energy used (5-7%), with maximum warm-up times in the living room dropping from nearly 50 minutes to about 36 minutes, giving a corresponding improvement in comfort metric.

Comparing the living room temperature trends shows a reduction in cooling rates, indicating floor insulation gives a significant reduction in overall room heat loss when at target temperature.

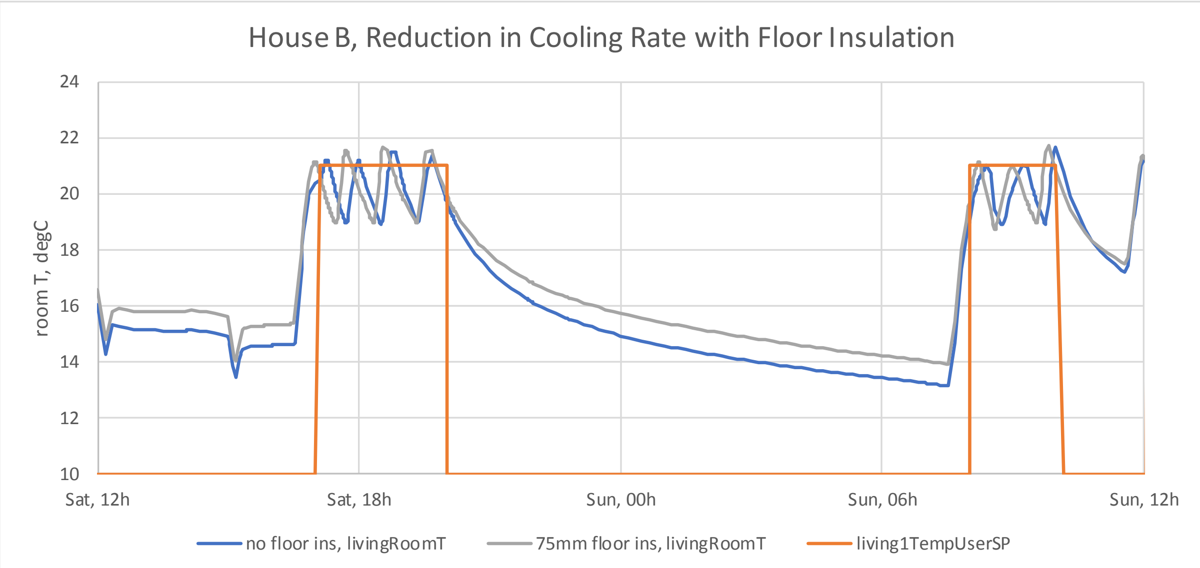

Figure A.5.2-3 - Effect of floor insulation on room cooling rate

Wall insulation cases, assuming expanded polystyrene (thermal conductivity=0.035 W/m/K) – note using polyisocyanurate could achieve the same results with about 40% reduction in thickness:

Table A.5.2-5 - wall insulation upgrade results summary (two weeks, mid-winter)

Case	Energy Used, kWh	Energy saving, %	Fraction of Demand Time Below T Range, %				
			Living Rm	Kitchen	Front Bed	Back Bed	Dining Rm
Base case (no wall insulation)	1018		1.4	1.2	0.5	2.0	0.5
10 mm EWI	939	7.7	1.4	0.3	0.1	0.8	0.4
20 mm EWI	895	12.1	1.3	0.0	0.0	0.6	0.2
30 mm EWI	863	15.2	1.2	0.0	0.0	0.4	0.3
40 mm EWI	843	17.2	1.2	0.0	0.0	0.3	0.2
50 mm EWI	827	18.7	1.1	0.0	0.0	0.3	0.1
70 mm EWI	807	20.7	1.0	0.0	0.0	0.0	0.0
100 mm EWI	790	22.4	1.0	0.0	0.0	0.0	0.0
5 mm IWI[1]	966	5.0	1.5	0.8	0.2	0.5	0.4
10 mm IWI	930	8.6	1.3	0.4	0.1	0.7	0.5
20 mm IWI	884	13.2	1.4	0.2	0.0	0.6	0.3
30 mm IWI	854	16.1	1.3	0.1	0.0	0.3	0.3
40 mm IWI	835	18.0	1.2	0.0	0.0	0.2	0.0

Note 1: range of thicknesses evaluated deliberately extends below practical range for model consistency checking.

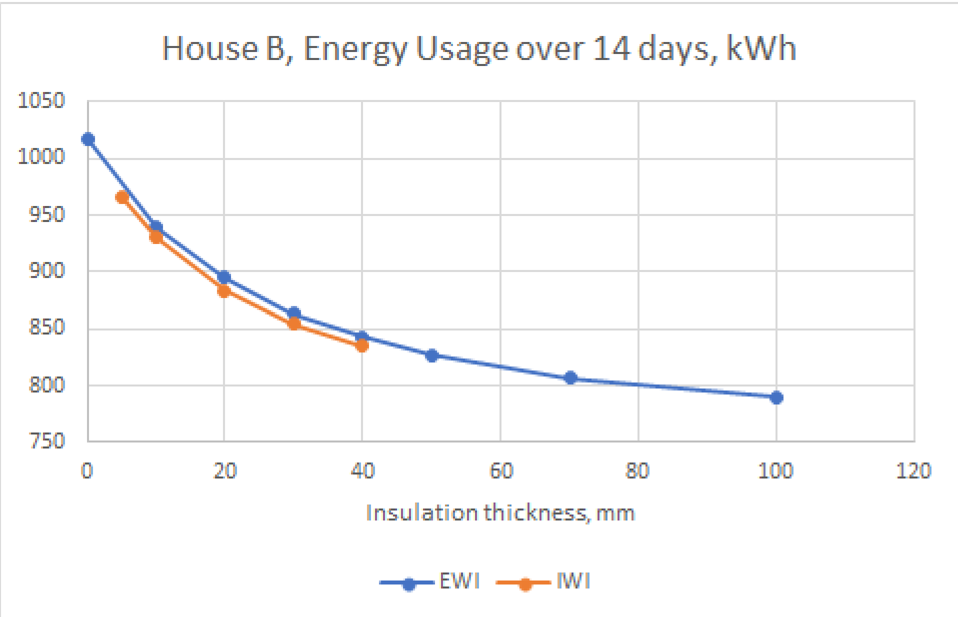

Figure A.5.2-4 - Reduction in energy consumption with increasing wall insulation thickness

The comfort metrics show small improvements (indicating the control is working well in all cases) but practical thicknesses of wall insulation show significant energy savings (e.g. 18% for 40 mm of internal insulation). The impact on warm up times is also significant, especially upstairs, where the maximum warm-up times in the back bedroom drops from about 45 minutes to about 20 minutes. Note that this level of insulation can lead to a small overshoot in room temperature, resulting from the much-reduced heat loss from the room being less than the residual heat output of the radiator for 5-10 minutes after it is turned off. This effect is slightly more pronounced with internal wall insulation due to the reduced thermal mass being heated.

Comparing 40mm of EWI with the same thickness of IWI shows the change in thermal capacity being heated (in the external walls) which results in room temperatures in the IWI case warming up and cooling down faster. It appears that, as well as reducing the internal room dimensions, IWI would give colder night time temperatures, and may be more susceptible to perceptible cold spots where the insulation is incomplete. These differences are also reflected in the internal surface temperatures of external walls, which are improved on average by both EWI and IWI, but the variations with EWI are smoothed over time, whereas IWI tends to give far higher surface temperatures during periods of heating.

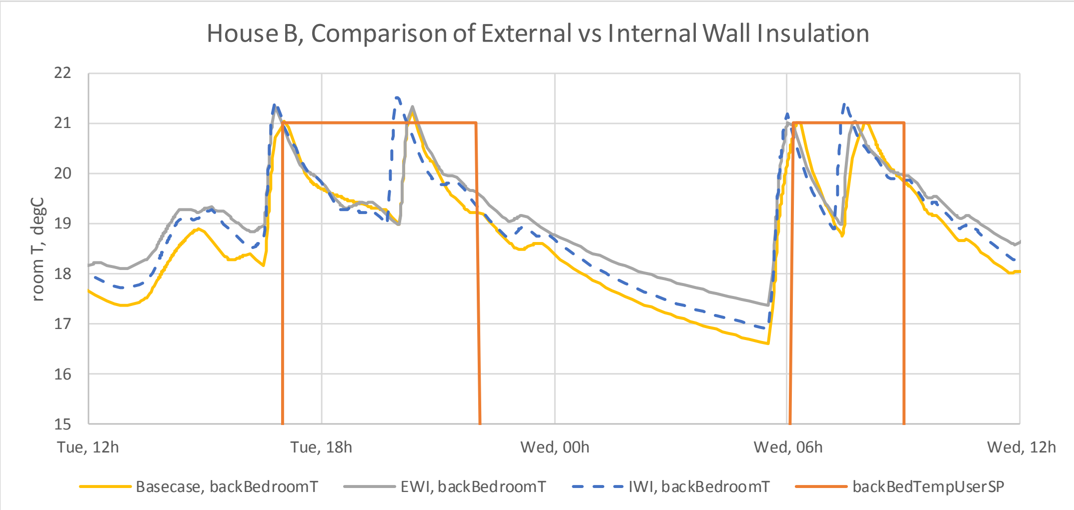

Figure A.5.2-5 - Effect of internal and external wall insulation on bedroom temperature

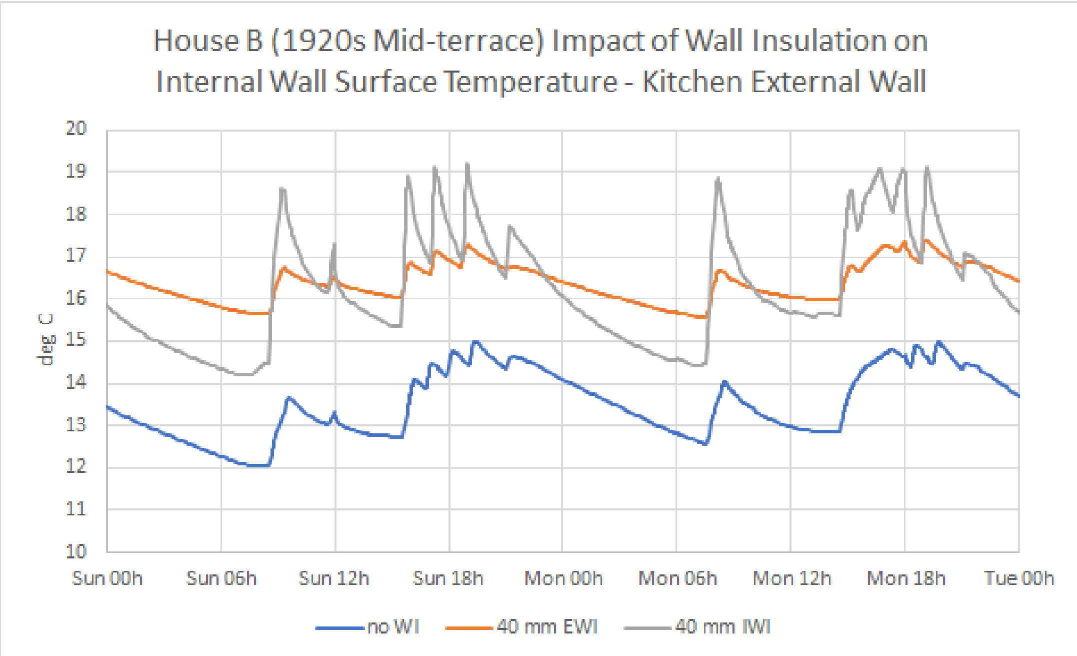

Figure A.5.2-6 - Effect of internal and external wall insulation on kitchen wall surface temperature

A.5.2.4.2. Possible combinations of upgrades

If energy saving is a priority of the upgrade pathway (likely if a heat pump is proposed) then the results suggest that the biggest gains would be found in upgrading the windows, draft proofing the front door, 75 mm of underfloor insulation in the living and dining rooms, and installing 100 mm of external wall insulation at the rear and 40 mm of internal wall insulation at the front of the house. This results in a 40% energy saving with respect to the single zone base case in mid-winter, falling to a saving of about 21% if no wall insulation is installed.

Table A.5.2-6 - upgraded building fabric results summary (two weeks, mid-winter)

Case	Energy Used, kWh	Fraction of Demand Time Outside Range, %				
		Living Rm	Kitchen	Front Bed	Back Bed	Dining Rm
new windows, draft proofing front door, 75 mm suspended floor insulation, 100mm EWI rear, 40mm IWI front	672	0.5[1]	0	0	0	0.3
new windows, draft proofing front door, 75 mm suspended floor insulation	885	0.3	0	0.1	0.1	0.1

Note 1: the anomalous living room comfort metric is a result of opening the front door during warm times.

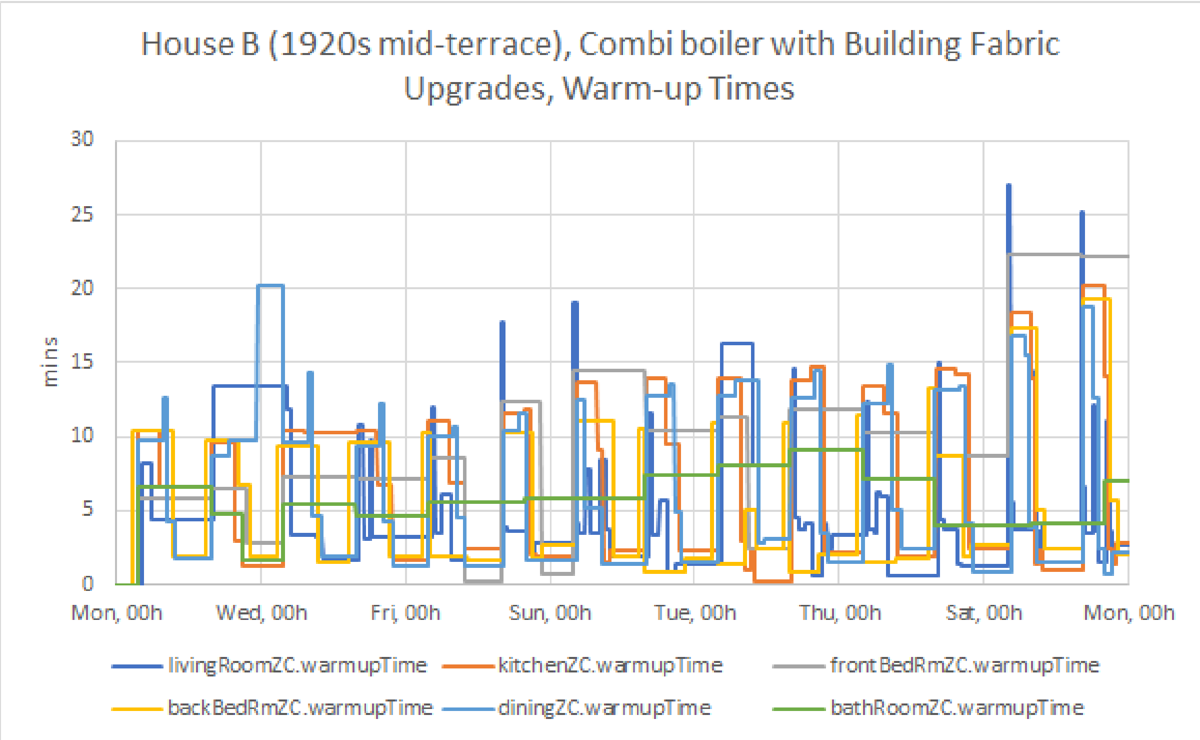

Figure A.5.2-7 - warm-up times with all building fabric upgrades and gas boiler

Annual consumption for the suggested upgraded building fabric case was estimated as for the base case, with the consumption for the partial upgrade being estimated by scaling from the base case using the two week mid-winter results.

Table A.5.2-7 – Upgraded building fabric: estimated annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	**Annual Energy Consumption, kWh**	**Energy Output for DHW, kWh**	**Energy Output for SH, kWh**
new windows, draft proofing front door, 75 mm suspended floor insulation, 100mm EWI rear, 40mm IWI front	9817	2335	5569
new windows, draft proofing front door, 75 mm suspended floor insulation	13654[1]	2335[1]	8505[1]

Note 1: partial upgrade case estimated by scaling from two week mid-winter results.

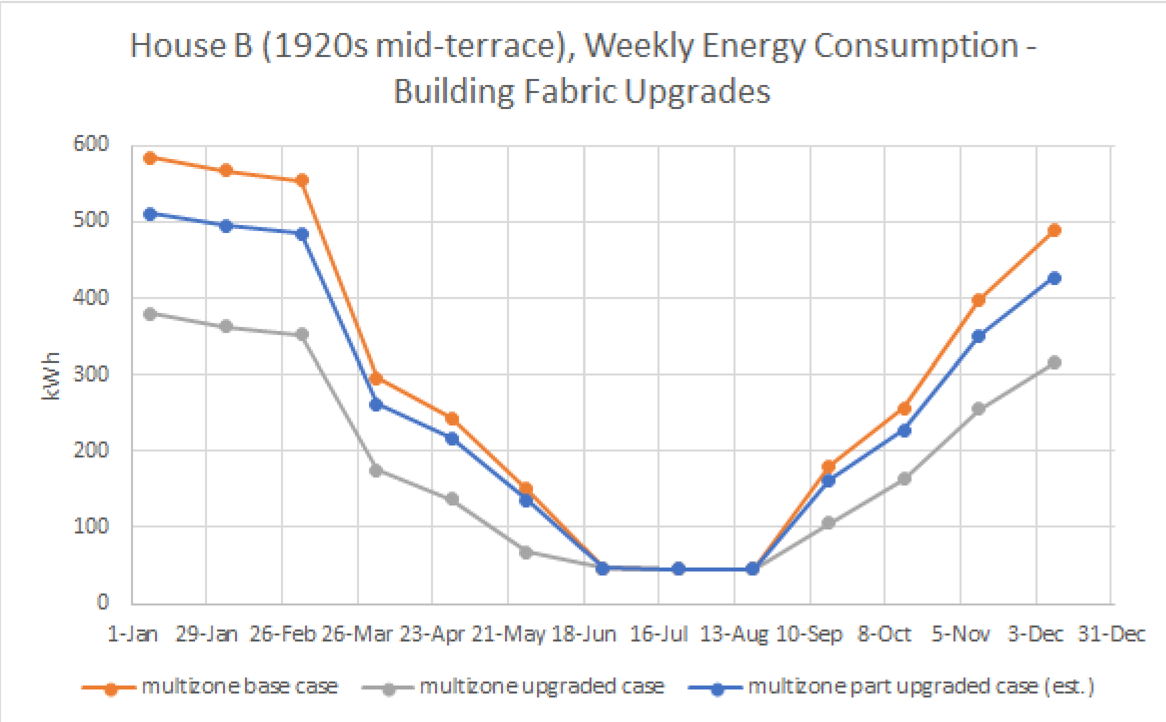

Figure A.5.2-8 - weekly energy consumption, upgraded building fabric cases

A.5.2.5. Air source heat pump

Using an air-source heat pump as the heat source was considered technically feasible for this house. From preliminary tests, House A results and the base case simulations reported above, it was clear that using a lower heating medium temperature with no other changes would give unacceptably long warm-up times. Therefore some heating system upgrades were considered for the cases using the heat pump. Also, assuming the bulk of the heat pump equipment is mounted externally, the boiler cupboard in the bathroom could provide space to reinstate a DHW cylinder, which would facilitate use of a heat pump without a supplementary water heater (other than an optional 3kW immersion heater).

A.5.2.5.1. ASHP with and without building fabric upgrades

Two cases using an air source heat pump were simulated, with the following common changes:

i. Combi boiler replaced with a 6 kW (nominal output) ASHP with an input power limit of 2.5 kW, coupled with a 200 litre insulated DHW cylinder (fitted with a 3 kW immersion heater to supplement the heat pump if necessary – not used in this case).
ii. Multizone control with lockshields more fully opened (especially in the bathroom), to increase the power output of the radiators (also assuming higher hot water pump flow rate than original combi boiler)
iii. Heat pump outlet temperature for SH set as a linear function of outside air temperature (rising to 55 °C at or below 5 °C outside) and increased to 5 °C above the DHW tank setpoint when higher than the SH requirement (in warm weather or to achieve 60 °C for 1 hour each morning to guard against legionella).
iv. 30 minute pre-heat times used for SH, 90 minutes for DHW tank.
v. Bathroom door left closed (rather than open when not in use).
vi. Back bedroom radiator upgraded to double panel double convector (DPDC)
vii. Temperature profile for DHW tank adjusted to avoid clashes with SH warm-up times (by heating to 60 °C at 5am), and allowed to heat both simultaneously (subject to power limits of the ASHP).

For comparison, one case used the building fabric as per the base case, while the second case assumed installation of all upgrades in the combined case suggested above.

Table A.5.2-8 – air source heat pump results summary (two weeks, mid-winter)

Case	**Energy Used, kWh**	**Peak Electricity Demand, W**	**Fraction of Demand Time Below T Range, %**				
			Living Rm	**Kitchen**	**Front Bed**	**Back Bed**	**Dining Rm**
ASHP without upgrades	289	2573	8.6	7.1	10	0.3	4.9
ASHP with upgrades	204	2623	1.3	0.0	0.5	0.0	0.0

The results indicate good comfort performance (better than the current situation, based on room temperatures during desired warm-times) can be achieved with an air source heat pump without excessive peak demand on the electricity grid, provided building fabric upgrades reduce heat loss from the dwelling. The mean effective COP (see glossary, **Appendix 1**) over two mid-winter weeks for the “with upgrades” case is 2.6, giving an energy consumption of about 18% of that used by the single-zone base case. Warm-up times in the two week mid-winter case with upgrades are predicted to be generally less than 30 minutes, and less than 50 minutes on the coldest days. Without building fabric upgrades the warm-up times are significantly longer, and on the coldest days, some rooms fail to reach their target temperature range within the required warm-time.

Note on ASHP water pump capacity: most heat pump data sheets inspected during this study indicate a much larger water flow rate than is typically provided by gas boilers (e.g. 35 litres/min instead of 18 litres/min). Larger flow rates can significantly improve warm-up times by reducing temperature drop through radiators, hence maximizing the temperature difference between radiators and room air. Such flow rates were used in this modelling work. However there is significant variation amongst manufacturers regarding the pump head available to drive the heating circuit flow, with some providing a pump with such small head (e.g. 14 kPa) that piping with an internal dimeter of 32 mm would be required throughout the dwelling – significantly increasing the cost and disruption of heat pump installation. Other manufacturers supply pumps producing 55 kPa at similar flowrates, which would not require pipework replacement. Further simulation work and field trials would be required to establish the optimum approach to delivering heat pump performance with minimum changes to the existing systems.

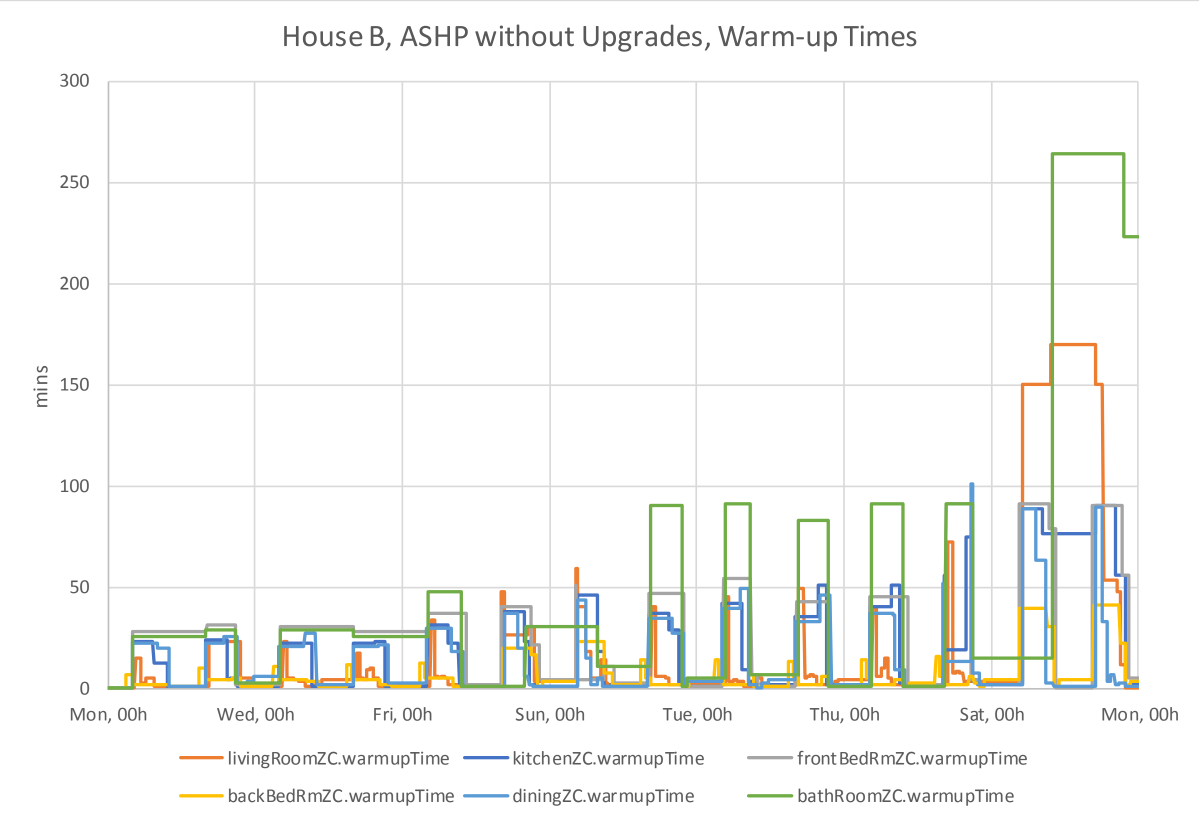

Figure A.5.2-9 – warm-up times, air source heat pump without building fabric upgrades

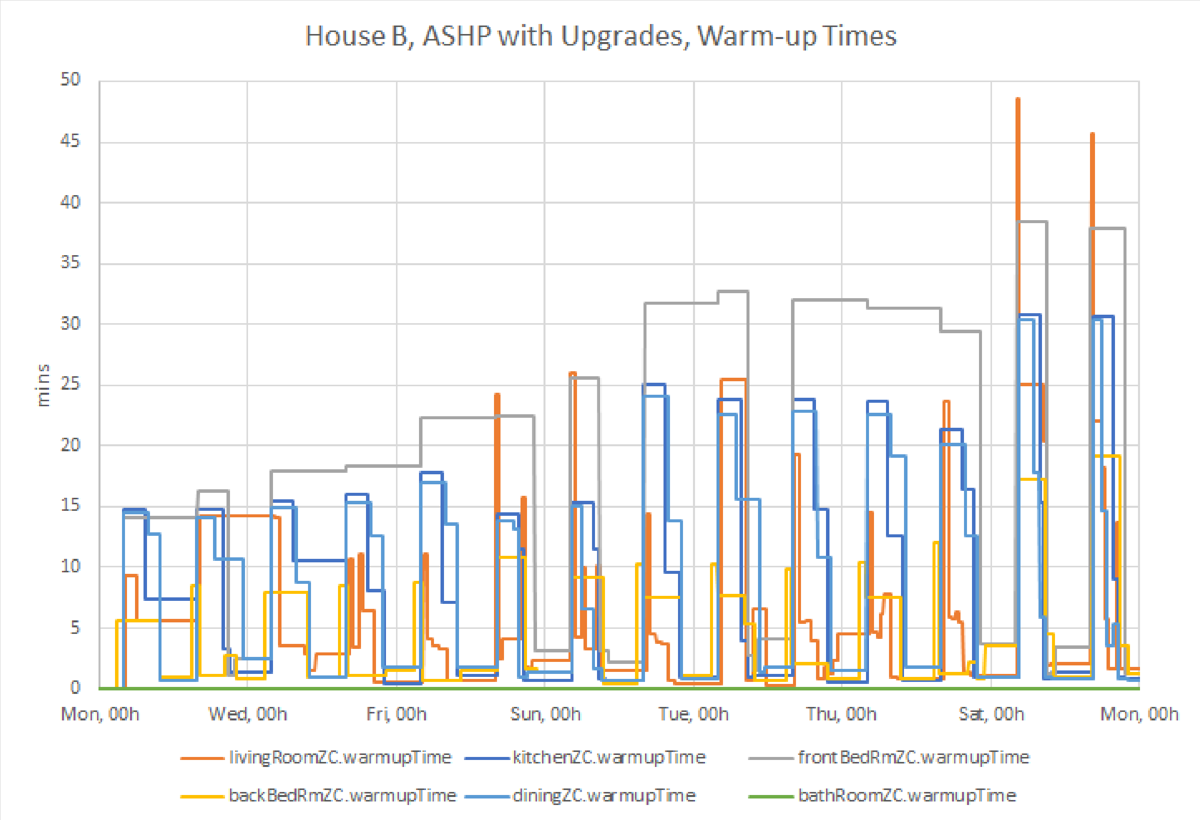

Figure A.5.2-10 – warm-up times, air source heat pump with building fabric upgrades

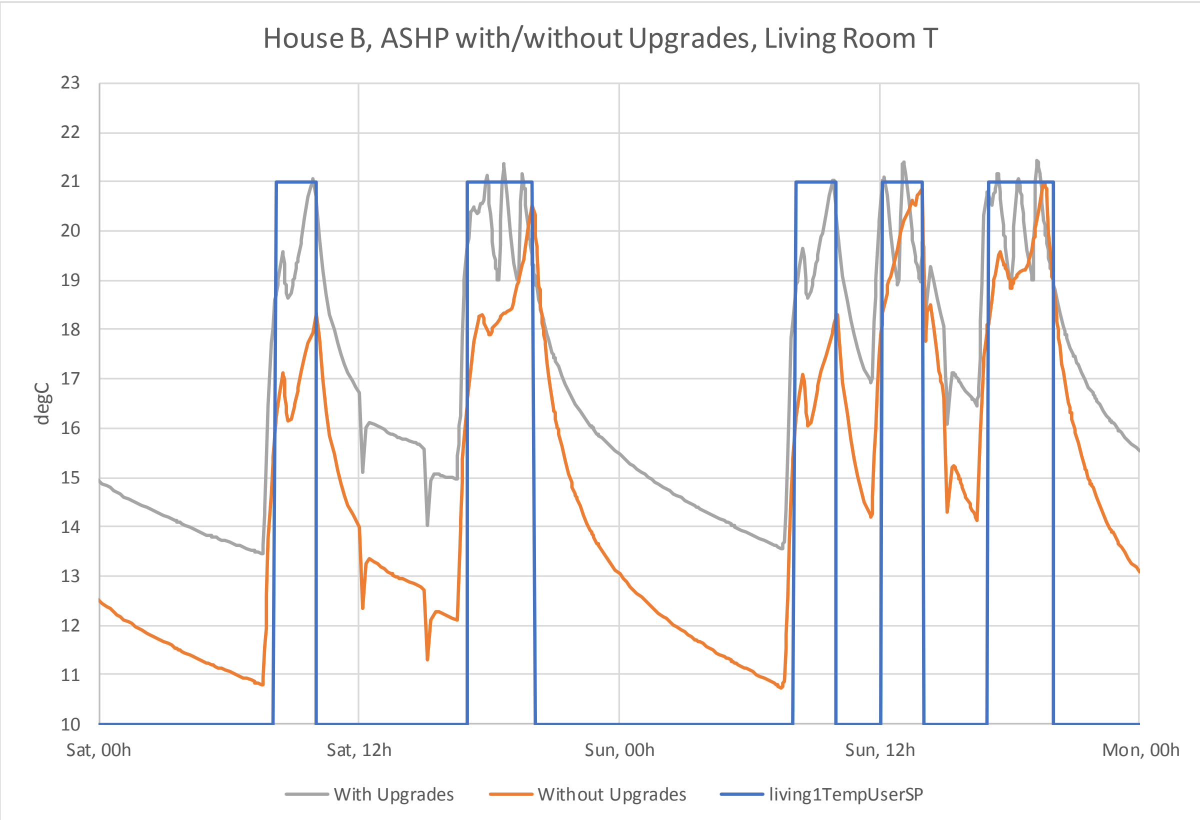

Figure A.5.2-11 – living room temperature, air source heat pump with and without building fabric upgrades

Figure A.5.2-12 shows the electricity demand for heating using the ASHP (with fabric upgrades) is significant at current peak times (e.g. 7-9am and 4-7pm) – suggesting that there is scope for extending the use of thermal storage to space heating to smooth demand.

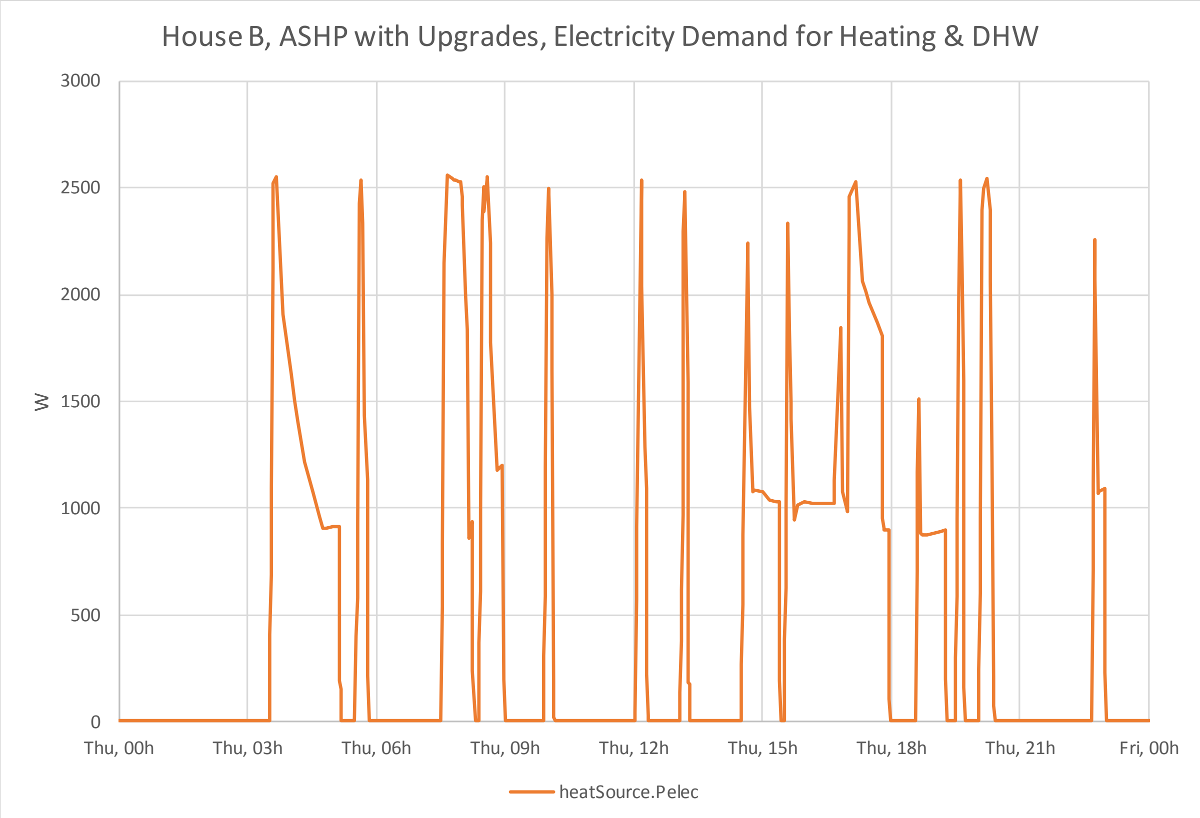

Figure A.5.2-12 – electricity demand for space heating and domestic hot water, air source heat pump with building fabric upgrades

A.5.2.5.2. ASHP with upgrades in extremely cold weather

To evaluate performance of the air source heat pump in extreme weather, the two-week mid-winter case was run with the external temperature 10 °C lower than the data file values. Predictably the heat pump was unable to maintain the desired level of comfort on days with minimum temperatures of -14 °C, particularly in the living room and front bedroom when all rooms are required to warm-up together. However, the room temperatures are rarely much more than 2 °C below the required range during warm-times, so considering the unusual severity of this type of weather in most of the UK, this occasional performance short-fall may not be reason for rejecting this technology. Furthermore, this performance could be improved by well-designed control of heat pump operation which reliably calculates pre-heat times and schedules the heating to avoid attempting to warm too many rooms simultaneously in cold weather.

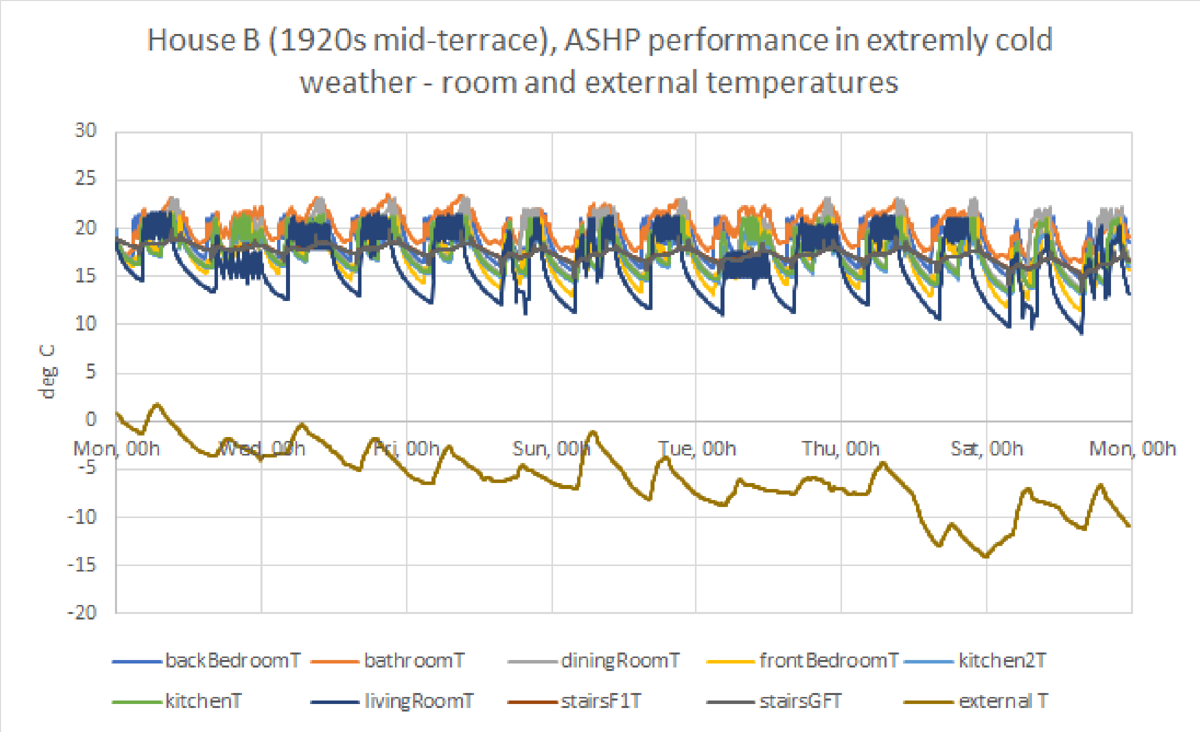

Figure A.5.2-13 – room temperatures during extremely cold two weeks with air source heat pump and building fabric upgrades

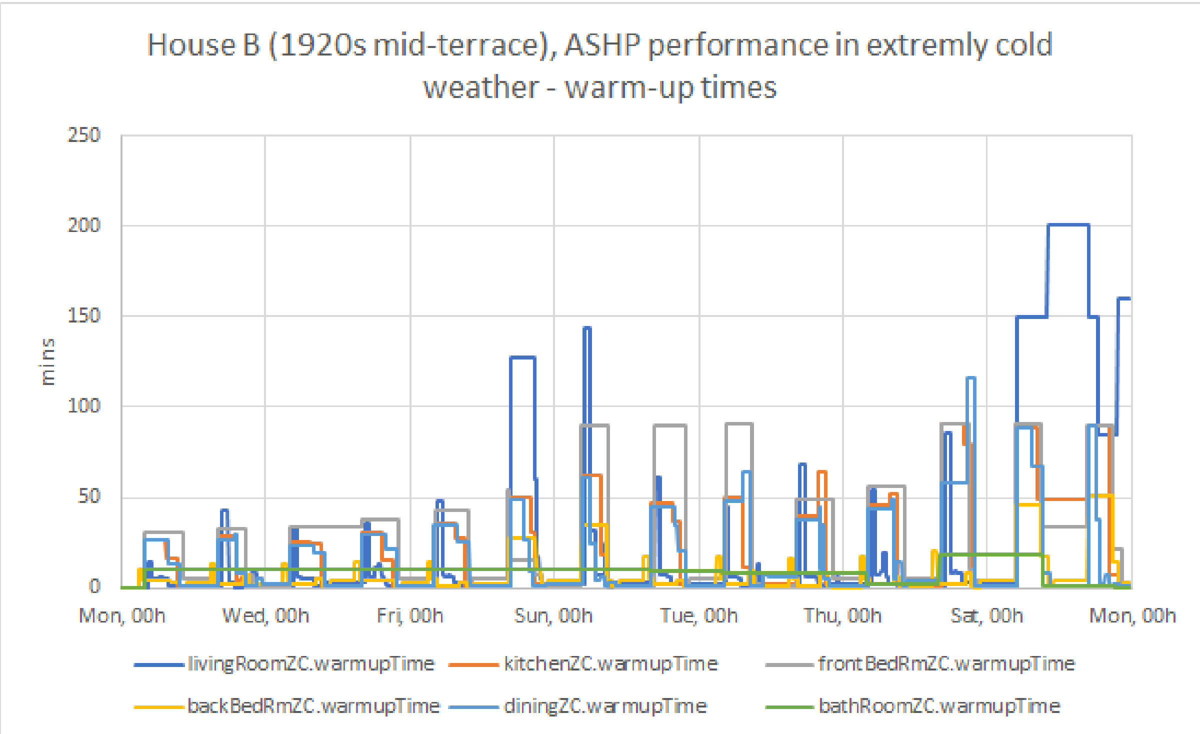

Figure A.5.2-14 – warm-up times during extremely cold two weeks with air source heat pump and building fabric upgrades

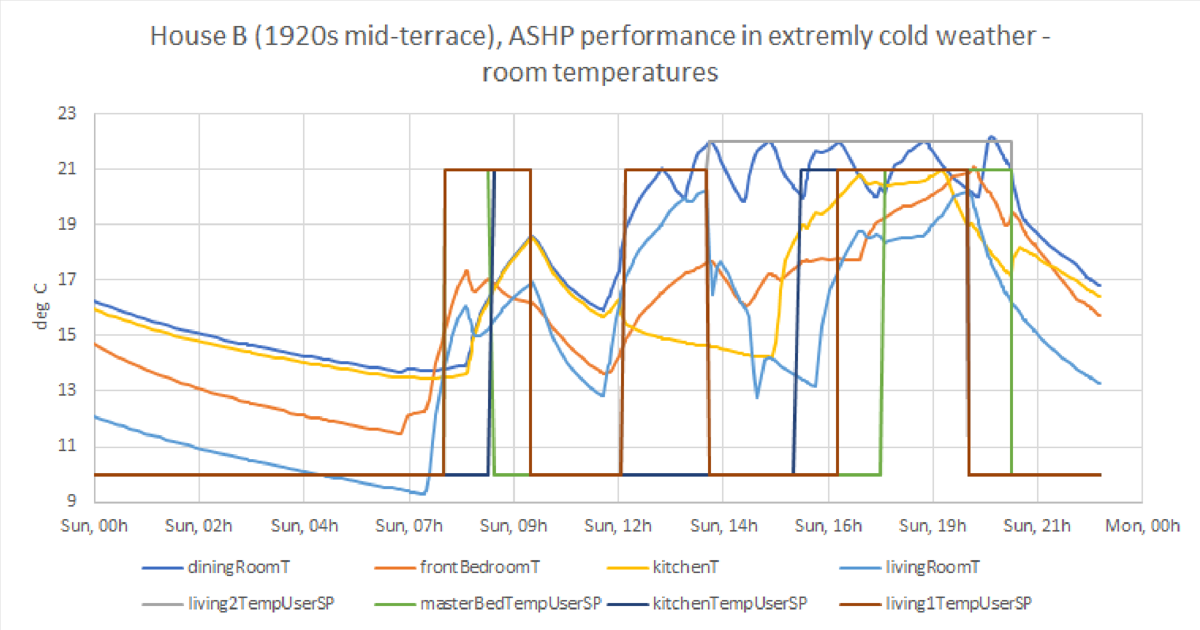

Figure A.5.2-15 – room temperatures during extremely cold 24 hours with air source heat pump and building fabric upgrades

A.5.2.5.3. Multizone + ASHP + upgrades: annual energy consumption

The upgraded heat pump case above was run for two weeks in every four for a year, with weekly energy consumption taken from the second week in each case (to minimize the influence of initial conditions). This gives an estimate of annual consumption for comparison with the combi-boiler results above. The overall energy consumption with a simple linear outlet temperature adjustment is only 19% of the base-line case (single zone control, no upgrades). The savings from changes to building fabric, control and heat source are nearly independent, such that their effects can be characterized as energy reduction factors which can be multiplied together to give the overall reduced consumption. In this case, multizone control reduces annual energy consumption by a factor of 0.91, building fabric by 0.66 and the change from a non-condensing boiler (effective efficiency of 0.79) to a heat pump with an average effective COP of about 2.5, gives a reduction factor for heat source change of 0.32.

Table A.5.2-9 – Air source heat pump with upgraded building fabric: estimated annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	Annual Energy Consumption, kWh	Energy Output for DHW, kWh	Energy Output for SH, kWh
6kW ASHP 2.5kW input limit, multizone control + fabric upgrades	3163	2367	5510

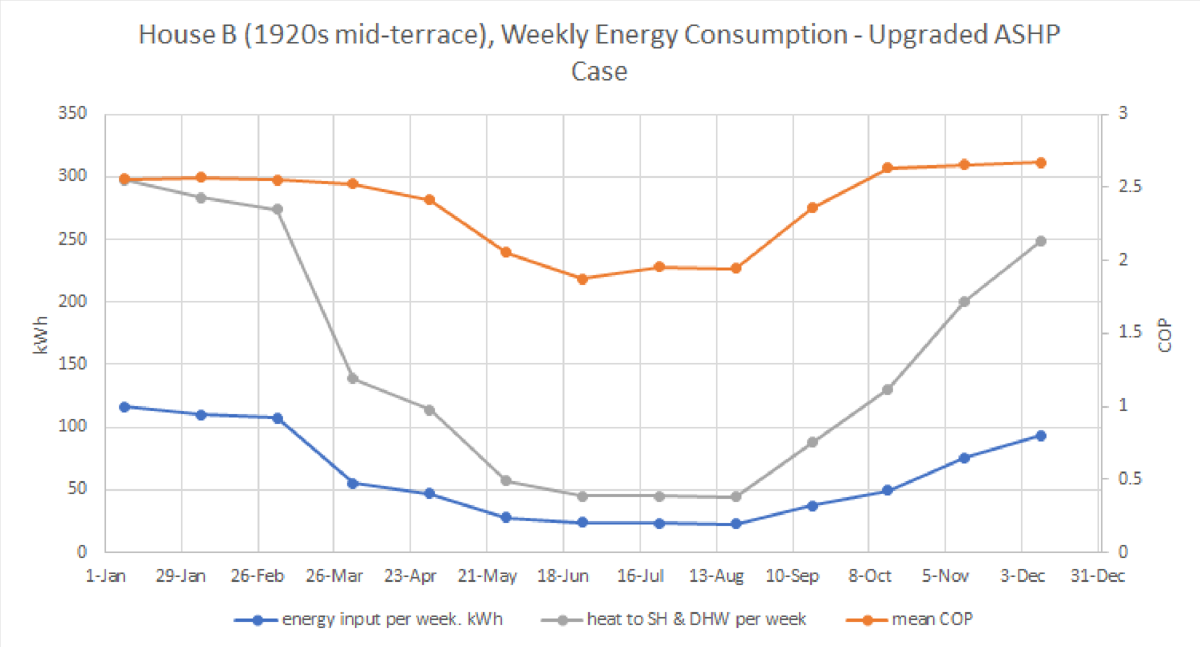

Figure A.5.2-16 – weekly energy consumption, air source heat pump with building fabric upgrades

Note that the heat lost from the water tank (and associated piping), which averages about 100 W, is a far greater proportion of heat pump output in summer months as the space heating requirements reduce. This combines with a small reduction in COP resulting from the requirement to heat the DHW tank to 60°C each day (using a heat pump outlet temperature at 65°C, rather than the maximum for space heating of 55°C) resulting in a lower average effective COP as the external temperature increases.

The nearly constant COP during colder months suggests that it may be possible to reduce energy consumption further by enhancing the function of external temperature used to adjust the heat pump outlet temperature (using a more physical calculation), and perhaps considering reducing the outlet temperature after the initial warm-up. Also, it may be possible to improve comfort performance (based on desired vs. achieved room temperature) by using a more physical calculation of pre-heat time based on radiator nominal power output, room cooling rate and external temperature.

A.5.2.6. District heating – via indirect heat interface unit

This house is in an urban setting which has been determined to be suitable for a district heating scheme. A model of a Heat Interface Unit (HIU) was added to the house model in place of the heat source, consisting of two separate exchangers, with design heat power ratings of 20kW for space heating and 36kW for instantaneous DHW (capable of supplying 15 l/min of DHW with a 35 °C temperature rise). The temperature of the DH supply was varied linearly between 110 and 80°C as the external air temperature varied from -6 to +5°C[48].

[48] From "District heating manual for London", Greater London Authority, February 2013

Five cases were simulated, all with suspended floor insulation and new windows, two with the addition of 100 mm of external wall insulation at the rear and 40 mm of internal wall insulation at the front, and two cases with 40 mm of external wall insulation on all external walls. All cases changed the bathroom door to normally closed. The pairs of cases with wall insulation were run with space heating flow temperatures set to 70°C and 55°C respectively.

The energy drawn from the DH supply (at the inlet to the HIU) is less than the gas energy consumed in the combi-boiler case with equivalent building fabric upgrades. This difference is attributable to the low heat loss from the HIU (it operates at far lower temperatures than the boiler, and there are no flue gas losses). However heat losses in the distribution network (which are not modelled) must be considered when judging the overall efficiency of DH. The SH and DHW are independent of each other, such that the SH is never interrupted to satisfy DHW demand. There are still interactions between radiators during warm-up, particularly at the lower flow temperature. Indeed the difference between the two cases is seen primarily in the warm-up times, which are typically about half the peak values tabulated below (the peaks corresponding to a day with a minimum external temperature of -4°C).

The partially and less upgraded cases indicate that adequate performance can be achieved without the expense and disruption of installing wall insulation, or by installing only 40 mm of wall insulation.

The peak power demands shown in Table A.5.2-10 coincide with warming-up the heat exchangers in the HIU (particularly when starting DHW supply, as this exchanger is exposed to a colder inlet temperature and hence tends to start colder) and typically only last 1-2 minutes. However the DH system would need to be designed to allow for simultaneous maximum demands from SH and DHW, which could be as high as 50 kW, and may last longer (filling a bath at the start of a pre-heat, for example). The DH heat source will also need to generate enough heat to supply these demands plus the heat losses to transport the heat to the dwellings. Typically DH systems are planned and designed to spread their load by supplying commercial as well as domestic properties on their network, thus making domestic peak demands well within the design envelope. Furthermore, although the peaks in demand for a single dwelling may be sharp, the network itself will tend to dissipate some of the effect on return temperatures acting to smooth out these peaks. Nevertheless, such demand patterns indicate that there would be value in further study into smoothing (and possibly shifting) peak demands by use of heat storage within dwellings, and it would also be useful to consider combining dwelling heat, heat storage and low temperature DH networks to reduce distribution losses.

The carbon intensity and operating costs of district heating is dependent on the technology used to generate the heat, which is out of the scope of the current modelling.

Table A.5.2-10 – district heating results summary (two weeks, mid-winter)

Case	Energy Input at HIU, kWh	Peak Power Input at HIU, kW	Peak Power Output from HIU, kW	Maximum warm-up time, mins				
				Living Rm	Kitchen	Front Bed	Back Bed	Dining Rm
DH, no WI, outlet=70°C	715	37.3	28.9	19.4	27.2	38.4	29.4	25.3
DH, 40 mm EWI, outlet=70°C	576	35.5	29.7	16.1	13.7	22.4	13.8	13.6
DH, 40 mm EWI, outlet=55°C	573	37.7	24.2	49.3	31.6	42.9	39.3	30.4
DH, 40 mm IWI (front), 100 mm EWI (rear), outlet=70°C	543	35.7	29.3	17.0	12.3	19.8	11.7	12.4
DH, 40 mm IWI (front), 100 mm EWI (rear), outlet=55°C	537	38.1	24.1	52.2	23.4	39.7	34.6	23.3

Note that the peak power input is calculated in the same way as a typical HIU heat meter by multiplying the DH supply flow rate by the fluid's specific heat capacity and by the difference between its inlet and outlet temperatures i.e. F*Cp*(Tin-Tout). The differences between the inlet and outlet powers are a reflection of the heat losses from the HIU and the heat required to initially warm-up the heat exchanger(s) at the start of each heat supply event. The input power peaks coincide with starting DHW supply events, whereas the output power peaks are at times when both SH and DHW are supplied simultaneously.

The inlet boundary is modelled as a nominal length insulated spur from the main network supply pipeline. When the HIU is not taking heat from the network this line slowly cools. The cases with a lower SH flow temperature (55 °C) tend to require longer and more periods of (lower power output) heat supply to warm the house. This means that there tend to be shorter times between heating events for SH and events for supplying DHW such that the water in the spur has less time to cool. As a result, at the start of the householder's late evening shower, the inlet temperature to the HIU tends to be warmer for the 55 °C cases than for the 70 °C cases. This is particularly noticeable on the coldest days, resulting in a higher inlet power peak for the lower SH flow temperature cases.

A.5.2.7. Upgrade pathway stages

The following stages in the pathway to fully upgraded building fabric and heat source have been identified (including considerations of practicalities, disruption and benefits to the householders):

Stage 1: multizone control + 75 mm suspended floor insulation + improve draft-proofing around front door

Stage 2: add 40 mm internal wall insulation at front, 100 mm external wall insulation at rear + replace windows + upgrade back bedroom radiator

Stage 3: ASHP or DH

The summary of the results for each stage in the pathway are shown below.

Table A.5.2-11 – pathway stages, summary (two weeks, mid-winter)

Case	Energy Used, kWh	Fraction of Demand Time Below T Range, %				
		Living Room	Kitchen	Front Bed	Back Bed	Dining Room
Base case	1124	41.8	15.9	7.1	0.5	1.4
Stage 1 (MZ + floor + front door)	965	0.7	0.0	0.1	0.1	0.1
Stage 2 (EWI/IWI + windows + radiator)	672	0.5	0.0	0.0	0.0	0.3
Stage 3 option 1 (ASHP)	204	1.3	0.0	0.5	0.0	0.0
Stage 3 option 2 (DH)	543	0.3	0.0	0.0	0.0	0.0

Table A.5.2-12 – pathway stages, estimated annual consumption for heating and hot water (Newcastle-upon-Tyne, typical mean year)

Case	Annual Energy Consumption, kWh	Energy Saving, %	Energy Output for DHW, kWh	Energy Output for SH, kWh
Base case	17024		2335	11242
Stage 1 (MZ + floor + front door)	14306	16	2340	8948
Stage 2 (EWI/IWI + windows + radiator)	9817	36	2335	5567
Stage 3 option 1 (ASHP)	3163	81	2367	5510
Stage 3 option 2 (DH)	7917[1]	53	2364	5644

Note 1: DH energy consumption estimated at HIU input.

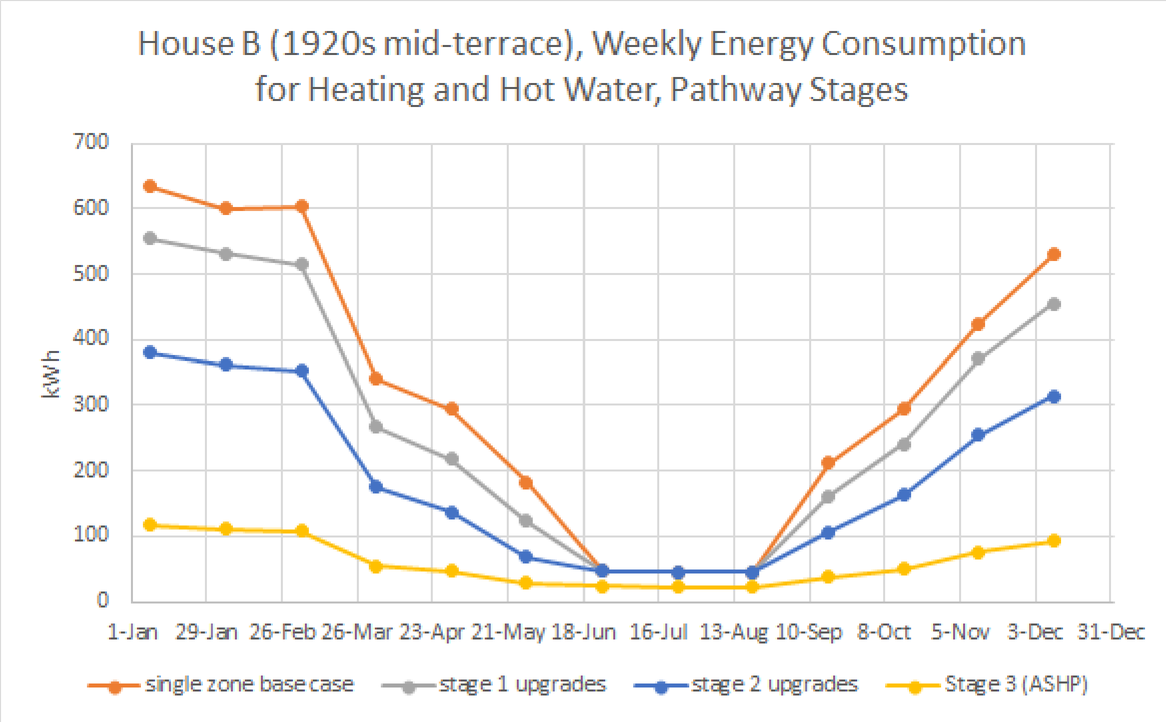

Figure A.5.2-17 – weekly energy consumption for heating and hot water, stages to full upgrade with air source heat pump and building fabric upgrades

A.5.3. Summary of IEHeat Results for House C (1930s semi-detached)

A.5.3.1. House and household description

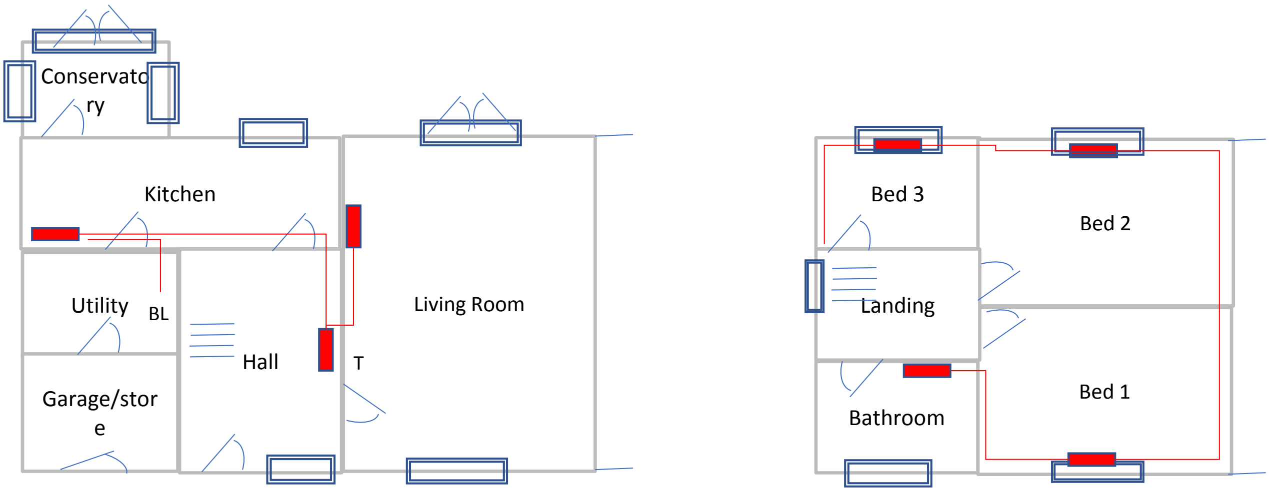

Figure A.5.3-1 House C schematic (simplified for modelling)

The original house has uninsulated walls formed of two brick layers separated by a small air gap (often referred to as "solid" walls) which are rendered on the first floor. The single storey extension (garage, utility and part of kitchen) is assumed to have insulated cavity walls. The living room, hall and original kitchen have suspended floors with underfloor vent bricks on the front and back elevations of the living room, while the extension has a solid floor. The windows are recently installed double glazing; the front and rear doors are also of recent uPVC construction, the rear door being fully glazed. The pitched roof has 75mm of insulation, while the flat roof on the extension is uninsulated.

The heating system comprises a combi-boiler with mostly modern radiators – double panel double convectors (DPDC) in the living room and kitchen, double panel single convector (DPSC) in the front bedroom, and single panel single convector (SPSC) in the hall and other bedrooms. The bathroom has a towel rail heated by the central heating. The heating is controlled by a single thermostat and timer (in living room) with TRVs on all radiators. For comparison with the upgrade evaluation cases (below), multizone on/off control was used, with minimum valve openings set to use the radiators as a buffer (see section **A.4.4**).

For the single zone case the radiators are roughly balanced to allow the TRVs to warm up the rooms together. For the multizone case this is not so necessary (as no room should over-heat) so the lockshield valves have been opened wider to improve warm-up times.

The following data was used to define the household requirements and behaviour: 7 day temperature profiles have been approximated from combined sets of HEMS data (which is per-room and varies over time) – for the single zone case this has been merged to give a boiler heat demand whenever any room requires heating; occupancy heat gains have also been estimated from sets of HEMS data; the doors are normally closed, with the exception of the kitchen (internal door to hall always open), bathroom (door closed only when showering) and some brief opening (for morning/midday/evening activity); all the windows are opened for 10 minutes at 8:30am each morning; DHW demands simulate morning and evening usage including a bath every evening (totalling about 190 litres per day at 40°C).

A.5.3.2. Base case results, winter

Results with the existing building fabric and heat source are shown in Table A.5.3-1.

Table A.5.3-1 - Base case results summary (mid-winter, two weeks)

Case	Energy Used, kWh[1]	Fraction of Demand Time Below T Range, %				
		Living Rm	Kitchen	Front Bed	Back Bed	Spare Bed
Base (single zone control)	1086	52.1	38.7	2.4	1.5	0.5
Base (multizone control)	989	12.7	9.9	1.4	8.3	1.8

Note 1: Gas energy stated is gross (i.e. including latent heat of water)

The poor comfort metrics for single zone control are a result of the following factors:

- Thermostatic radiator valves (TRVs) – which typically operate in a way that reduces available radiator power - are set at 19 °C, in conflict with the single room thermostat which is set to keep the living room between 19 and 21 °C.
- Single zone systems require radiators to be balanced to try to get rooms to warm-up at approximately the same rate (to avoid over or under heating some rooms)
    - even if perfectly balanced (very unusual) this means some rooms will be held back to match the room with the slowest warm-up
    - despite balancing, single room thermostat will tend to cut off heating before some rooms reach their desired temperature, or maintain heating longer than some rooms need resulting in over-heating.

Multizone control can avoid these problems by replacing TRVs with radiator valves controlled by individual room (or zone) temperature measurements – in this case in a simple on/off mode. This makes radiator balancing less important since once a room has reached the top of its desired temperature range the radiator is turned off, avoiding over-heating, and allowing the cooler rooms to continue heating as required. Hence the lockshield valves can be opened wider to reduce warm-up times in most rooms.

Figure A.5.3-4 shows room temperatures under single zone control, from which it can be seen that most rooms are over-heated with respect to the TRV settings. This also results in elevated night time temperatures, particularly in the bedrooms. As the TRV settings are used to calculate comfort metrics in the single zone case, this leads to the bedroom "too cold fraction" metrics appearing small, despite the sluggish warm-up rates.

With multizone control the lockshields have been opened wider and adjusted to reduce warm-up times, resulting in improved comfort metrics in most cases. The household chooses to set the bedrooms to 19 °C during the week, which is now achieved without over-heating, but the lower night time temperatures are revealed in the higher fraction of warm-time spent below the desired temperature range in the smaller bedrooms.

Note that the occupants have a preference to keep the kitchen door open, which has an impact on the kitchen temperature when attempting to heat the hall to a lower target.

On weekends the occupants choose not to warm the house in the mornings. However this allows the house to cool significantly resulting in excessive warm-up times in the evenings.

To reduce the impact of this the profiles have been modified to include a 16°C target during weekend mornings. Nevertheless, the warm-up times on cold days are longer than would normally be acceptable in both cases – often exceeding 90 minutes.

The multizone case gives a 9% reduction in energy usage and will be used for comparison with building fabric upgrade options.

Note: secondary heating

The occupants confirm the tendency for the house to be rather cold, and respond by using a secondary heater in the living room with the door closed. Since the single thermostat is also in the living room use of the secondary heating risks the thermostat turning off the central heating before the rest of the house has fully warmed.

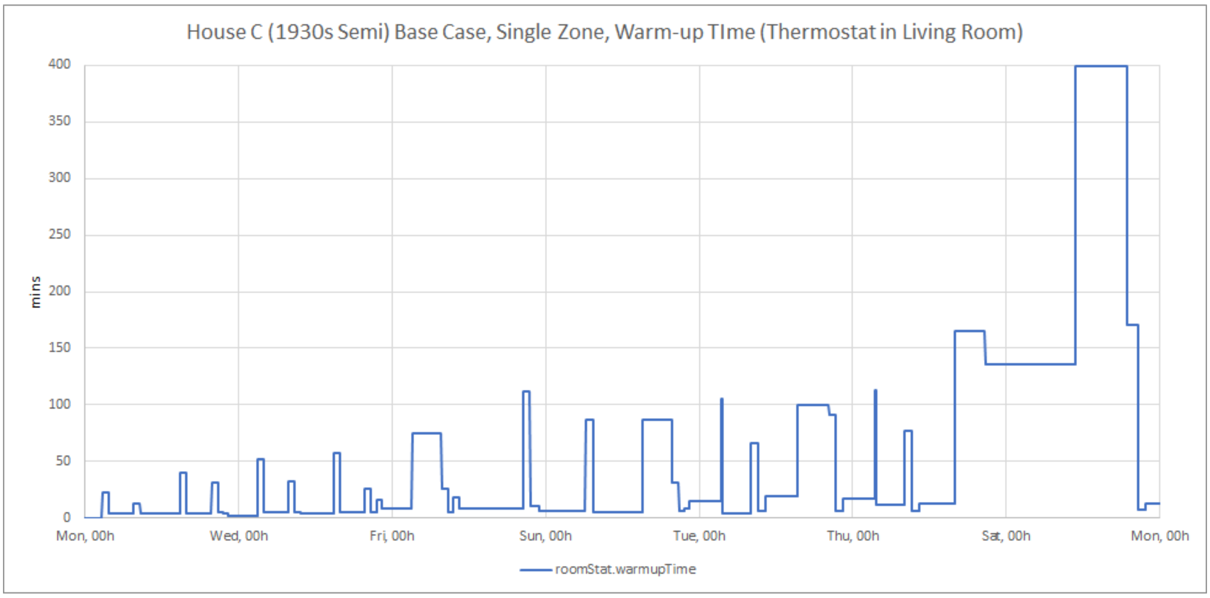

Figure A.5.3-2 – warm-up times, base case, single zone control

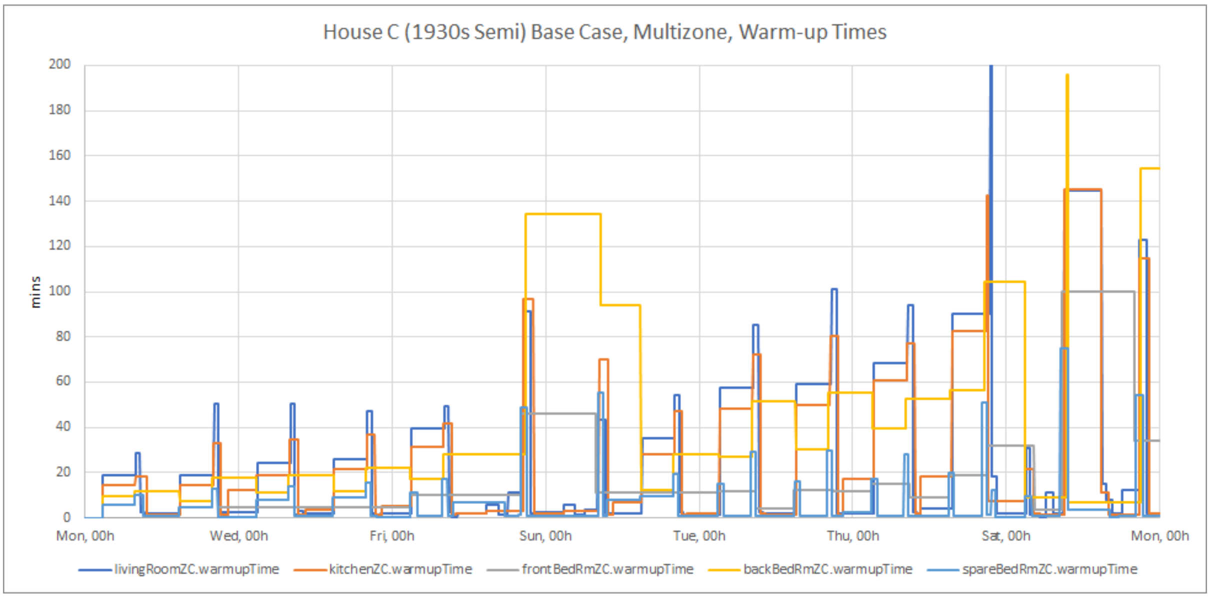

Figure A.5.3-3 – warm-up times, base case, multizone control

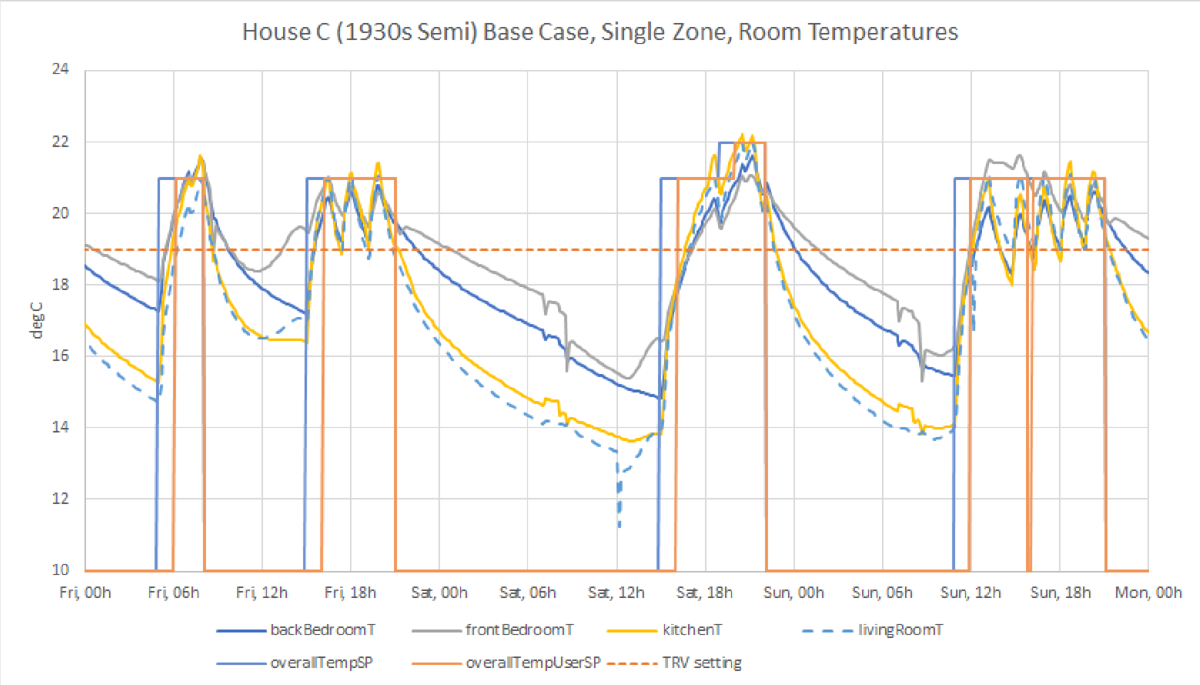

Figure A.5.3-4 – room temperatures, single zone control, base case

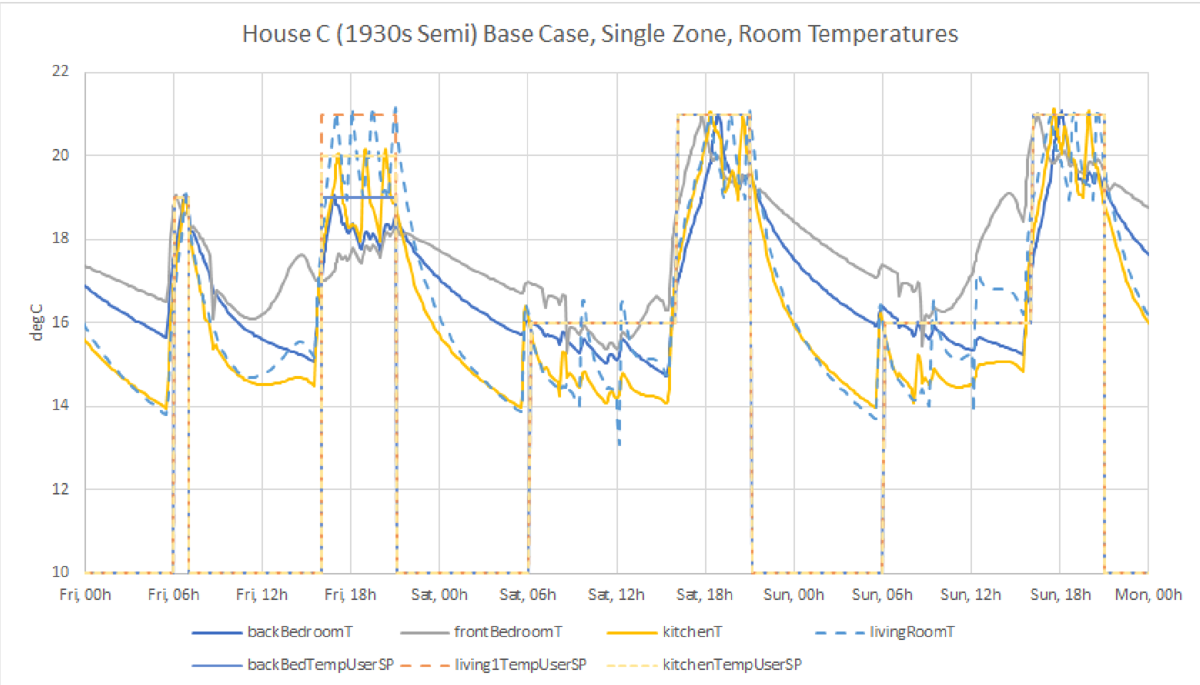

Figure A.5.3-5 – room temperatures, multizone control, base case

A.5.3.3. Base case annual energy consumption

The annual energy consumption has been estimated as described at the beginning of **Appendix 5**. The multizone case uses about 12% less energy over the year as some rooms are heated for only a fraction of the overall demand period used in the single zone case.

Table A.5.3-2 - Base case estimated annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	Annual Energy Consumption, kWh	Energy Output for DHW, kWh	Energy Output for SH, kWh
Base (single zone control)	14969	2445	10854
Base (multizone control)	13187	2454	9234

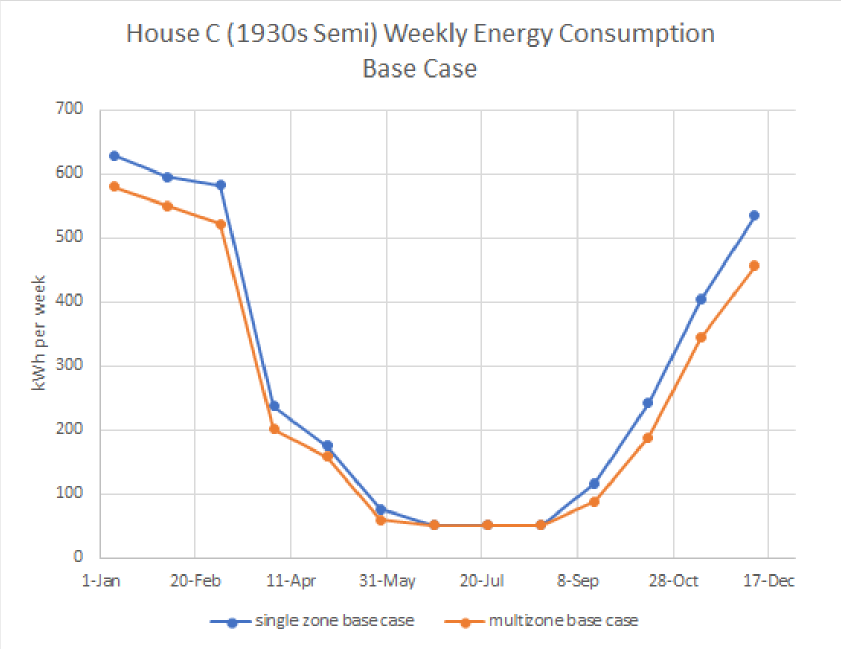

Figure A.5.3-6 - weekly energy consumption, base case

A.5.3.4. Building fabric upgrade evaluation cases

A summary of results of evaluation cases are presented below, investigating the impact of building fabric upgrades, to enable energy and comfort gains to be incorporated with practical and household issues in the decision process to choose upgrades to recommend.

The windows and external doors have been replaced recently and so are not considered for upgrading. Lack of access and the negative visual impact (particularly with respect to uniformity with the attached house) make external wall insulation unacceptable. Floor insulation has also been rejected due to the recently fitted wooden floor coverings. Hence the upgrades considered include internal wall insulation, loft insulation, flat roof insulation (on the extension), conservatory roof insulation and upgrading radiators to make them all DPDC.

A.5.3.4.1. Evaluation cases: loft and wall insulation

Main loft insulation cases:

Table A.5.3-3 –Main loft insulation upgrade results summary (mid-winter, two weeks)

Loft insulation (total), mm	Energy Used, kWh	Energy saving, %	Fraction of Demand Time Below T Range, %				
			Living Rm	Kitchen	Front Bed	Back Bed	Spare Bed
75	989		12.7	9.8	1.4	8.3	1.8
150	977	1.3	12.2	9.1	1.3	7.0	1.7
250	972	1.7	11.8	9.0	0.9	6.1	1.4

Full (250mm) loft insulation can achieve about 1.7% energy saving with minimal disruption, assuming good access to the roof space.

Wall insulation cases, assuming expanded polystyrene (thermal conductivity=0.035 W/m/K) – note using polyisocyanurate could achieve the same results with about 40% reduction in thickness:

Table A.5.3-4 – internal wall insulation upgrade results summary (two weeks, mid-winter)

Case	**Energy Used, kWh**	**Energy saving, %**	**Fraction of Demand Time Below T Range, %**				
			Living Rm	**Kitchen**	**Front Bed**	**Back Bed**	**Spare Bed**
Base case (no wall insulation)	989		12.7	9.9	1.4	8.3	1.8
10 mm IWI	913	7.7	8.4	7.0	0.5	3.8	0.0
20 mm IWI	866	12.4	7.0	6.4	0.3	2.6	0.0
30 mm IWI	843	14.8	6.1	5.4	0.1	1.9	0.0
40 mm IWI	829	16.2	5.7	5.0	0.1	1.5	0.0
50 mm IWI	812	17.9	5.5	4.6	0.0	1.1	0.0

The comfort metrics show significant improvements and practical thicknesses of wall insulation show significant energy savings (e.g. 18% for 50 mm of internal insulation). The impact on warm up times is also significant, especially upstairs, where the maximum warm-up times in the back bedroom drops from about 190 minutes to about 66 minutes. Warm-up times longer than normally acceptable still occur when heating all rooms simultaneously, suggesting inadequate radiator, water pump or heat source sizing.

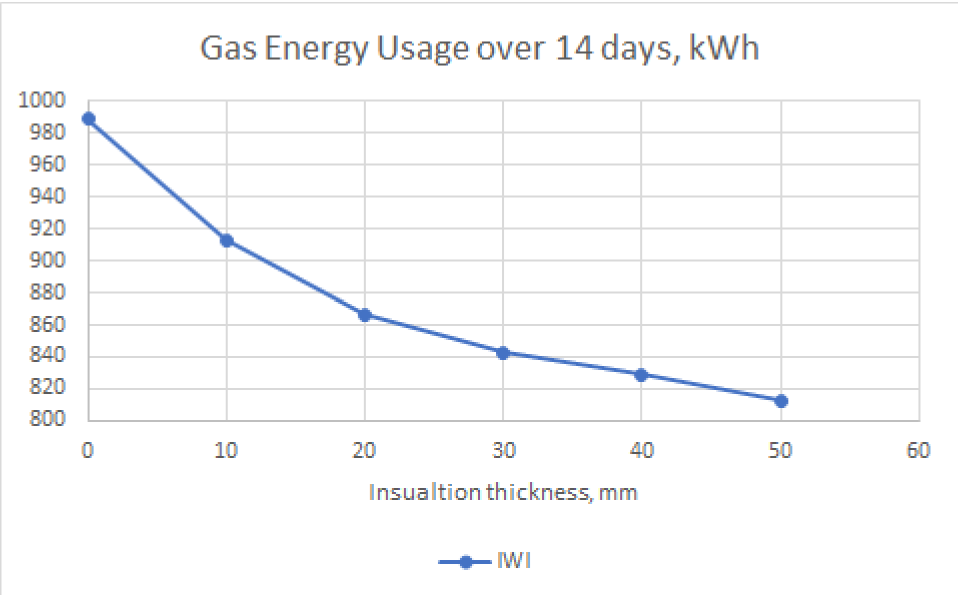

Figure A.5.3-7 - Reduction in energy consumption with increasing wall insulation thickness

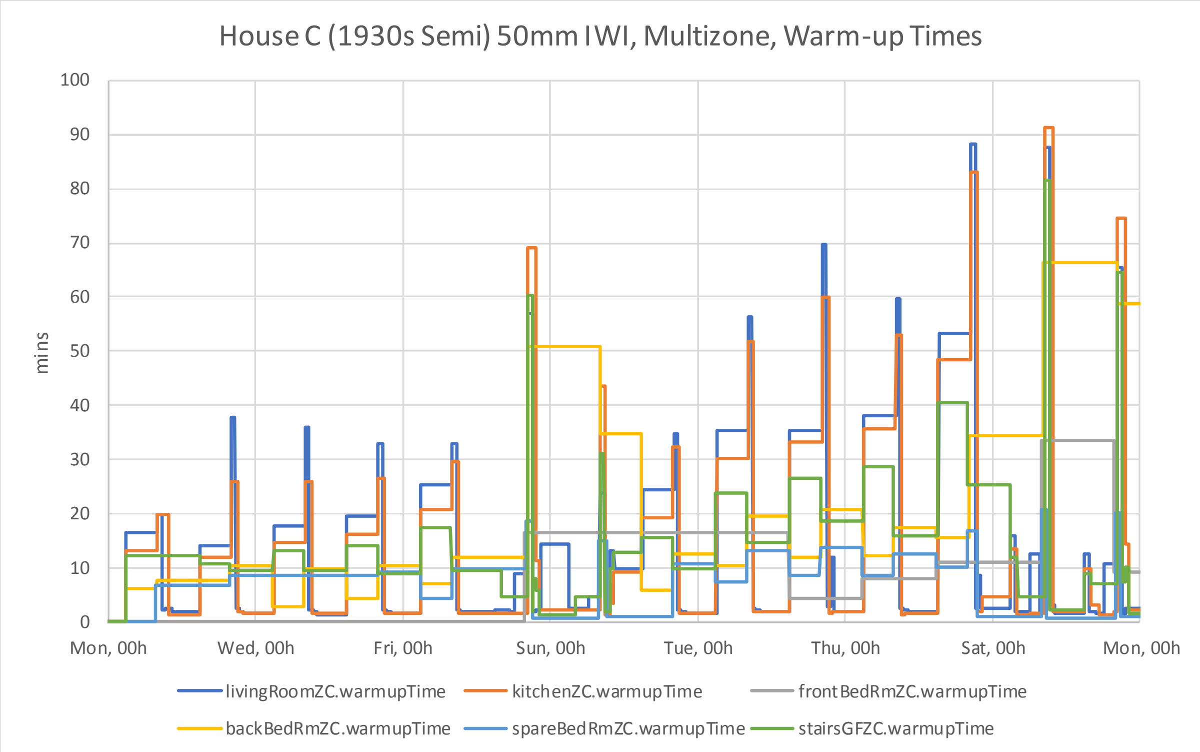

Figure A.5.3-8 - warm-up times with 50 mm of internal wall insulation and gas boiler

A.5.3.4.2. Upgraded radiators

In order to reduce warm-up times, cases were run with all radiators not already DPDC upgraded, with the increase in nominal radiator power assisted by the associated reduction in fraction of heat transferred direct to adjacent walls. The boiler outlet temperature was also increased from 60 °C (occupant's setting) to 70 °C, and the lockshields adjusted to boost flows to the downstairs radiators. Without any other upgrades these changes significantly improve warm-up times and comfort metrics, without greatly increasing the energy consumption. Note that increasing the radiator powers reduces the return temperature to the boiler during warm-up and hence increases boiler efficiency. This partially offsets the efficiency decrease due to the increased outlet temperature when combined.

Table A.5.3-5 – radiator upgrades and boiler outlet temperature increase, summary (two weeks, mid-winter)

Case	**Energy Used, kWh**	**Fraction of Demand Time Below T Range, %**				
		Living Rm	**Kitchen**	**Front Bed**	**Back Bed**	**Spare Bed**
Boiler outlet 70 °C (multizone control)	1009	6.4	4.6	0.5	4.0	0.2
Upgraded radiators (multizone control)	982	9.8	7.2	0.5	1.0	0.1
Boiler outlet 70 °C and upgraded radiators	994	4.3	3.6	0.0	0.1	0.0

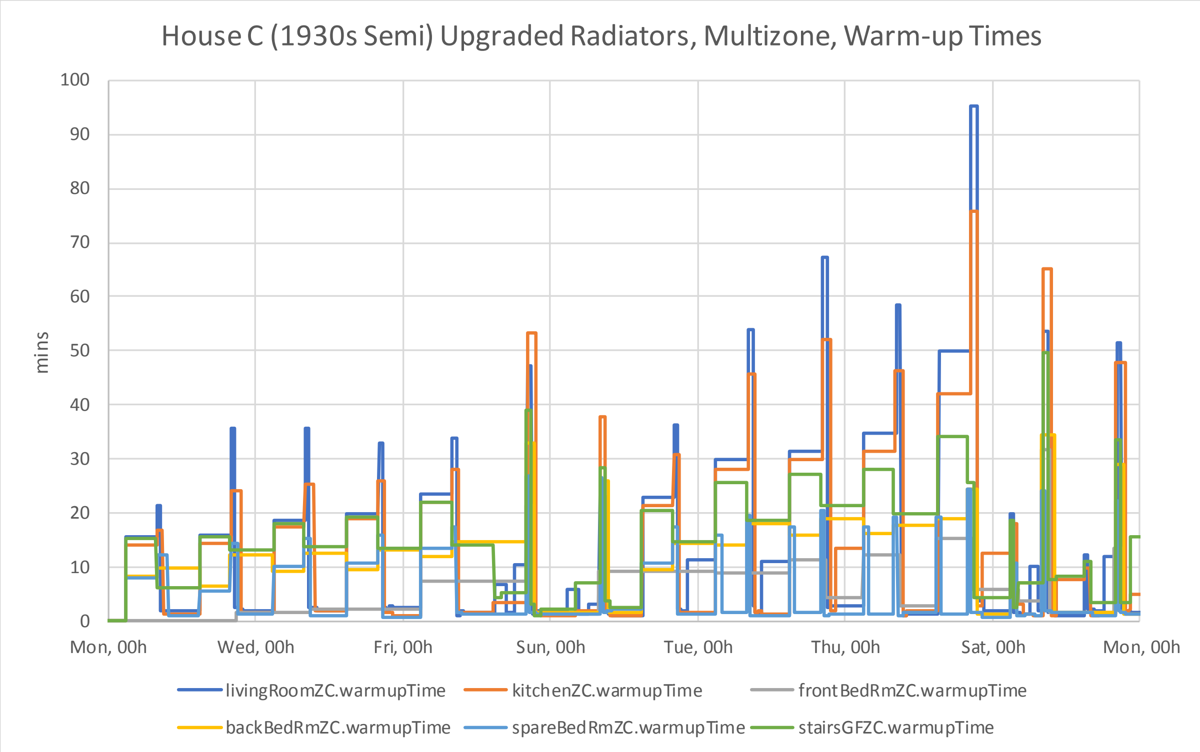

Figure A.5.3-9 - warm-up times with upgraded radiator and increased boiler outlet temperature

This upgrade was used for the further evaluations below.

A.5.3.4.3. Conservatory and flat roof insulation

Two cases were run (with upgraded radiators) to evaluate the benefit of insulating the conservatory and extension roofs.

Table A.5.3-6 – conservatory and flat roof insulation with radiator upgrades, summary (two weeks, mid-winter)

Case	Energy Used, kWh	Fraction of Demand Time Below T Range, %				
		Living Rm	Kitchen	Front Bed	Back Bed	Spare Bed
Upgraded radiators with insulated conservatory roof (U=0.6 W/m2/K)	989	4.3	3.0	0.0	0.1	0.0
Upgraded radiators with insulated flat (extension) roof (150mm)	950	4.3	2.0	0.1	0.2	0.1

Both insulating the conservatory roof (e.g. with a solid roof replacement) and insulating the extension's flat roof reduce the kitchen warm-up time, and raise the winter temperatures in the unheated spaces. These measures may also improve comfort in these rooms in the summer months. When compared to radiator upgrades alone (with increased boiler outlet temperature), adding insulation to the flat roof reduces the kitchen maximum warm-up time from 75 to 60 minutes, saving about 4% of the energy used to heat the house in winter.

A.5.3.4.4. Possible combinations of upgrades

To combine comfort (warm-up time) improvements and energy saving, such that use of a heat-pump becomes feasible, the results above suggest that the biggest gains would be found in:

- upgrading the heating control (to multizone),
- upgrading radiators in the hall and bedrooms to double-panel-double-convector, allowing boiler outlet temperature to be increased to 70 °C
- installing 50mm internal wall insulation on external walls,
- adding 150 mm of flat roof insulation,
- increasing the loft insulation to 250 mm and
- fitting a solid (insulated) roof to the conservatory.

This results in a 31% energy saving with respect to the single zone base case, giving far better comfort (warm-up times).

Table A.5.3-7 - upgraded building fabric results summary (two weeks, mid-winter)

Case	Energy Used, kWh	Fraction of Demand Time Below T Range, %				
		Living Rm	Kitchen	Front Bed	Back Bed	Spare Bed
Multizone, upgraded radiators, 50mm IWI, 250mm loft insulation, 150mm flat roof insulation, solid roof on conservatory	749	1.8	0.8	0	0	0

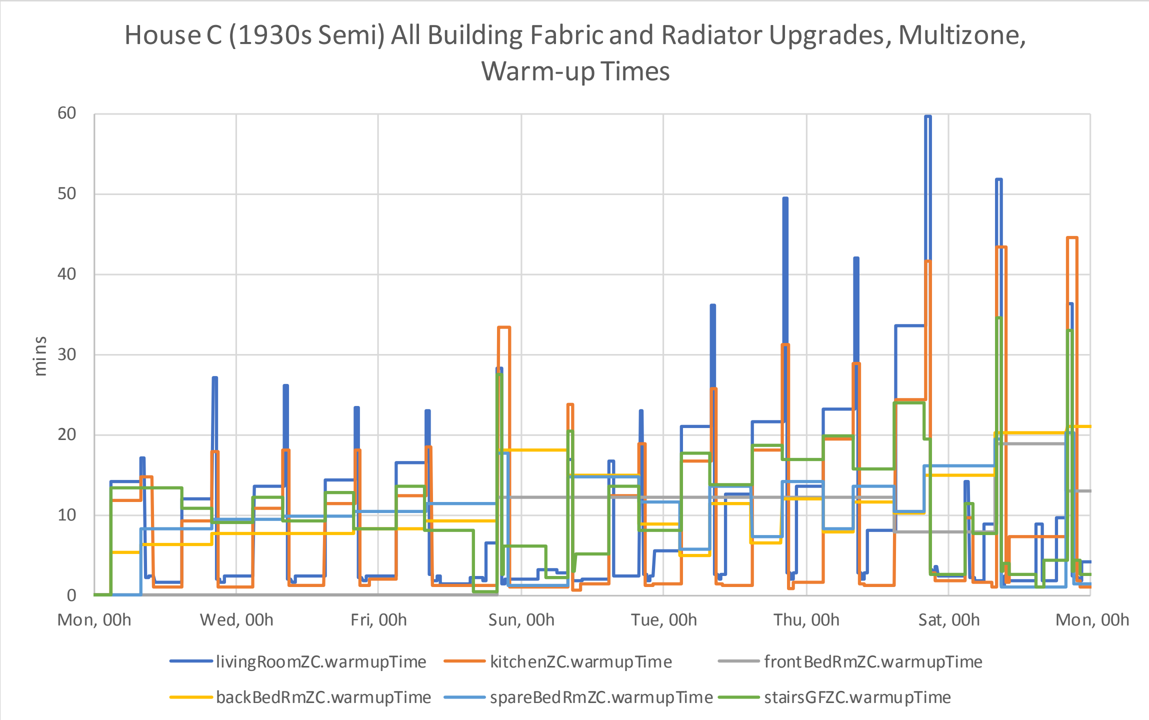

Figure A.5.3-10 - warm-up times with all building fabric upgrades and gas boiler

Annual consumption for the suggested upgraded building fabric case was estimated as for the base case.

Table A.5.3-8 – Proposed building fabric upgrades, annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	Annual Energy Consumption, kWh	Energy Output for DHW, kWh	Energy Output for SH, kWh
Multizone, upgraded radiators, 50mm IWI, 250mm loft insulation, 150mm flat roof insulation, solid roof on conservatory	9842	2455	6371

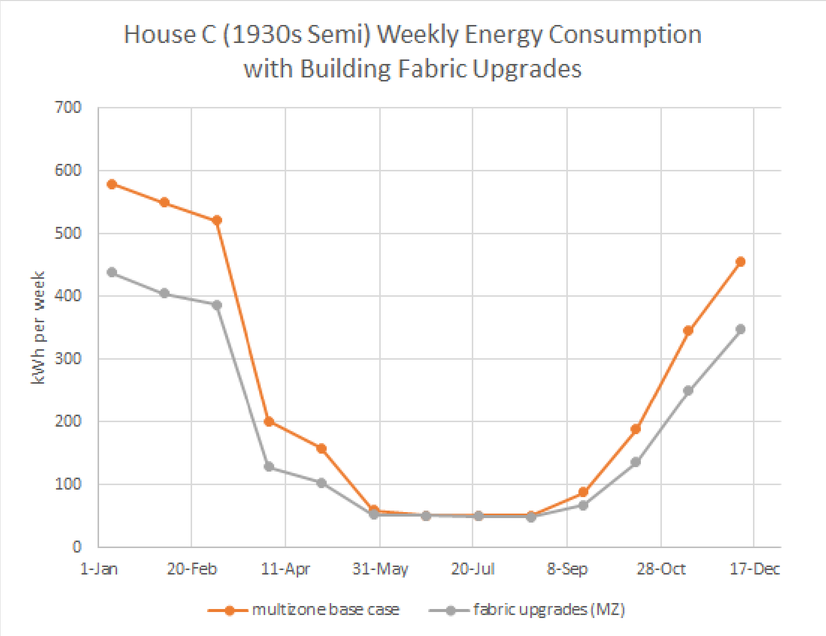

Figure A.5.3-11 - weekly energy consumption, upgraded building fabric

A.5.3.5. Air source heat pump

Using an air source heat pump as the heat source was considered technically feasible for this house. From preliminary tests, House A results and the base case simulations reported above, it was clear that using a lower heating medium temperature with no other changes would give unacceptably long warm-up times. Therefore some heating system upgrades were considered for the cases using the heat pump. Also, assuming the bulk of the heat pump equipment is mounted externally, perhaps on the first floor external wall above the extension’s flat roof, the utility room should have sufficient space to reinstate a DHW cylinder. This should facilitate use of a heat pump without a supplementary water heater (other than an optional 3kW immersion heater).

A.5.3.5.1. ASHP with building fabric upgrades

The case using an air source heat pump was simulated with the following changes relative to the base case:

i. All building fabric upgrades installed as suggested in the combined case above, plus increased size of radiators in the kitchen (1.6m long) and living room (0.8m high, 1.8m long).

ii. Combi boiler replaced with an 8 kW (nominal output) air source heat pump with an input power limit of 3 kW, coupled with a 250 litre insulated DHW cylinder (fitted with a 3kW immersion heater to supplement the heat pump if necessary – not used in this case).

iii. Multizone control with lockshields more fully opened (especially in the downstairs rooms), to increase the power output of the radiators (also assuming higher hot water pump flow rate than original combi boiler).
iv. Heat pump outlet temperature for SH set as a linear function of outside air temperature (rising to 55 °C at or below 5 °C outside) and increased to 5 °C above the DHW tank setpoint when higher than the SH requirement (e.g. to achieve 60 °C for 1 hour each day to guard against legionella).
v. 30 minute pre-heat times used for SH, 90 minutes for DHW tank.
vi. Temperature profile for DHW tank adjusted to avoid clashes with SH warm-up times (by heating to 60°C at 3pm), and allowed to heat both simultaneously (subject to power limits of the ASHP).

Table A.5.3-9 – air source heat pump results summary (two weeks, mid-winter)

Case	**Energy Used, kWh**	**Peak Electricity Demand, SH+DHW, W**	**Fraction of Demand Time Below T Range, %**				
			Living Rm	**Kitchen**	**Front Bed**	**Back Bed**	**Spare Bed**
8kW ASHP with upgrades	262.6	3135	2.6	1.6	0.3	0.5	0.1

The results indicate good comfort performance (better than the current situation, based on room temperatures during desired warm-times) can be achieved with an air source heat pump without excessive peak demand on the electricity grid, provided building fabric upgrades reduce heat loss from the dwelling. The warm-up times are, as expected, longer than the upgraded case with a gas boiler, being generally less than 60 minutes, but up to 110 minutes in the living room on the coldest days. Thanks to the larger radiators these are not excessive apart from during the very coldest weather, when the temperatures in the kitchen and living room are still within one degree of the target range by the start of the required warm-time.

The mean COP over two mid-winter weeks with upgrades is about 2.5, giving an energy consumption of about 24% of that used by the single-zone base case.

See note in section **A.5.2.5.1** on ASHP water pump capacity.

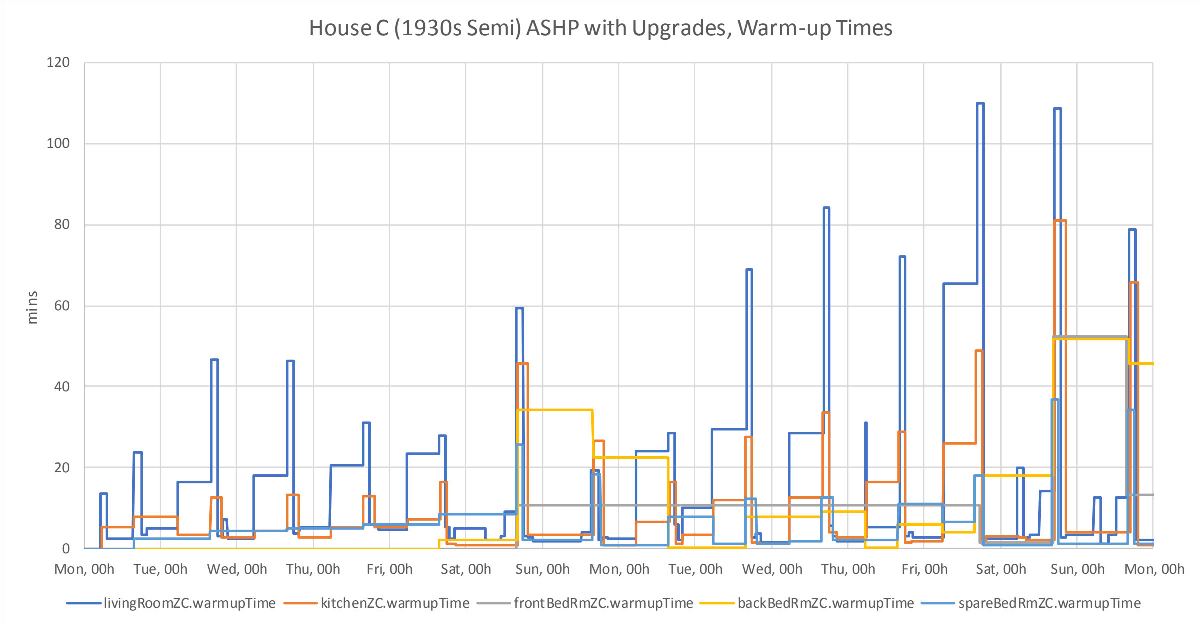

Figure A.5.3-12 - warm-up times with all building fabric upgrades and air source heat pump

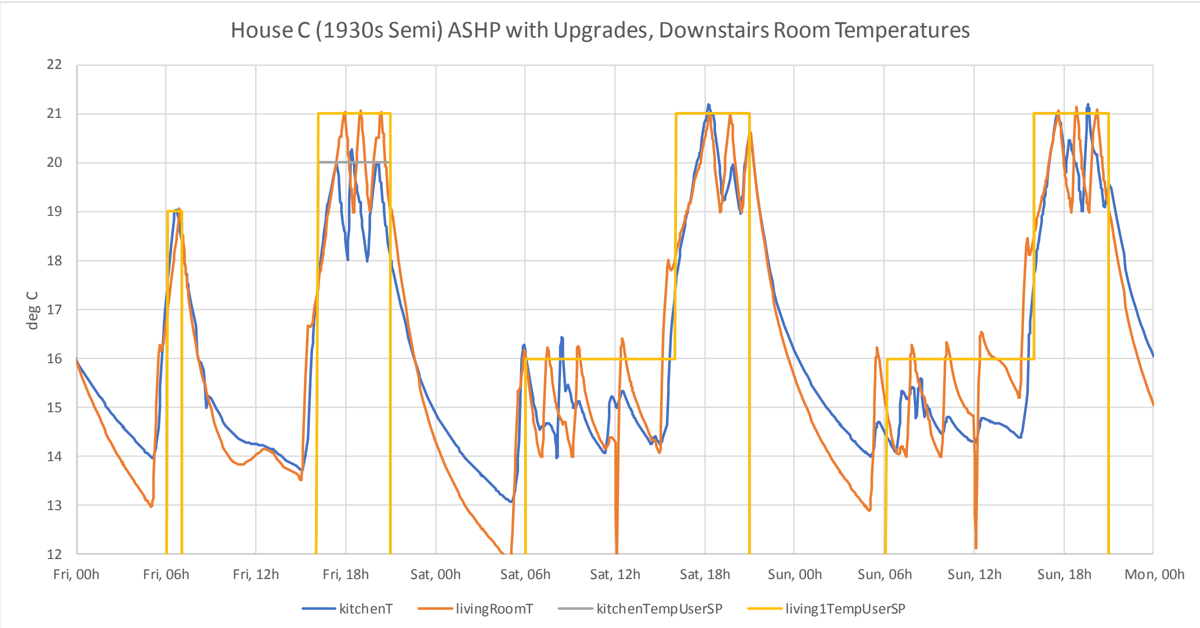

Figure A.5.3-13 – downstairs room temperatures with all building fabric upgrades and air source heat pump

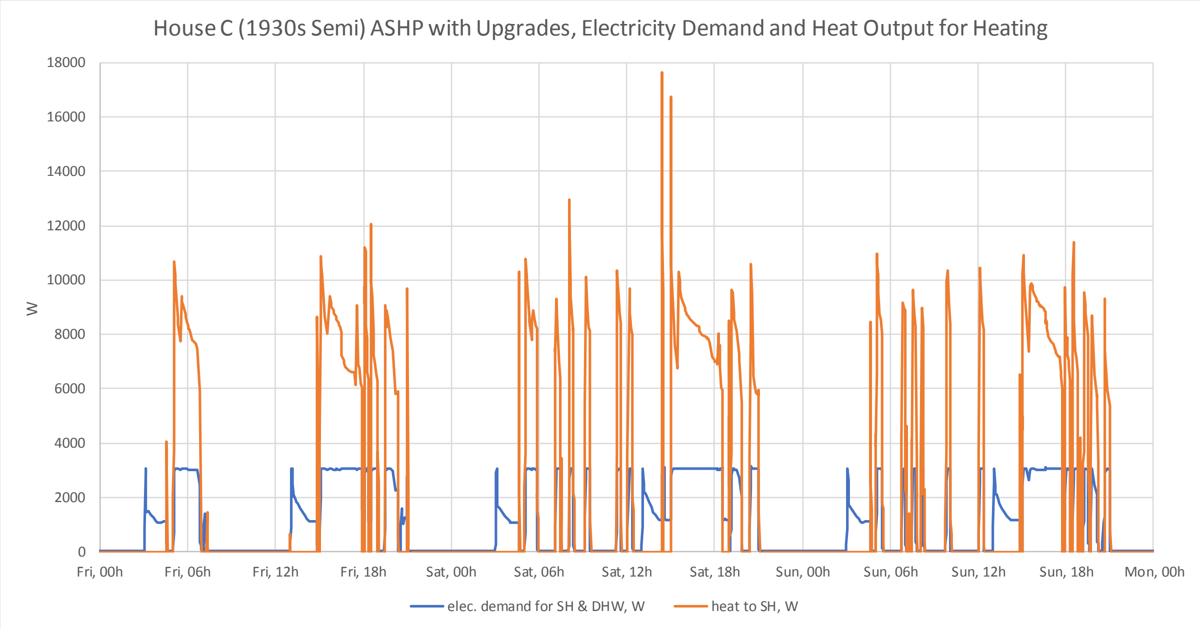

Figure A.5.3-14 – air source heat pump power input and output to space heating, all building fabric upgrades

Note on underfloor heating: Preliminary simulations of UFH in the living room of this house were unable to provide satisfactory heating. Due to the occupants' reluctance to lift their newly laid wooden flooring, this was not pursued further, but the following discussion indicates the reasons for the poor performance. During warm-up, the power output of the increased size radiator in the living room, with a flow temperature of 55°C, is about 3 kW. Meanwhile this 28 m^2 room typically loses about 1 kW through the external walls, large windows at each end (totalling about 10m^2) and through the suspended, uninsulated floor (which loses about 300 W during warm-up). When combined with the relatively large thermal mass of the walls and room contents, this rate of heat loss explains the long warm-up times of the living room in cold weather. Underfloor heating is often proposed as suitable for low temperature heat sources. Typically for a suspended floor UFH can provide about 70-100 W/m^2, for a 35°C flow temperature, giving a maximum heat output of about 2-3 kW. However, in order to provide this heat to the room the UFH has to first raise the temperature of the floor covering, which takes a significant time. Hence, for successful use of UFH in this house, the living room would require a significant further reduction in heat loss and the heating profile may have to consider much longer pre-heat times, or preventing the living room floor from fully cooling during winter months. It would be useful for future work to investigate criteria for successful use of UFH in retrofit settings.

A.5.3.5.2. Multizone + ASHP + upgrades: annual energy consumption

The upgraded heat pump case above was run for two weeks in every four for a year, with weekly energy consumption taken from the second week in each case to give an estimate of annual consumption for comparison with the combi-boiler results above. The overall energy consumption with a simple linear outlet temperature adjustment is less than 25% of the base-line case (single zone control, no upgrades). The savings from changes to building fabric, control and heat source are nearly independent, such that their effects can be characterized as energy reduction factors which can be multiplied together to give the overall reduced consumption. In this case, multizone control reduces annual energy consumption by a factor of 0.88, building fabric by 0.75 and the change from a condensing boiler (effective efficiency of 0.89) to a heat pump with an average effective COP of about 2.4, gives a reduction factor for heat source change of 0.37.

Table A.5.3-10 – Air source heat pump with upgraded building fabric: annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	Annual Energy Consumption, kWh	Energy Output for DHW, kWh	Energy Output for SH, kWh
8kW ASHP 3kW input limit, multizone control + fabric upgrades	3695	2513	6361

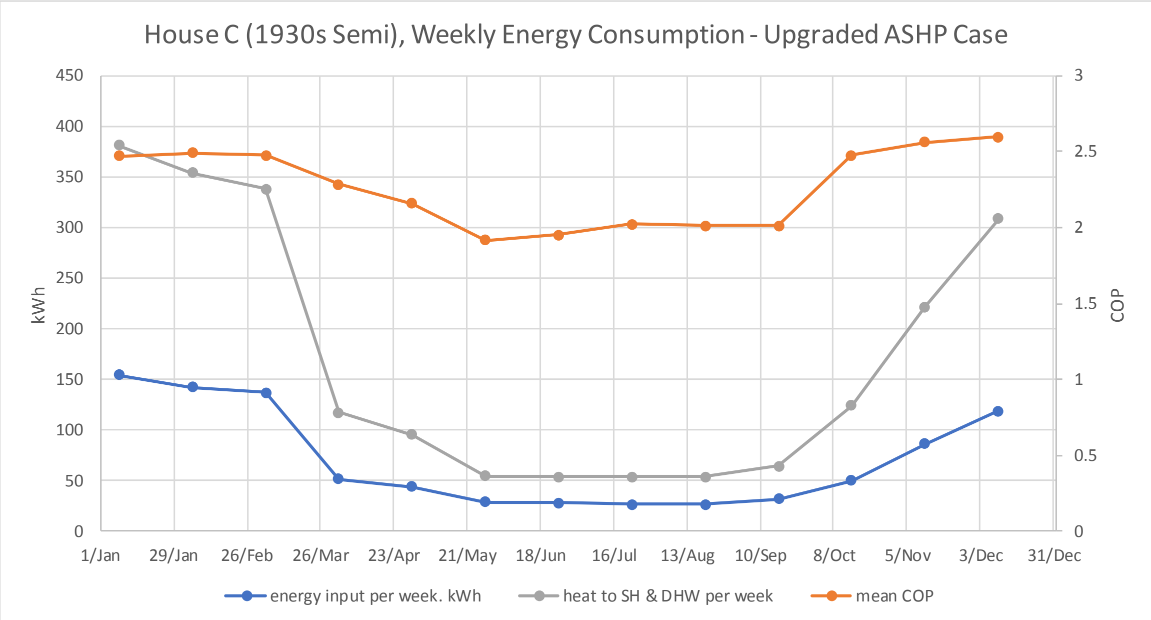

Figure A.5.3-15 – weekly energy consumption, air source heat pump with building fabric upgrades

As discussed in House B results summary, the drop in mean weekly effective COP in summer is due largely to the increased proportion of heat lost around the DHW tank. Also as discussed in House B results, the simple control logic used in this case is effective but indicates scope for improvement.

A.5.3.6. Hybrid ASHP + gas boiler

Hybrids of heat pumps and gas boilers are seen to offer a number of potential advantages: the gas boiler can be used to provide DHW directly, removing the need for thermal storage (e.g. water cylinder) and providing the flexibility of supply the occupants are used to from a combi-boiler. It has also been suggested that hybrids offer the possibility of reducing peak electricity demands that heat pumps on their own may require. Furthermore hybrids may allow a reduction in carbon emissions without the need for full energy saving building fabric upgrades, or at least by providing a transitional stage on the upgrade pathway they may allow spreading the cost of the upgrades over some years.

As discussed in section **A.5.1.6** the configuration of hybrid selected for evaluation is a new heat pump in series with the existing gas boiler with both outlet temperatures set to 55 °C. It is assumed again that the gas boiler's DHW function is retained, thus eliminating the need for a storage tank.

Four cases using a hybrid air source heat pump with gas boiler were simulated with the following changes relative to the base case:

i. Both cases use the following building fabric upgrades
   - upgrading radiators in the hall and bedrooms to double-panel-double-convector, increased size of radiators in the kitchen (1.6m long) and living room (0.8m high, 1.8m long)
   - adding 150 mm of flat roof insulation,
   - increasing the loft insulation to 250 mm
ii. Existing combi boiler supplemented by an ASHP with the SH return fed to the heat pump, whose outlet is fed to the return connection of the boiler. The cases were run with two ratings of heat pump:
   - 6 kW (nominal output) with an input power limit of 2.5 kW
   - 8 kW (nominal output) with an input power limit of 3 kW
iii. Multizone control with lockshields more fully opened (especially in the downstairs rooms), to increase the power output of the radiators (also assuming higher hot water pump flow rate than the original combi boiler, to compensate for the lower flow temperature)
iv. Heat pump outlet temperature for SH set as a linear function of outside air temperature (rising to 55 °C at or below 5 °C outside).
v. 30 minute pre-heat times used for SH.

The full upgrade cases also assume installation of 50mm internal wall insulation on external walls, and fitting of a solid (insulated) roof to the conservatory.

Table A.5.3-11 – Hybrid air source heat pump/gas boiler with upgraded building fabric, summary (two weeks, mid-winter)

Case	Energy Used, Gas/Elec kWh	Peak Electricity Demand, SH+DHW, W	Fraction of Demand Time Below T Range, %				
			Living Rm	Kitchen	Front Bed	Back Bed	Spare Bed
6kW ASHP +combi with full upgrades	371/111	2649	3.3	0.3	0	0	0
6kW ASHP +combi with partial upgrades	425/151	2649	6.7	0.6	0.4	0.8	0
8kW ASHP +combi with full upgrades	339/123	3156	3.7	0.5	0	0	0
8kW ASHP +combi with partial upgrades	376/167	3151	7.3	0.7	0.5	1.0	0

The results indicate a possible 50-55% reduction in gas consumption relative to the combi-boiler case with the full building fabric upgrades. The electricity consumption for space heating is equivalent to about 30% of the energy previously supplied by gas. The full upgrades (i.e. including internal wall insulation) save about 10-12% of the gas consumption relative to the partially upgraded case. However, the hybrid may offer a route to significant carbon savings at an early stage, before wall insulation is installed. The 8kW option would be preferred if eventually it were intended to use it with heat storage instead of the gas boiler.

The charts in Figure A.5.3-16 to Figure A.5.3-21 show the performance of the hybrid heat pump/gas boiler as described above (6 kW HP case). The power trends illustrate the uses of the boiler for warm-up operation and for DHW supply. The case without wall insulation can be seen to warm-up more slowly, particularly in very cold weather. More sophisticated control logic could use the boiler on its own with a higher outlet temperature for these conditions, at the expense of greater gas consumption.

A further trial with the 8 kW ASHP but with fewer upgrades (multizone control and extra loft insulation, but no new radiators) found that the hybrid was unable to maintain sufficient comfort in winter (significantly worse than the gas boiler alone). This was caused by a drop in COP resulting from lower return water temperatures reducing the maximum heat pump output (with the 3 kW input limit) at times to below the rate of heat loss without wall insulation at target room temperatures (about 5-8 kW) and also making the heat pump performance very sensitive to interactions with the WRV openings. Even with more sophisticated control it is unlikely that a hybrid of this power, in this house, would be able to provide sufficient comfort without at least first installing high output radiators.

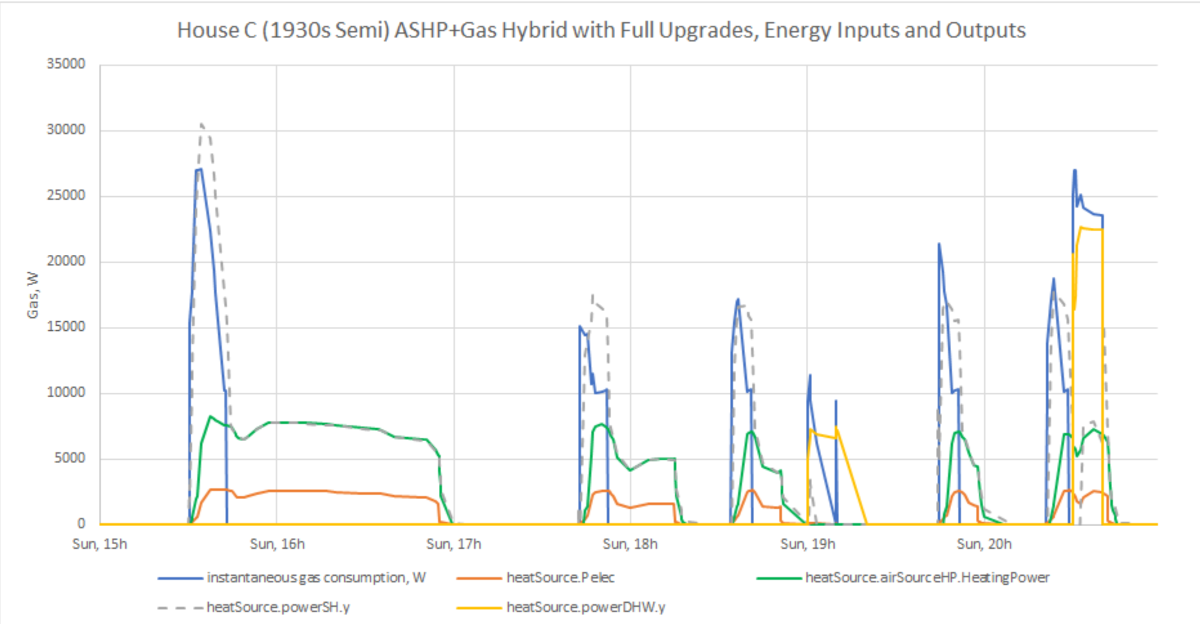

Figure A.5.3-16 – energy inputs and outputs, hybrid air source heat pump (6kW)/gas boiler with full building fabric upgrades

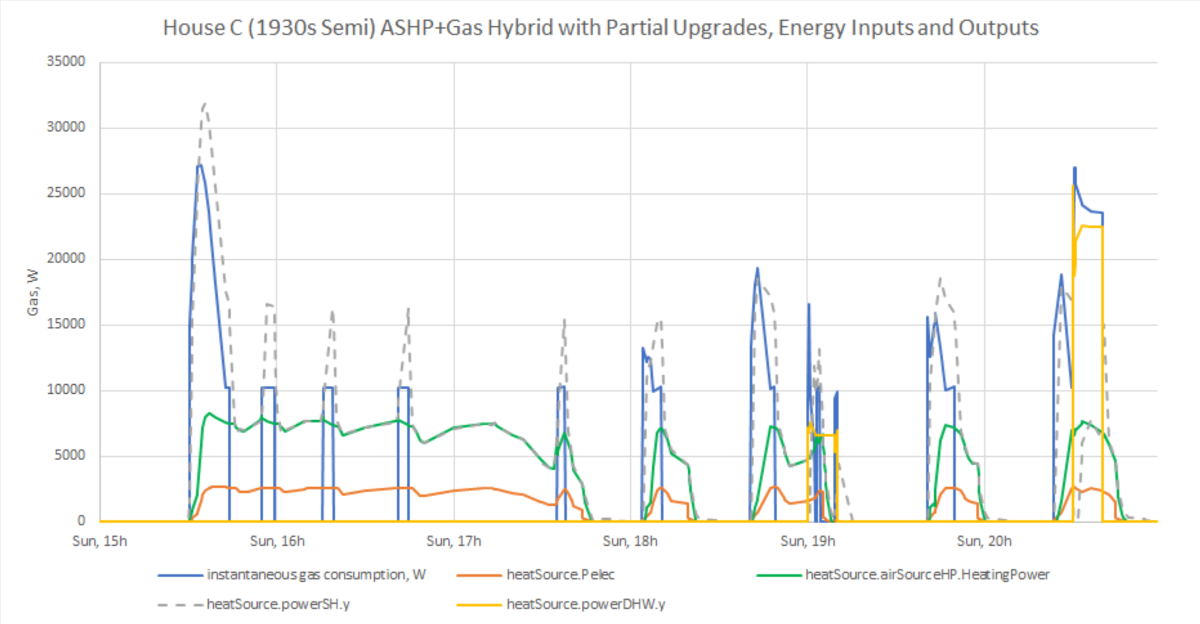

Figure A.5.3-17 – energy inputs and outputs, hybrid air source heat pump (6kW)/gas boiler with partial building fabric upgrades

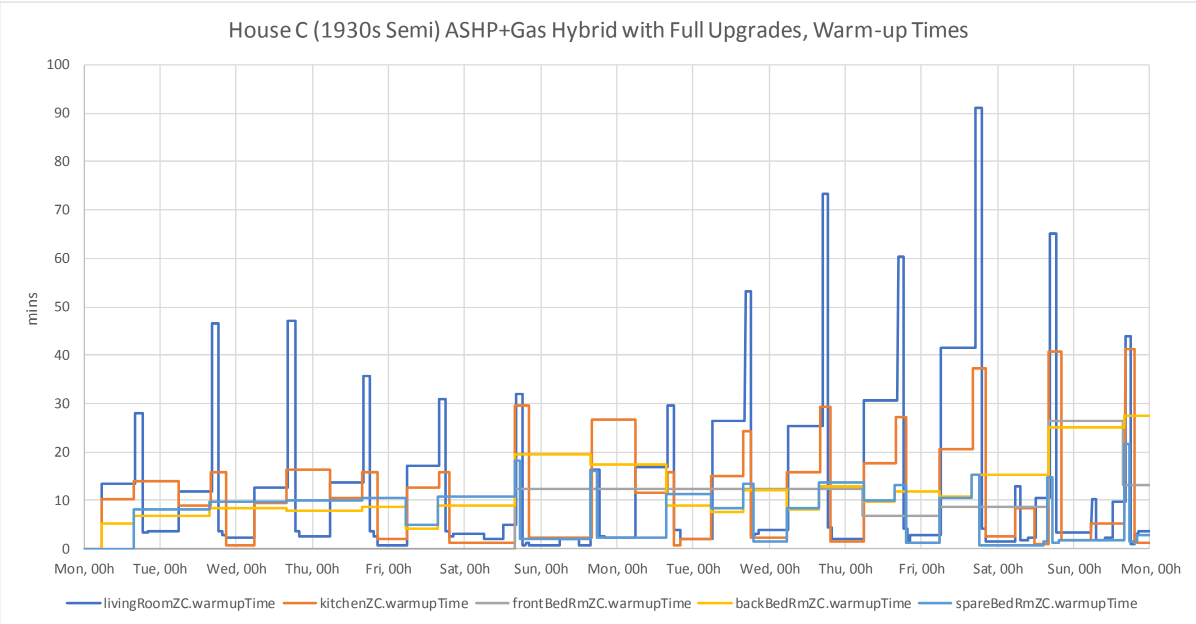

Figure A.5.3-18 – warm-up times, hybrid air source heat pump (6 kW)/gas boiler with full building fabric upgrades

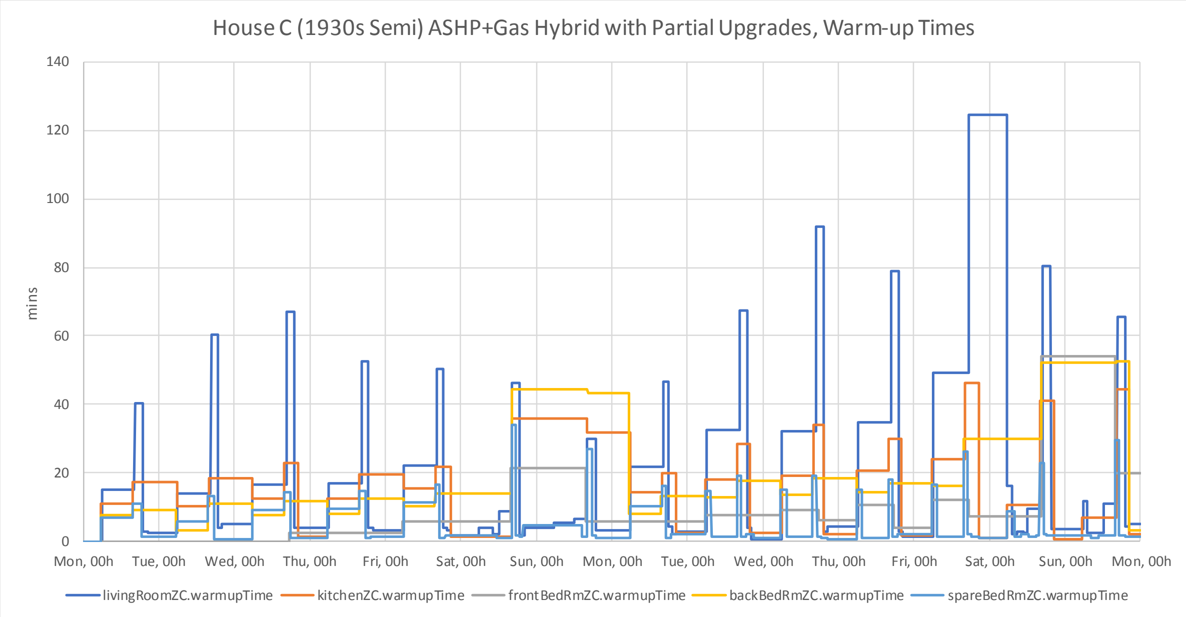

Figure A.5.3-19 – warm-up times, hybrid air source heat pump (6kW)/gas boiler with partial building fabric upgrades

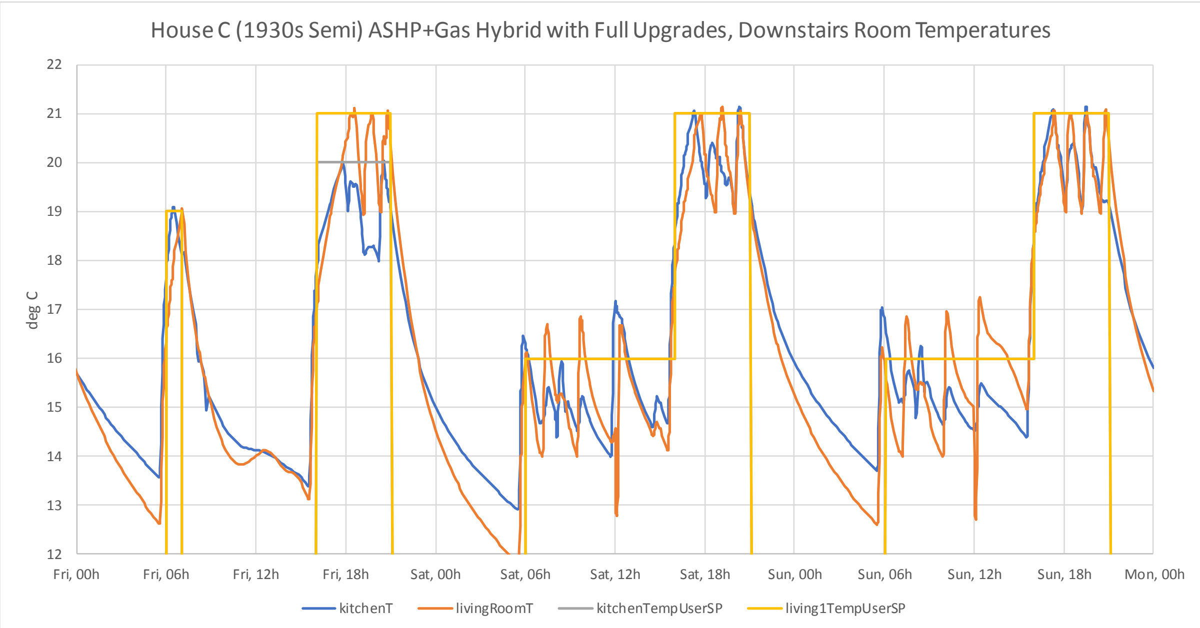

Figure A.5.3-20 – downstairs room temperatures, hybrid air source heat pump/gas boiler with full building fabric upgrades

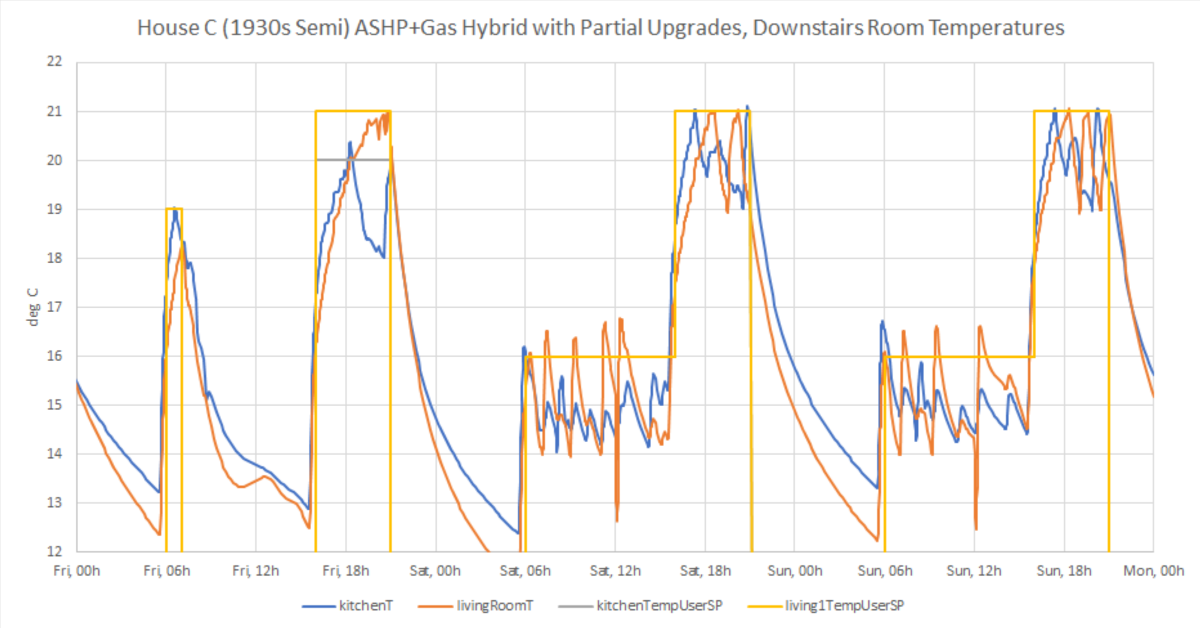

Figure A.5.3-21 – downstairs room temperatures, hybrid air source heat pump/gas boiler with partial building fabric upgrades

A.5.3.7. Upgrade pathway stages

The following stages in the pathway to full upgraded building fabric and heat source have been identified:

Stage 1: multizone control + 250 mm loft insulation + upgraded radiators

Stage 2: install 8 kW ASHP in series with existing boiler

Stage 3: 50 mm internal wall insulation

Stage 4: remove boiler and install hot water tank, insulate flat roof and conservatory roof

The summary of the results for each stage in the pathway are shown in Table A.5.3-12 and Table A.5.3-13.

Table A.5.3-12 – pathway stages, summary (two weeks, mid-winter)

Case	**Energy Used, kWh**	**Fraction of Demand Time Below T Range, %**				
		Living Rm	**Kitchen**	**Front Bed**	**Back Bed**	**Spare Bed**
Base case	1086	52.1	38.7	2.4	1.5	0.5
Stage 1 (MZ + loft + radiators)	968	8.8	7.0	0.3	0.5	0.1
Stage 2 (ASHP/gas hybrid)	376 (gas) 167 (elec.)	7.3	0.7	0.5	1.0	0.0
Stage 3 (IWI)	339 (gas) 123 (elec.)	3.7	0.5	0.0	0.0	0.0
Stage 4 (ASHP + flat roof)	263	2.6	1.6	0.3	0.5	0.1

Table A.5.3-13 – pathway stages, estimated annual consumption for heating and hot water (Newcastle-upon-Tyne, typical mean year)

Case	Annual Energy Consumption, kWh	Energy Saving	Energy Output for DHW, kWh	Energy Output for SH, kWh
Base case	14969		2445	10854
Stage 1 (MZ + loft + radiators)	12950	13%	2449	9086
Stage 2 (ASHP/gas hybrid)[1]	6043 (gas), 2074 (elec.)	46%	2450	9090
Stage 3 (IWI)	5532 (gas), 1492 (elec.)	53%	2451	6852
Stage 4 (ASHP + flat roof)	3695	75%	2513	6361

Note 1: estimated from winter case results and annual results from other cases.

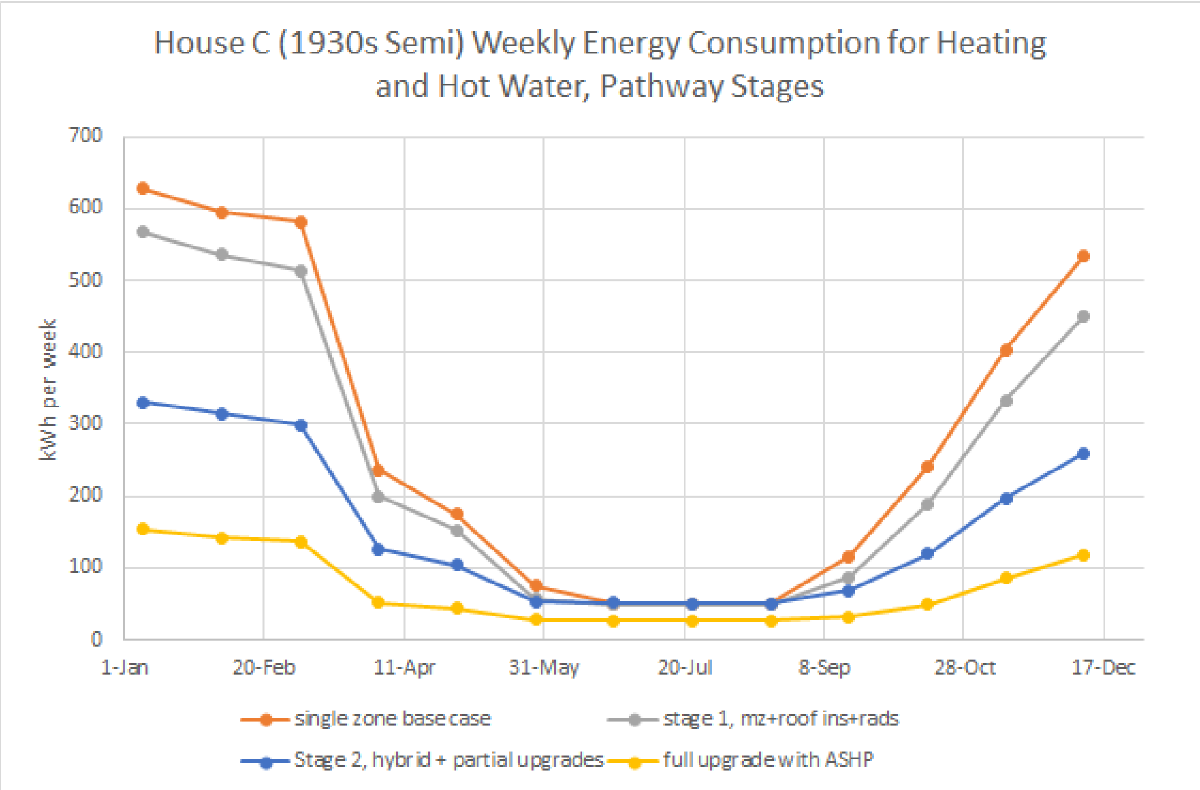

Figure A.5.3-22 – weekly energy consumption for heating and hot water, stages to full upgrade with air source heat pump and building fabric upgrades

A.5.4. Summary of IEHeat results for House D (1970s mid-terrace)

A.5.4.1. House and household description

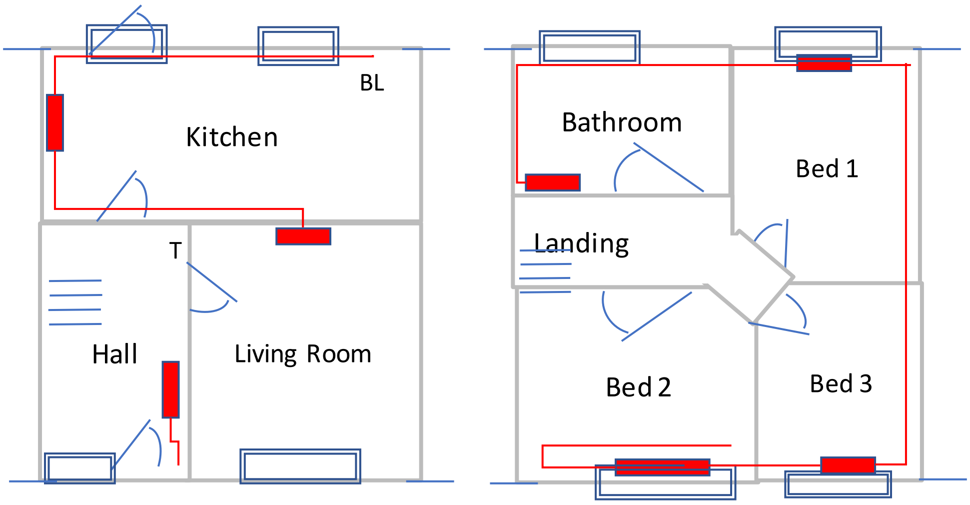

Figure A.5.4-1 House D schematic (simplified for modelling)

The house has uninsulated cavity walls (rendered on ground floor, tile-faced on the first floor). Internal walls are plastered single brick on the ground floor and lath & plaster partitions upstairs. The ground floors are solid and uninsulated. The windows are pre-2002 installed double glazing; the front and rear doors are also of aging uPVC construction, the rear door being fully glazed. The pitched roof has 100mm of insulation.

The heating system comprises a combi-boiler with double panel double convector radiators (DPDC) in all rooms. The heating is controlled by a single thermostat and timer (in the hall) with TRVs on all radiators other than the hall. For comparison with the upgrade evaluation cases (below) multizone on/off control was also used, including adding an actuated valve on the hall radiator, with minimum valve openings set to use the radiators as a buffer (see section **A.4.4**).

For the single zone case the radiators are roughly balanced to allow the TRVs to warm up the rooms together. For the multizone case this is not so necessary (as no room should over heat) so the lockshield valves have been opened wider to improve warm-up times.

The following data was used to define the household requirements and behaviour: 7 day temperature profiles have been approximated from combined sets of HEMS data (which is per-room and varies over time) – for the single zone case this has been merged to give a boiler heat demand whenever any room requires heating; occupancy heat gains have also been estimated from sets of HEMS data; the occupants typically left internal doors open with single zone control, with the exception of the bathroom (door closed only when showering); external doors are assumed to briefly open for morning/midday/evening activity; all the windows are kept closed; DHW demands simulate morning and evening usage (totalling about 120 litres per day at 40 °C).

A.5.4.2. Base case results, winter

Results with the existing building fabric and heat source are shown in Table A.5.4-1. Note that the poor comfort metrics for the single zone case result from the long downstairs warm-up times in cold weather resulting from the sub-optimal radiator balancing, significant heat loss on the ground floor and insufficient pre-heat time of 60 minutes for the kitchen and living room – though the upstairs rooms over-heat even with this compromise. With multizone control the lockshields have been opened wider and adjusted to reduce warm-up times, especially downstairs. Also, to accommodate the occupants' desire for different heating profiles in different rooms (e.g. on four mornings the living room is not heated) the doors of the most used rooms (kitchen, living room and front bedroom) have been closed, apart from some morning/midday/evening activity. This allows the downstairs rooms to reach their target temperature range more quickly and reliably (the heating doesn't turn off while they are still warming-up), giving a significant improvement in the comfort metric for these rooms. However, since half the house is now able to reach the higher (desired) temperatures, and the occupants have chosen to heat some rooms to 24°C, the overall energy used for the multizone control case is slightly higher than for the colder single zone case. Multizone control is used for comparison of building fabric upgrade options, as discussed in **Appendix 4**.

Table A.5.4-1 - Base case results summary (mid-winter, two weeks)

Case	Energy Used, kWh[1]	Fraction of Demand Time Below T Range, %				
		Living Rm	Kitchen	Front Bed	Back Bed	Spare Bed
Base (single zone control)	1027	67	59	0	0	0
Base (multizone control)	1034	3.8	6.7	0	0.7	0.2

Note 1: Gas energy stated is gross (i.e. including latent heat of water)

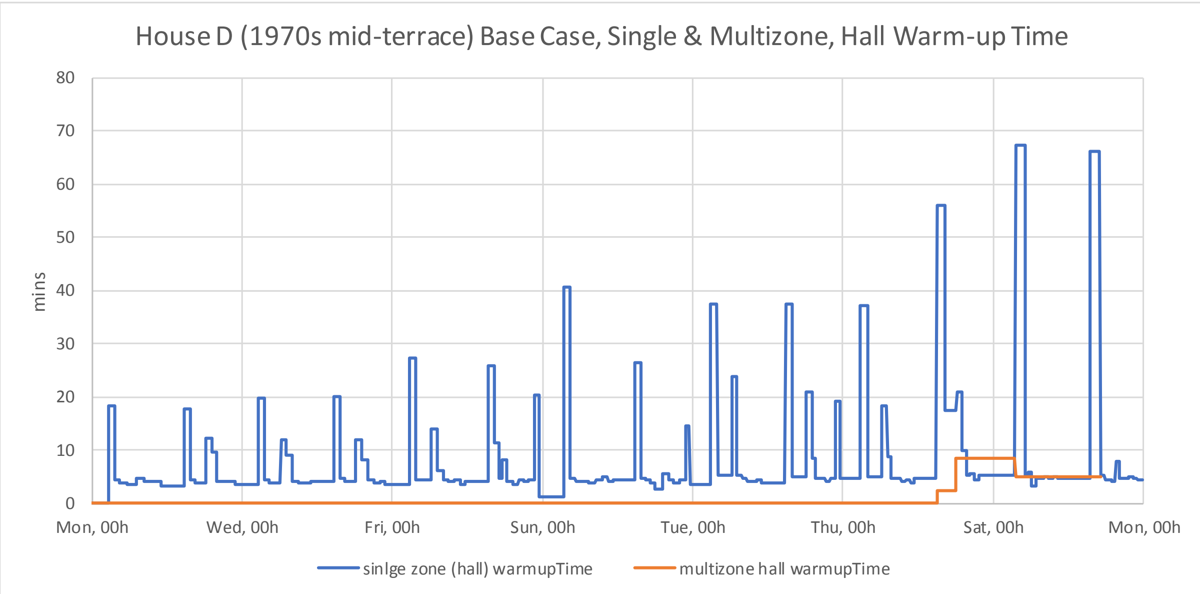

Figure A.5.4-2 - warm-up times in the hall (location of thermostat), single zone (internal doors open) vs multizone control (internal doors closed), base case, gas boiler

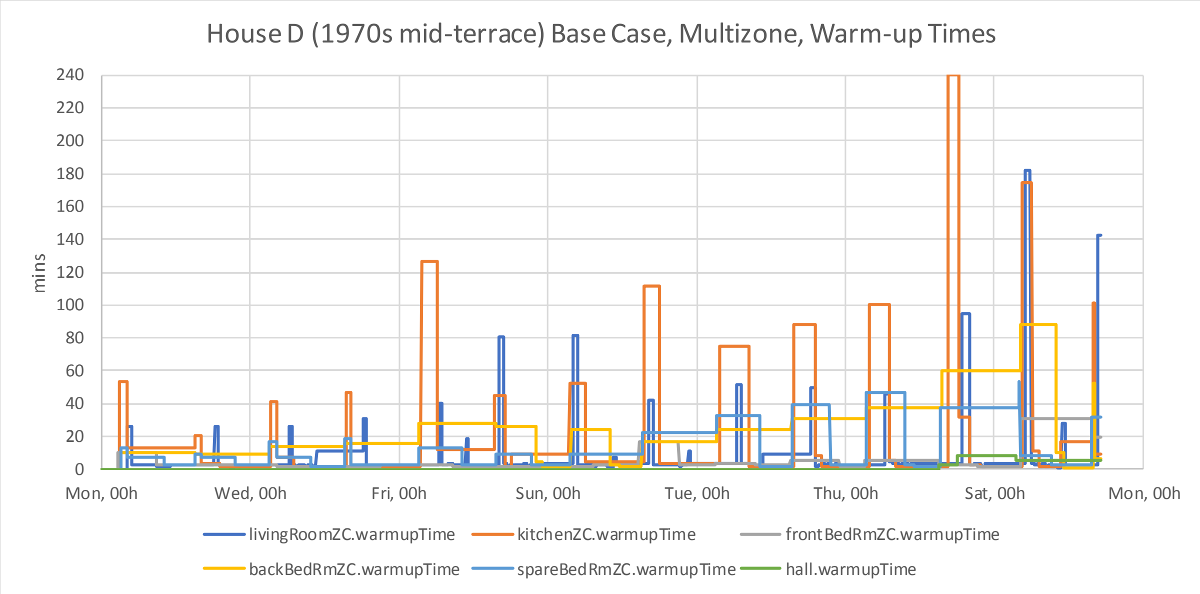

Figure A.5.4-3 - warm-up times, multizone control, base case, gas boiler

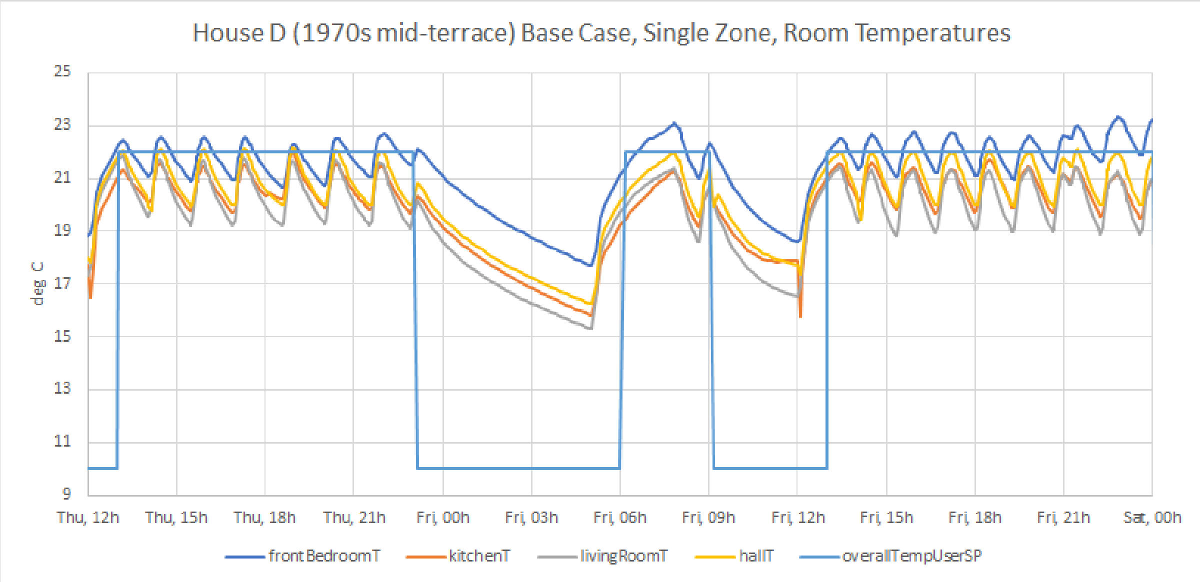

Figure A.5.4-4 - room temperatures, single zone control, base case, gas boiler

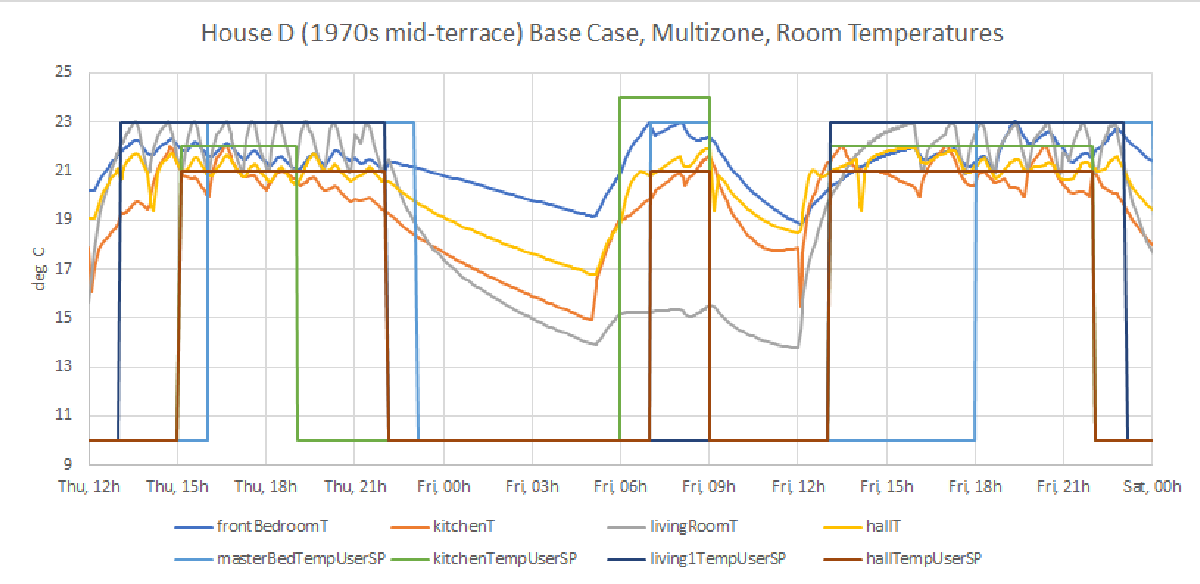

Figure A.5.4-5 - room temperatures, multi zone control, base case, gas boiler

A.5.4.3. Base case annual energy consumption

The annual energy consumption has been estimated as described in the introduction to the results summaries. The multizone case is shown to use about 5.7% more energy over the year as some rooms are significantly warmer than in the single zone, doors open case.

Table A.5.4-2 - Base case estimated annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	**Annual Energy Consumption, kWh**	**Energy Output for DHW, kWh**	**Energy Output for SH, kWh**
Base (single zone control)	14087	1547	11131
Base (multizone control)	14897	1555	11674

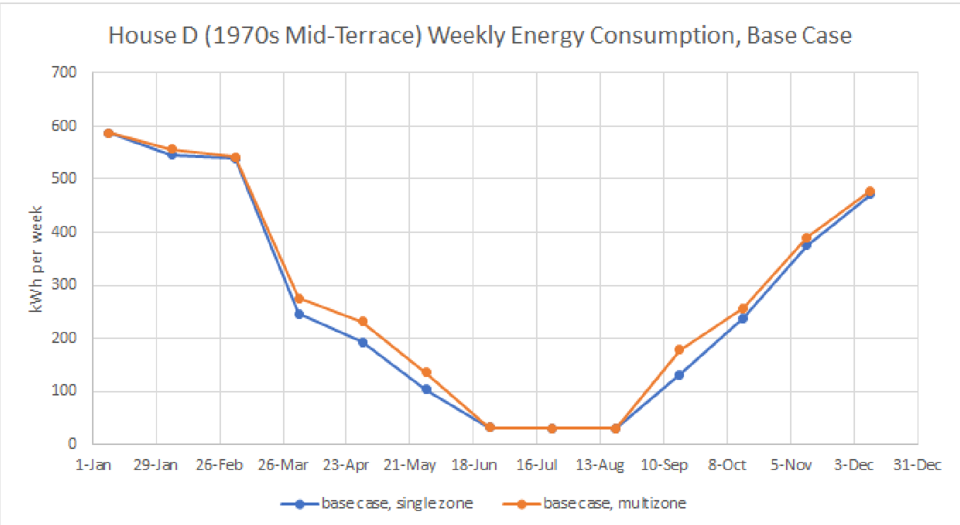

Figure A.5.4-6 - weekly energy consumption, base case

A.5.4.4. Building fabric upgrade evaluation cases

A summary of results of evaluation cases are presented below, investigating the impact of building fabric upgrades, to enable energy and comfort gains to be incorporated with practical and household issues in the decision process to choose upgrades to recommend.

The windows and external doors are showing signs of age and are therefore considered for upgrading, together with loft and cavity wall insulation.

A.5.4.4.1. Evaluation cases: windows, doors, loft and wall insulation

Reducing all window U-values from 2.8 to 2 W/m2/K gave a 6.5% saving in energy used in winter. Note that the back door is fully glazed and so is included in upgrading the windows. Updating the front doors to thicker, better insulated/draft-proofed (modern standard, external U=1.8-2.2) had a much smaller impact of about 0.4% saving. However it is apparent that opening of the front door, especially with internal doors open, causes noticeable drop in room temperatures. A porch could improve occupant comfort and energy efficiency.

Table A.5.4-3 – Windows and doors upgrade results summary (mid-winter, two weeks)

Case	Energy Used, kWh	Energy saving, %	Fraction of Demand Time Below T Range, %				
			Living Rm	Kitchen	Front Bed	Back Bed	Spare Bed
New windows and back door	968	6.4	2.9	4.0	0.0	0.3	0.5
New front door	1030	0.4	3.5	6.7	0.0	0.6	0.1
New windows and both doors	963	6.9	3.1	3.9	0.0	0.4	0.4

It is interesting to note that the fraction of time spent below the desired temperature range does not always change as expected when upgrades are made. This can be seen in the spare bedroom (compared to the base case) and the living room (comparing the cases with new windows and with/without the new front door). In both these cases the upgrades change the timing of the rooms' heating cycles such that the cases with better insulation clash with provision of DHW. For example, the spare room, with new windows, has faster warm-up times (40 mins rather than 54 mins) such that its radiator is turned off sooner, allowing the room to cool to the lower boundary of the desired range sooner than with the old windows –sometimes this happens to coincide with the start of a shower, which means there is a longer delay before the space heating can respond, thus making the room spend longer outside the range, resulting in a slightly larger "too-cold fraction".

Loft insulation cases:

Table A.5.4-4 – Loft insulation upgrade results summary (mid-winter, two weeks)

Loft insulation (total), mm	Energy Used, kWh	Energy saving, %	Fraction of Demand Time Below T Range, %				
			Living Rm	Kitchen	Front Bed	Back Bed	Spare Bed
100	1034		3.8	6.7	0.0	0.7	0.2
150	1027	0.7	3.7	6.5	0.0	0.5	0.0
250	1018	1.6	3.5	6.6	0.0	0.5	0.0

Full (250 mm) loft insulation can achieve about 1.6% energy saving with minimal disruption, assuming good access to the roof space.

Wall insulation cases:

Table A.5.4-5 - wall insulation upgrade results summary (two weeks, mid-winter)

Case	Energy Used, kWh	Energy saving, %	Fraction of Demand Time Below T Range, %				
			Living Rm	Kitchen	Front Bed	Back Bed	Spare Bed
CWI ground floor only	989	4.4	2.4	3.5	0.2	0.7	0.4
Full CWI	910	12.0	2.7	3.2	0.0	0.0	0.2

Installing cavity wall insulation fully on both external walls is shown to give energy savings of about 12% in mid-winter. The comfort metrics show some improvement and warm-up times are reduced significantly, although the kitchen and living room still show unacceptably long warm-up times during the coldest weather, suggesting inadequate radiator, water pump or heat source sizing.

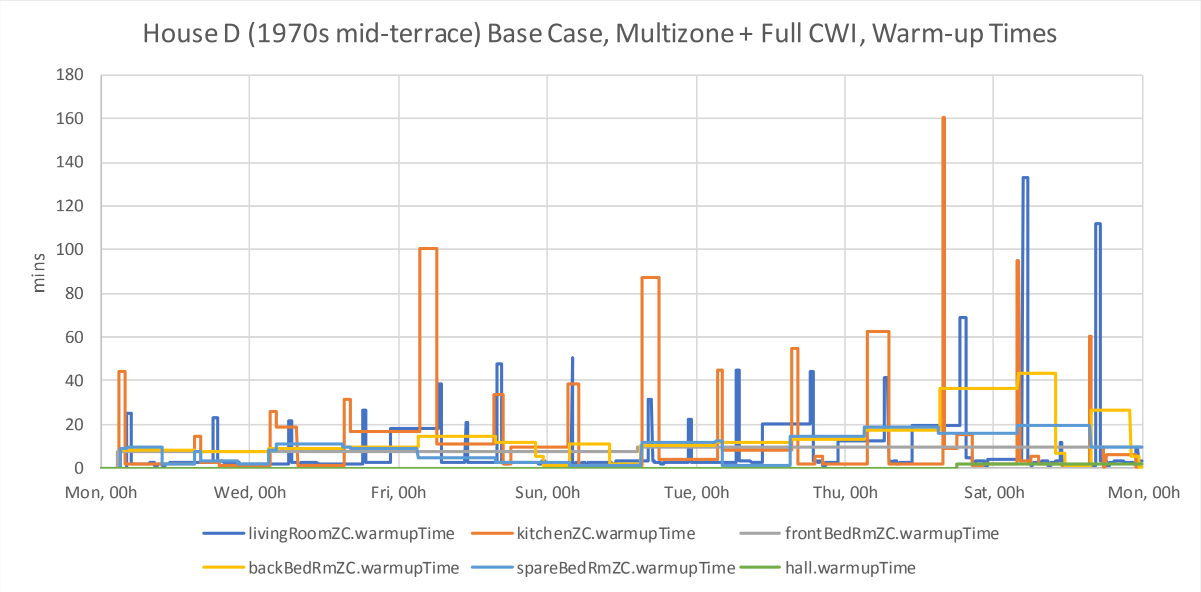

Figure A.5.4-7 - warm-up times, multizone control, full cavity wall insulation, gas boiler

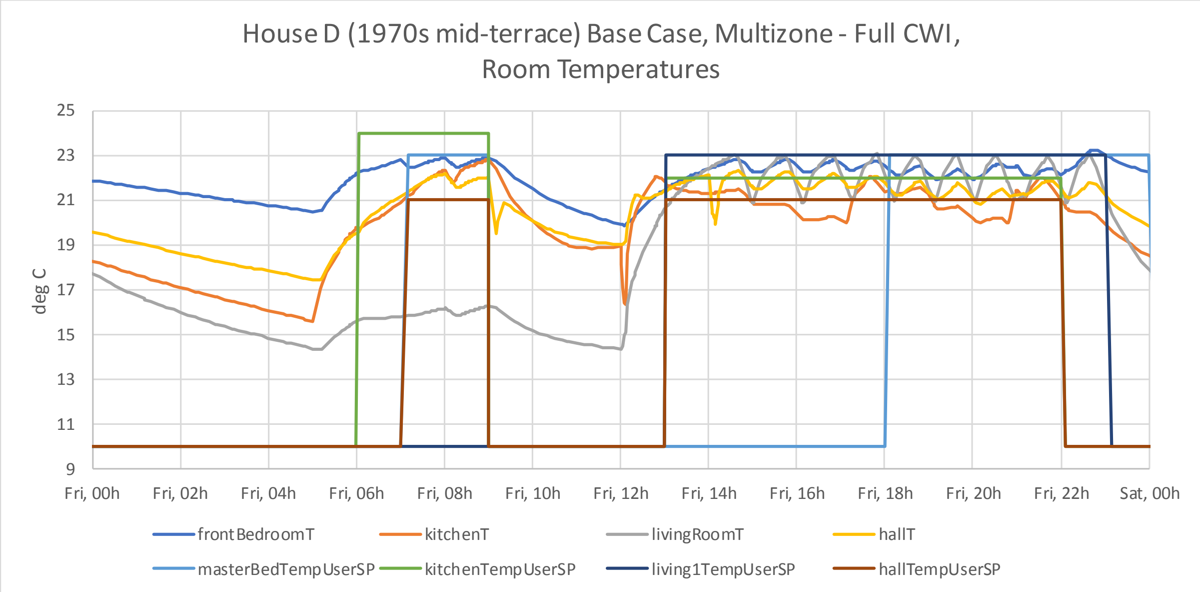

Figure A.5.4-8 – room temperatures, multizone control, full cavity wall insulation, gas boiler

Figure A.5.4-8 shows the living room and kitchen being significantly more difficult to heat than the bedrooms, even with wall insulation. This is due to the larger windows downstairs (e.g. taking up nearly half the living room front wall area, as opposed to less than a quarter in the front bedroom). This is also assumed to increase the ventilation rate, such that the overall heat losses through external walls and windows in the living room and kitchen are 60-100% more than the bedrooms and hall, for the same temperature difference. The slower rate of cooling in the kitchen, compared to the living room, is due to the larger thermal inertia of the contents and floor covering in the kitchen.

Note on solid floor insulation

This house has uninsulated solid floors but adding insulation would be very disruptive and the already low ceilings would make it unlikely to be an acceptable upgrade. An investigation into the likely effects of solid floor insulation was carried out to identify the effect that such a decision has on energy usage and comfort.

The solid floor is modelled as a number of layers, with wood or tiles over layers representing the screed, concrete slab, hardcore and then dry soil beneath. Heat transfer vertically to these layers acts like thermal storage, since there is very little heat loss at the bottom of a large depth of soil, but has an effect on cool down and warm-up times. Therefore, changes to the vertical heat transfer through these layers has very little impact on total energy consumed to heat the room above, but may affect the room temperature dynamics. Horizontal heat loss from the layers of material under the floor is not returned to the building and is therefore significant both to comfort and energy usage. This is modelled by allowing the layers to exchange heat with the undisturbed ground temperature (or air temperature for those layers above ground level), through an appropriate thickness of wall, concrete or soil. This revealed that most of the horizontal heat loss is through the uppermost layers, especially if the walls below floor level are not insulated, as they would almost certainly not be for an existing uninsulated solid floor.

Four cases were modelled to compare the impact of floor insulation in the living room and kitchen with the base case: insulation under the concrete slab with and without insulation around the inside of the wall beneath floor level (down to level of foundations, as per current building practise); insulation above the existing concrete slab without wall insulation below floor level and insulation just on the periphery of the upper layers.

Table A.5.4-6 - floor insulation upgrade results summary (two weeks, mid-winter)

Case	Energy Used, kWh	Energy saving, %	Fraction of Demand Time Below T Range, %				
			Living Rm	Kitchen	Front Bed	Back Bed	Spare Bed
Floor insulation below slab with wall insulation below floor	1011	2.2	3.7	5.5	0.0	0.6	0.1
Floor insulation below slab without wall insulation below floor	1033	0.1	4.1	6.6	0.0	0.7	0.2
Floor insulation above slab without wall insulation below floor	1018	1.6	4.2	7.4	0.0	0.8	0.1
External insulation from floor level down to 400 mm below ground	1011	2.2	3.4	5.9	0.0	0.7	0.3

One practical way to insulate an existing solid floor would be to remove the floor covering, add a layer of insulation above the existing structural layers and then relay the floor coverings. The raised floor height may also require adjustment of doors, moving of skirting boards, electrical sockets and radiators. This would cause significant disruption (as well as loss of room height) for a saving of less than 2% in energy consumption and a small loss of comfort (due to the reduced utilization of the floor’s thermal inertia giving a higher rate of room cooling and lower overnight temperatures).

Considering the high proportion of heat lost through the floor that is lost horizontally from the upper layers, it may be more effective and less disruptive to focus on this area by adding external insulation. Providing access is not impeded, this could be fitted to the walls below the floor level (assuming other wall insulation does not already extend below the damp proof course) and to the outside of the external wall foundations to a depth of 300-400 mm or to the bottom of the foundations (if lower), using insulating material suitable for use below ground.

A.5.4.4.2. Combinations of upgrades with and without larger downstairs radiators

Combinations of building fabric upgrades were modelled to maximize energy savings and comfort improvements, within limits imposed by disruption to the occupants, including:

- upgrading the heating control system (to multizone),
- injecting cavity wall insulation into both external walls,
- upgrading the windows and doors to modern standards, and
- increasing the loft insulation to 250 mm.

Two cases, one with all the above upgrades, the other with all but the extra loft insulation and new front door, resulted in energy savings of around 20% relative to the base case, but still left the living room and kitchen with excessive warm-up times. The cases were repeated with larger downstairs radiators (the kitchen increased from 0.7 m to 1.2 m in length, the living room increased from 0.9 m to 1.3 m). This resulted in much improved comfort with warm-up times reduced to less than 20 minutes (upstairs) and 30 minutes (downstairs) except on the coldest days when the full upgrade case achieved less than an hour in all rooms.

Table A.5.4-7 - upgraded building fabric and downstairs radiators, results summary (two weeks, mid-winter)

Case	Energy Used, kWh	Fraction of Demand Time Below T Range, %				
		Living Rm	Kitchen	Front Bed	Back Bed	Spare Bed
Full building fabric upgrades	821	1.2	2.5	0.0	0.0	0.2
Full BF upgrades with larger d/s radiators	797	0.6	0.5	0.0	0.1	0.2
Partial building fabric upgrades	841	1.7	2.2	0.0	0.0	0.3
Partial BF upgrades with larger d/s radiators	811	1.1	1.6	0.0	1.0	0.3

Note that with multizone control, increasing the size of the downstairs radiators gave a further 2-3% energy saving, counter to popular expectations. With single zone control the same change to the radiators only provided a 1-1.5% saving. These savings are achieved through improved boiler efficiency due to a reduction in return temperature and also through reduced boiler cycling. These savings would be smaller if the change to radiators made a significant difference to the average temperature of the rooms during warm-times (and hence increased heat loss).

The larger radiators dissipate more heat for a given flow rate and inlet temperature, which results in a cooler return temperature (after the faster warm-up), thus allowing increased condensation in the boiler with a corresponding increase in efficiency of around 1%. With multizone control there is also a reduction in heat supplied to the radiator network to achieve slightly better room temperature results. When the multizone control achieves the required range of temperatures in the bedrooms, the downstairs radiators are left on with a combined maximum heat output of 3.6kW (with the original radiators) – not enough to dissipate the minimum firing rate of the boiler (about 6 kW). As a result the boiler tends to cycle – older style boilers (as modelled) using a high temperature indication to turn the boiler off until it has cooled sufficiently (using a measurement or a timer) when it re-lights and returns to minimum firing. This results in the average flow temperature (during times operating at minimum power) being higher than the target setpoint, causing higher losses from pipework etc. With larger radiators this effect is reduced as the rooms reach their target range earlier (not spending as long with only two radiators heating) and the radiators have greater capacity (nearly 6 kW) to dissipate the minimum firing power of the boiler (less time at higher boiler outlet temperatures). The reduction in these boiler cycles also contributes to the increase in overall boiler efficiency.

Note that the reduction in time with the boiler at its minimum firing rate has the side-effect of slightly increasing the warm-up times of the bedrooms (particularly the smaller rooms which have their doors open and are therefore also partially heated by the hall radiator).

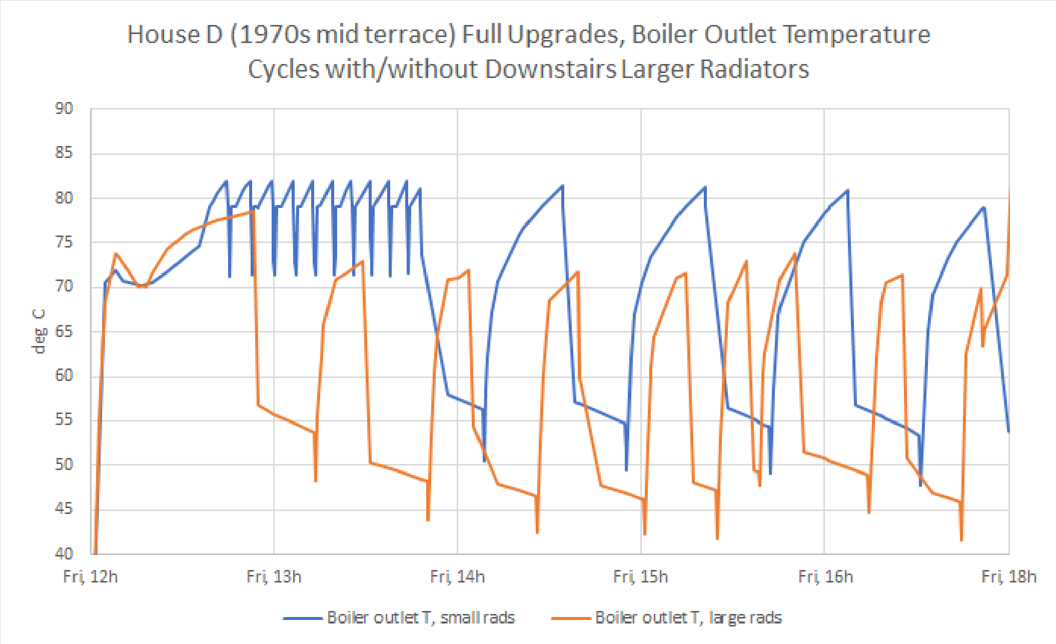

Figure A.5.4-9 – comparison of gas boiler cycles with/without larger downstairs radiators

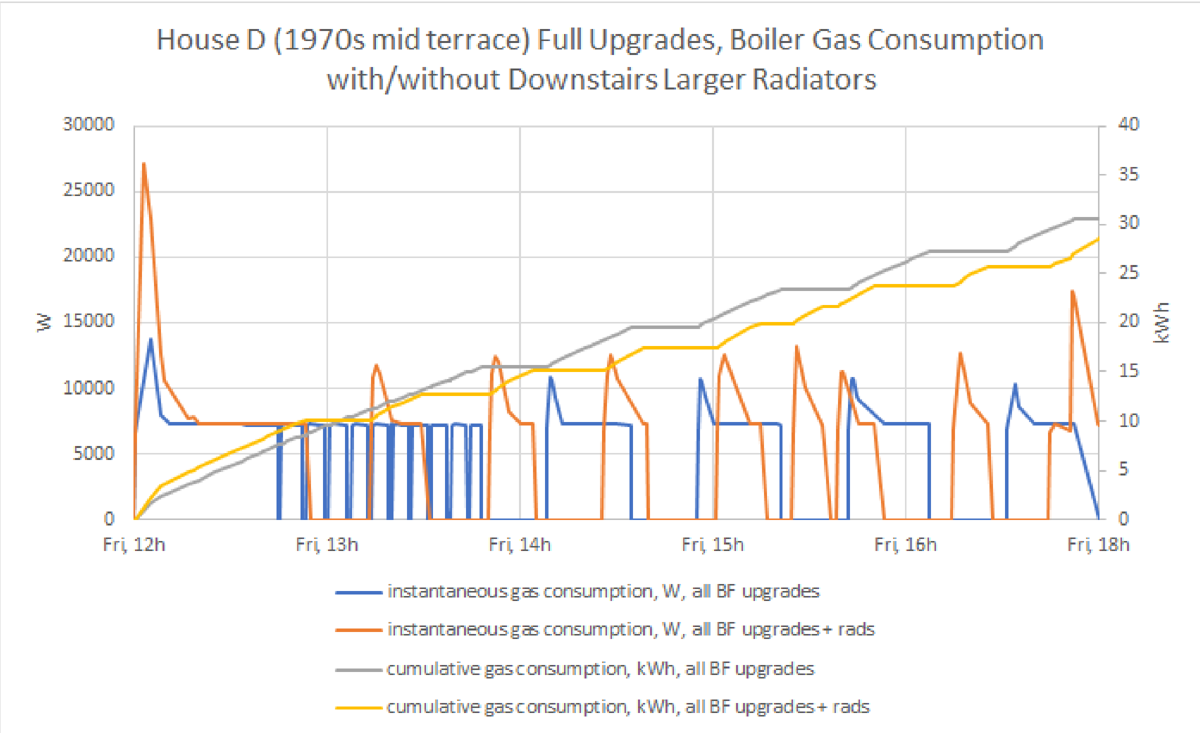

Figure A.5.4-10 – gas consumption with/without larger downstairs radiators

Despite the faster warm-up times achieved with larger radiators, there is little to be gained by reducing the pre-heat times since the heating cycle times (cycling between maximum [off] and minimum [on] temperatures) and are quite long in comparison with the possible change in pre-heat time (maybe 60 mins down to 30 mins). Hence there may be no change in number of heating cycles and therefore little or no change in time within the target temperature range (see Figure A.5.4-11 below).

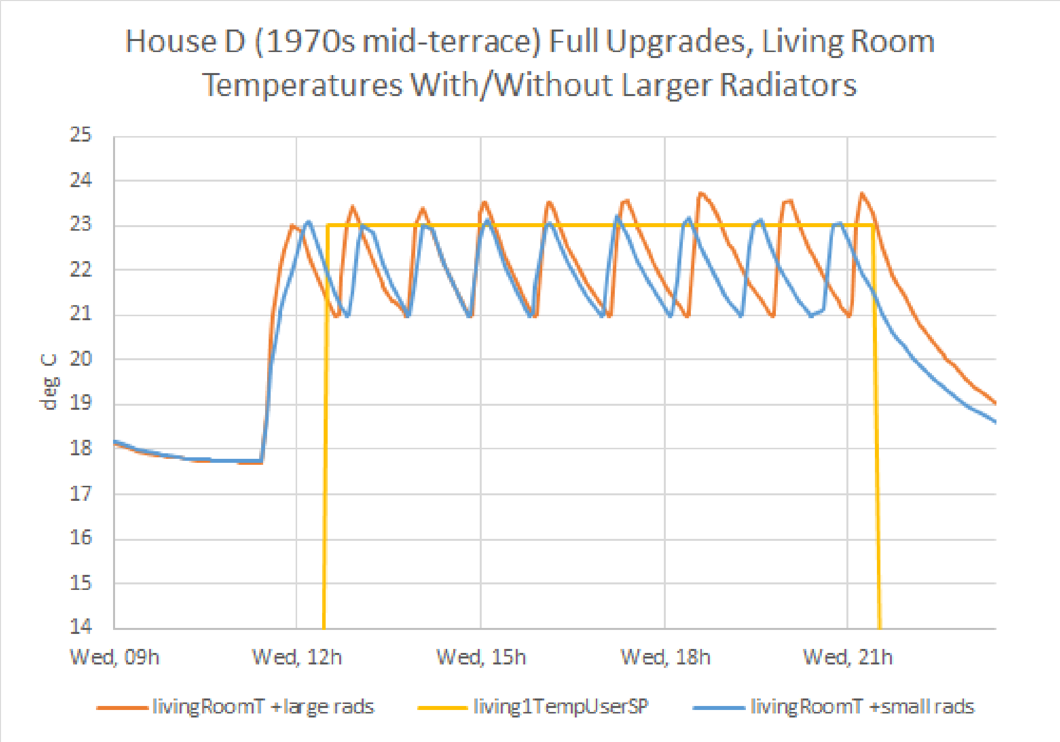

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Figure A.5.4-11 – living room temperature with/without larger downstairs radiators

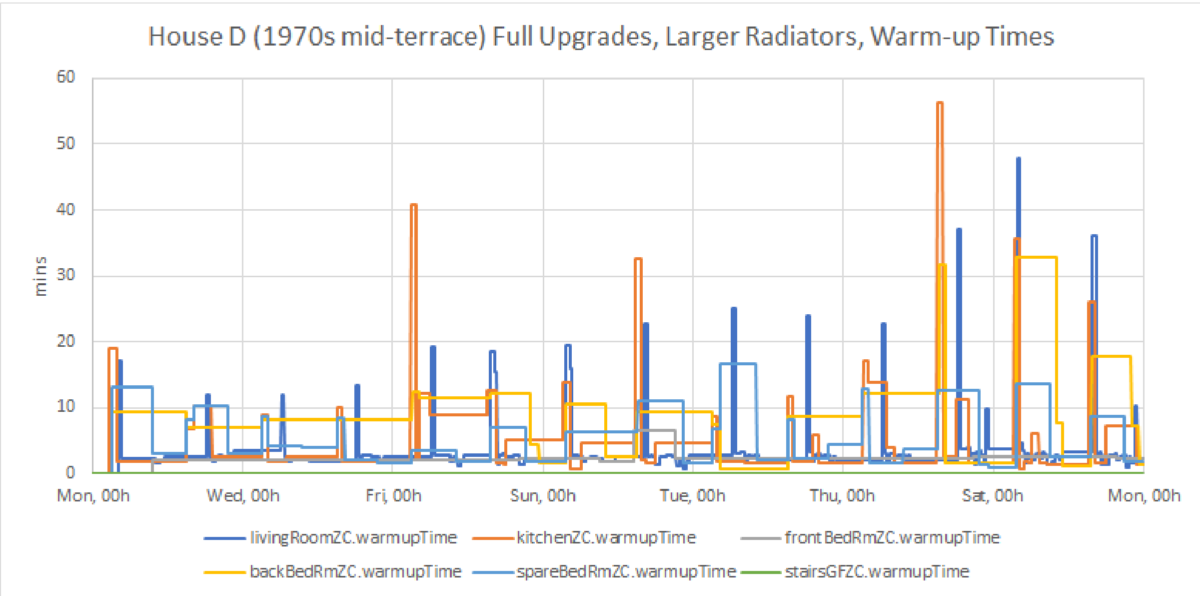

Figure A.5.4-12 - warm-up times, full building fabric upgrades, larger downstairs radiators, gas boiler

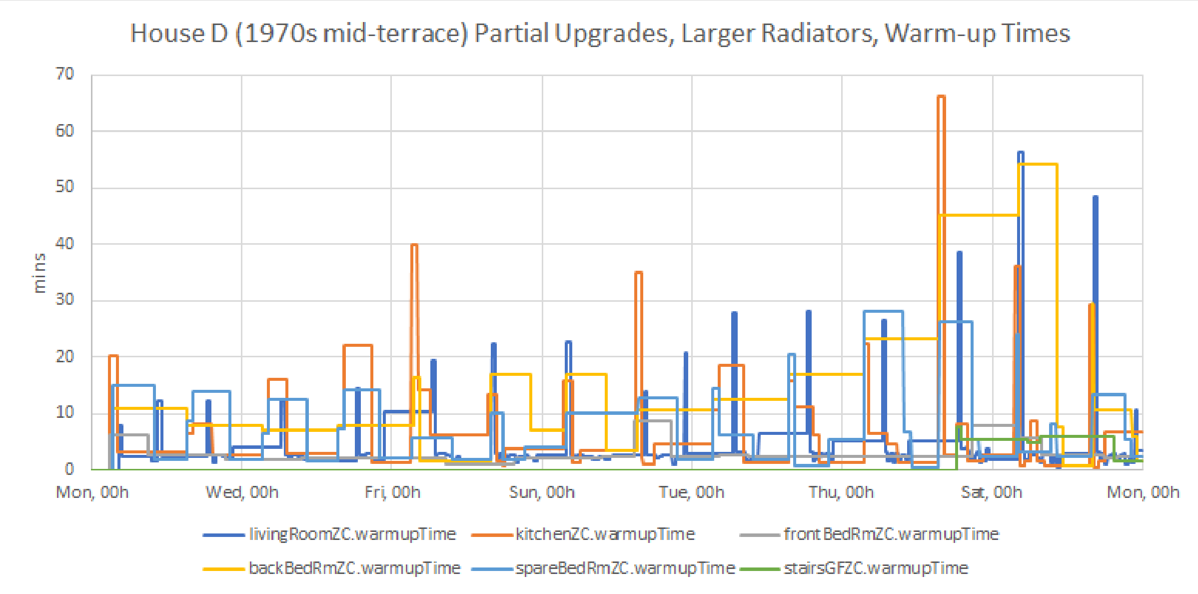

Figure A.5.4-13 - warm-up times, partial building fabric upgrades, larger downstairs radiators, gas boiler

Annual consumption for the upgraded building fabric cases with larger radiators were estimated as for the base case.

Table A.5.4-8 - Upgraded cases estimated annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	Annual Energy Consumption, kWh	Energy Output for DHW, kWh	Energy Output for SH, kWh
Full BF upgrades with larger d/s radiators	11320	1550	8657
Partial BF upgrades with larger d/s radiators	11545	1551	8847

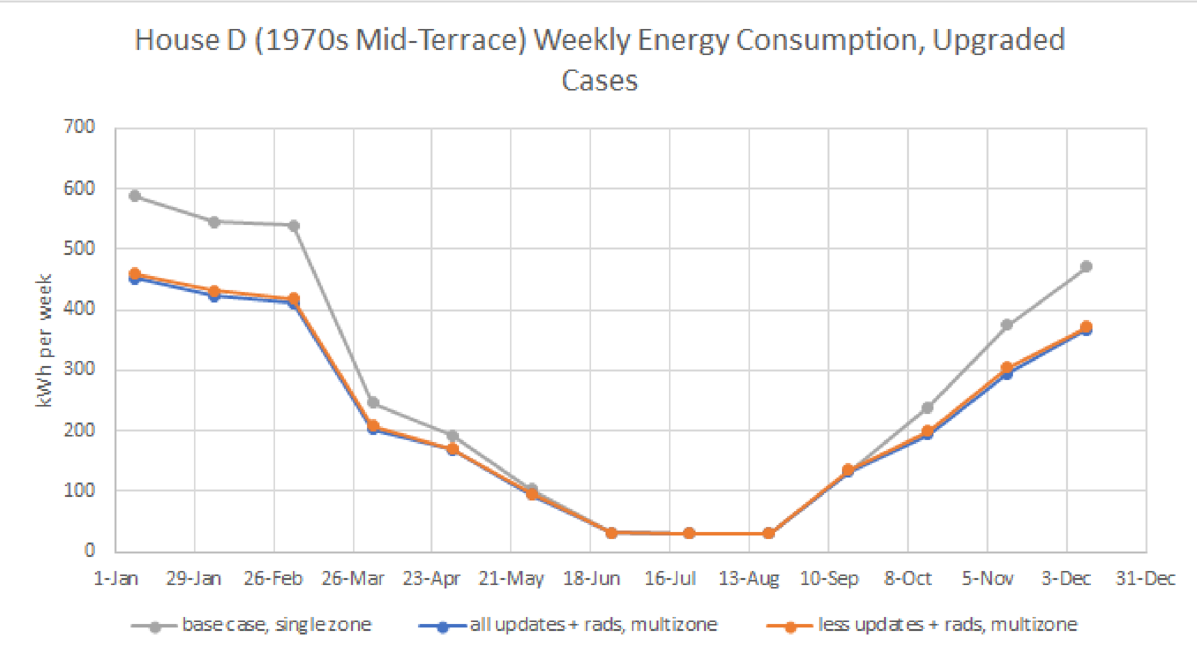

Figure A.5.4-14 - weekly energy consumption, building fabric and radiator upgrades

A.5.4.5. Air source heat pump

Using an air source heat pump as the heat source was considered technically feasible for this house. From preliminary tests, House A results and the base case simulations reported above, it was clear that using a lower heating medium temperature with no other changes would give unacceptably long warm-up times. Therefore some heating system upgrades were considered for the cases using the heat pump. Also, the cupboard on the upstairs landing should have sufficient space to reinstate a DHW cylinder. This should facilitate use of a heat pump without a supplementary water heater (other than an optional 3kW immersion heater).

A.5.4.5.1. ASHP with building fabric upgrades

The case using an air source heat pump was simulated with the following changes relative to the base case:

i. All building fabric upgrades installed as suggested in the combined case above, including increased size of radiators in the kitchen (1.2m long) and living room (1.3m long).
ii. Combi boiler replaced with a 6 kW (nominal output) air source heat pump with an input power limit of 2.5 kW, coupled with a 200 litre insulated DHW cylinder (fitted with a 3kW immersion heater to supplement the heat pump if necessary – not used in this case).
iii. Multizone control with lockshields more fully opened (especially in the downstairs rooms), to increase the power output of the radiators (also assuming higher hot water pump flow rate than the original combi boiler)
iv. Heat pump outlet temperature for SH set as a linear function of outside air temperature (rising to 55 °C at or below 5 °C outside) and increased to 5 °C above the DHW tank setpoint when higher than the SH requirement (e.g. to achieve 60 °C for 1 hour each day to guard against legionella).
v. 60 minute pre-heat times used for SH, 90 minutes for DHW tank.
vi. Temperature profile for DHW tank adjusted to avoid clashes with SH warm-up times (by heating to 60 °C at 4am), and allowed to heat both simultaneously (subject to power limits of the ASHP).

Table A.5.4-9 – ASHP with upgraded building fabric and downstairs radiators, results summary (two weeks, mid-winter)

Case	Energy Used, kWh	Peak Electricity Demand, SH+DHW, W	Fraction of Demand Time Below T Range, %				
			Living Rm	Kitchen	Front Bed	Back Bed	Spare Bed
6kW ASHP with upgrades	268	2566	4.1	1.7	0	1.0	0.2
6kW ASHP with upgrades, max room temperature setpoint=22°C	254	2562	2.6	0.9	0	0	0

The results indicate reasonable comfort performance (better than the current situation, based on room temperatures during desired warm-times) can be achieved with an air source heat pump without excessive peak demand on the electricity grid, provided building fabric and radiator upgrades achieve a better balance of heat loss from and heat supply to the dwelling. The warm-up times are, as expected, longer than the upgraded case with a gas boiler, being generally less than 80 minutes, but up to 180 minutes in the living room on the coldest days. Thanks to the larger downstairs radiators these are not excessive apart from during the very coldest weather, when the temperatures in the kitchen and living room are still within two degrees of the target range by the start of the required warm-time.

The mean COP over two mid-winter weeks with upgrades is about 2.6, giving an energy consumption of about 26% of that used by the single-zone base case.

Note that energy consumption is significantly affected by the occupants' choice to set maximum temperatures of 23 °C for much of the week, with some periods at 24 °C in the front bedrooms and kitchen. With the improved performance of the heating achieved via upgrades to building fabric, radiators and heating control, it may be possible that sufficient comfort would now be achieved with a maximum desired temperature of 22°C in all rooms. This assertion is supported by Figure A.5.4-5 which shows that the long warm-up times (without upgrades) result in some rooms not always meeting their higher target temperatures. A case with a maximum desired temperature of 22°C showed a further energy saving (5% less than the higher temperature case) and warm-up times generally less than 60 minutes, rising to about 150 minutes in the living room on the coldest days.

See note in section **A.5.2.5.1** on ASHP water pump capacity.

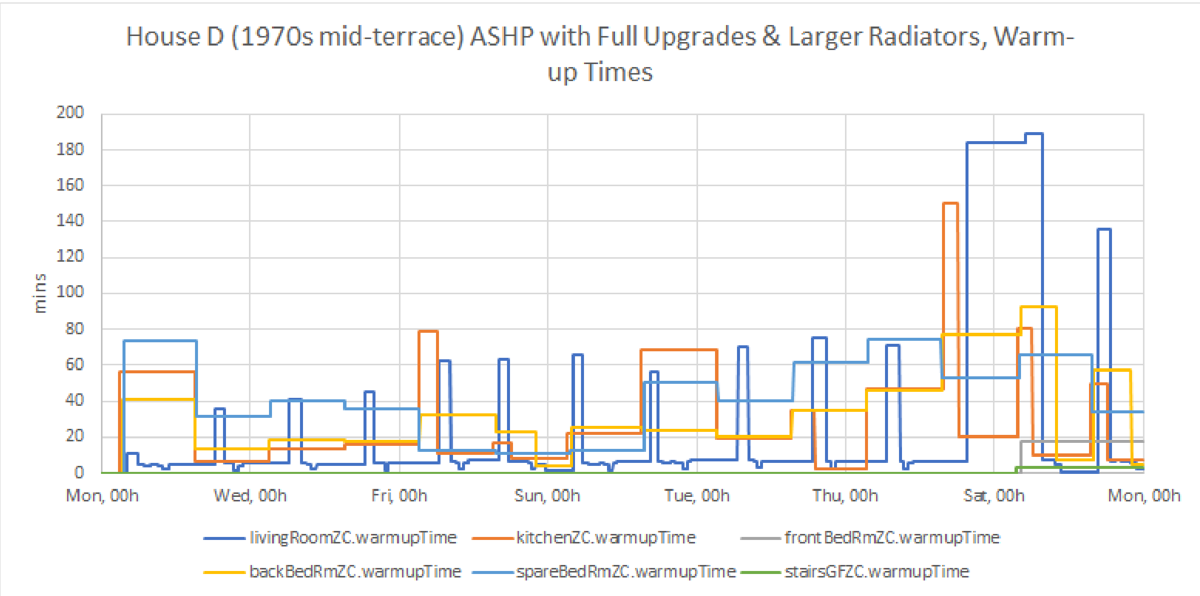

Figure A.5.4-15 – warm-up times, air source heat pump with full building fabric upgrades and larger downstairs radiators

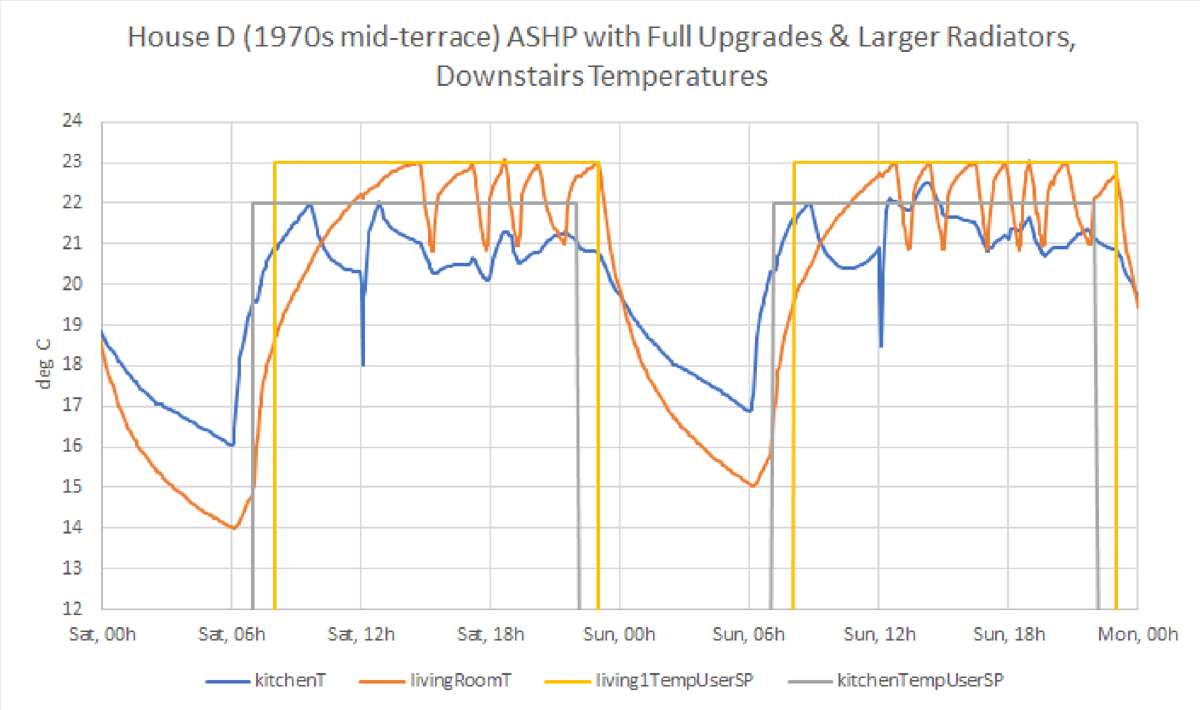

Figure A.5.4-16 – downstairs room temperatures on coldest days, air source heat pump with full building fabric upgrades and larger downstairs radiators

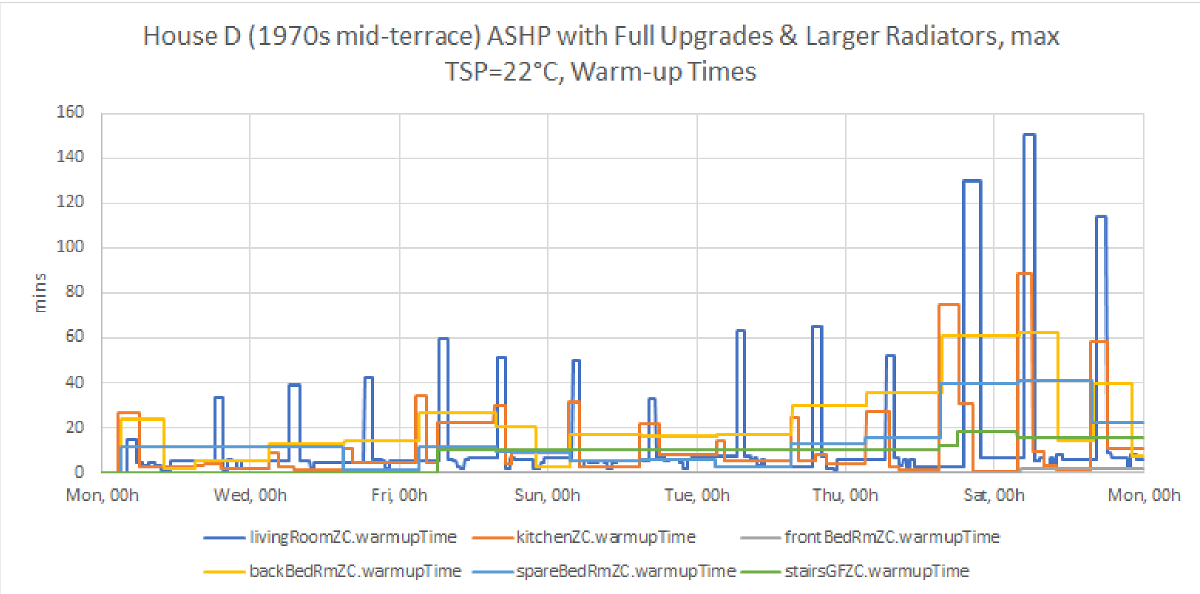

Figure A.5.4-17 – warm-up times, air source heat pump with full building fabric upgrades and larger downstairs radiators, maximum desired temperature of 22°C

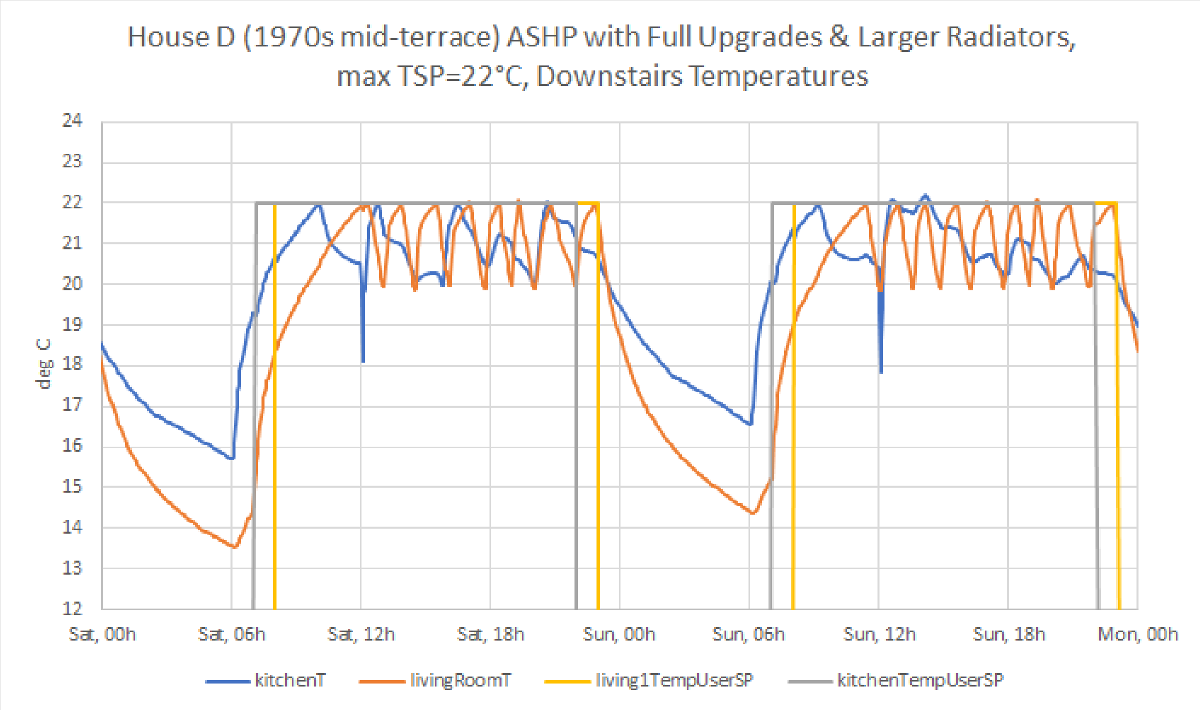

Figure A.5.4-18 – downstairs room temperatures on coldest days, air source heat pump with full building fabric upgrades and larger downstairs radiators, maximum desired temperature of 22°C

A.5.4.5.2. Multizone + ASHP + upgrades: annual energy consumption

The upgraded heat pump case above, with the original desired temperature profiles, was run for two weeks in every four for a year, with weekly energy consumption taken from the second week in each case (to minimize the influence of initial conditions). This gives an estimate of annual consumption for comparison with the combi-boiler results above. The overall energy consumption with a simple linear outlet temperature adjustment is only 26% of the base-line case (single zone control, no upgrades). About 23% is saved by upgrading the building fabric, with the saving of energy previously lost by the inefficiency of the gas boiler combining with the heat pump average COP of about 2.6 to save over 65% of the remainder.

Table A.5.4-10 – Air source heat pump with upgraded building fabric: estimated annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	**Annual Energy Consumption, kWh**	**Energy Output for DHW, kWh**	**Energy Output for SH, kWh**
6kW ASHP 2.5kW input limit, multizone control + fabric upgrades + larger radiators	3909	1577	8638

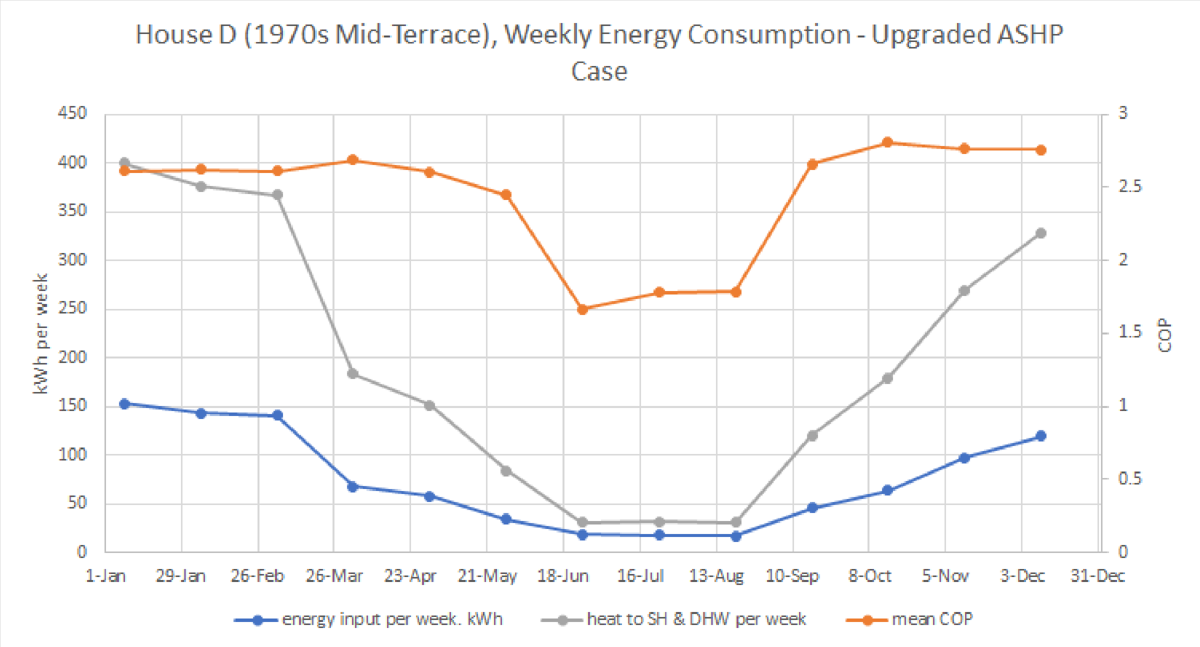

Figure A.5.4-19 – weekly energy consumption, air source heat pump with building fabric upgrades

As discussed in House B results summary, the drop in mean weekly effective COP in summer is due largely to the increased proportion of heat lost around the DHW tank. Also discussed in House B results, the simple control logic used in this case is effective but indicates scope for improvement.

A.5.4.6. Upgrade pathway stages

The following stages in the pathway to full upgraded building fabric and heat source have been identified:

Stage 1: multizone control + cavity wall insulation + 250 mm loft insulation + larger downstairs radiators

Stage 2: replace windows & doors

Stage 3: replace gas boiler with 6kW output Air-Source Heat Pump and 200 litre hot water cylinder

The summary of the results for each stage in the pathway are shown below.

Table A.5.4-11 – pathway stages, summary (two weeks, mid-winter)

Case	Energy Used, kWh	Fraction of Demand Time Below T Range, %				
		Living Rm	Kitchen	Front Bed	Back Bed	Spare Bed
Base (single zone control)	1027	67	59	0	0	0
Stage 1 (MZ + insulation + larger radiators)	871	0.5	0.7	0	0	0
Stage 2 (windows + doors)	797	0.6	0.5	0.0	0.1	0.2
Stage 3 (ASHP +DHW tank)	268	4.1	1.7	0	1.0	0.2

Table A.5.4-12 – pathway stages, estimated annual consumption for heating and hot water (Newcastle-upon-Tyne, typical mean year)

Case	Annual Energy Consumption, kWh	Energy Saving	Energy Output for DHW, kWh	Energy Output for SH, kWh
Base (single zone control)	14087		1547	11131
Stage 1 (MZ + insulation + larger radiators)	12375	12%	1552	9590
Stage 2 (windows + doors)	11320	20%	1550	8657
Stage 3 (ASHP +DHW tank)	3909	72%	1577	8638

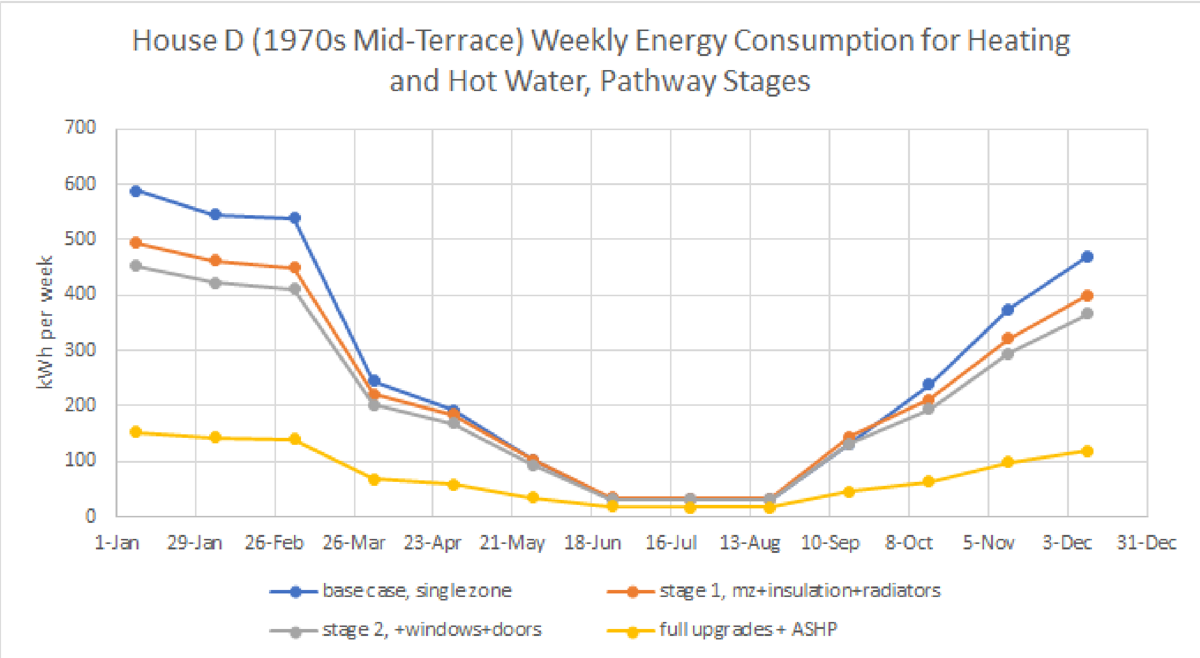

Figure A.5.4-20 – weekly energy consumption for heating and hot water, stages to full upgrade with air source heat pump and building fabric upgrades

A.5.5. Summary of IEHeat results for House E (1980s detached)

A.5.5.1. House and household description

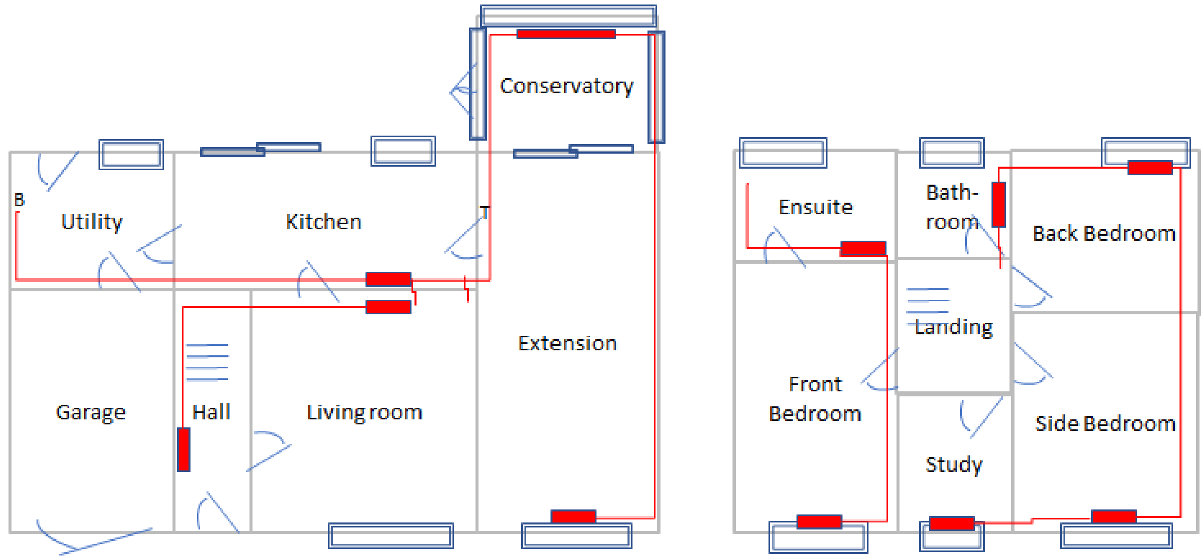

Figure A.5.5-1 - House E Schematic (simplified for modelling)

The original house has been extended on both sides, adding a single storey extension (with pitched roof) and conservatory on the right (as seen from the front) and a new master bedroom with ensuite shower room above the garage and utility room on the left. All external walls have insulated cavities and are assumed to have light weight (aerated) concrete block inner skins. The floors are solid, without insulation in the original building, but insulated in the extensions. The upstairs windows have recently installed double glazing, with the downstairs windows double glazed but pre-2002 standard; the rear door is also of aging uPVC construction, while the front door is of a more recent composite material with minimal glazing. The loft insulation in the original roof is 100 mm thick (with boards over), 100 mm (without boards) in the single storey extension and 250 mm in the more recent extension.

The heating system comprises a combi-boiler in the utility room with mostly modern radiators – double panel double convectors (DPDC) downstairs (except for a single panel in the conservatory) and single panel single convector (SPSC) radiators upstairs (apart from a DPDC in the back bedroom). The bathroom and ensuite have towel rails heated by the central heating. The heating is controlled by a single thermostat and timer (in the ground floor extension) with TRVs on all radiators except in the hall. For comparison with the upgrade evaluation cases (below) multizone on/off control was used, with minimum valve openings set to use the radiators as a buffer (see section **A.4.4**).

For the single zone case the radiators are roughly balanced to allow the TRVs to warm up the rooms together, which is not so important for the multizone case (as no room should over-heat).

The following data was used to define the household requirements and behaviour: 7 day temperature profiles have been approximated from combined sets of HEMS data (which is per-room and varies over time) – for the single zone case this has been merged to give a boiler heat demand whenever any room requires heating (but note the maximum temperature setting was reduced to 21°C to avoid excessive overheating in the other rooms); occupancy heat gains have also been estimated from sets of HEMS data; the doors are normally closed, with the exception of the kitchen (internal door to living room has been removed), living room (door open during the day, closed during the evening and night) and some brief opening (for morning/midday/evening activity); DHW demands simulate morning and evening usage (totalling about 150 litres per day at 40°C) plus a bath (120 litres) once a week (Saturday evening).

A.5.5.2. Base case results, winter

Results with the existing building fabric and heat source are tabulated below.

Table A.5.5-1 - Base case results summary (mid-winter, two weeks)

Case	Energy Used, kWh[1]	Fraction of Demand Time Below T Range, %						
		Living Rm	Kitchen	Front Bed	Back Bed	Side Bed	Extension	Study
Base (single zone control)	1268	7.9	10.2	0.9	0.9	2.0	44.8	0.2
Base (multizone control)	1266	1.2	0.2	0.1	0.0	0.0	2.2	0.0

Note 1: Gas energy stated is gross (i.e. including latent heat of water)

The poor comfort metrics for single zone control are a result of the single room thermostat being located in the extension, which is one of the slowest rooms to warm up, thanks to a large front window and a large patio door to the conservatory (which is very cold in mid-winter). Hence despite the action of TRVs set to 22 °C the bedrooms tend to over-heat, while poor radiator balancing contributes to the ensuite typically being colder than desired.

Multizone control allows each room to follow its desired temperature profile far better, with radiator balancing less important since once a room has reached the top of its desired temperature range the radiator is turned off, avoiding over-heating, and allowing the cooler rooms to continue heating as required. Hence the lockshield valves can be opened wider to reduce warm-up times in most rooms.

The householders choose to set profiles with some rooms warming to 23 or 24 °C at times, whilst other, less used rooms are set to 20 or 21 °C. This would typically result in significant energy savings, however in this case the multizone control achieves higher conservatory temperatures, including heating during some very cold nights to keep it between 8-10 °C. As a result, for the base case, multizone control achieves a better match of desired room temperatures but without noticeable energy savings.

With multizone control the warm-up times are typically well below 30 minutes, apart from on the coldest days, when the wash rooms, living room and extension approach 60 minutes. However, this partly due to a clash between the start of the morning warm-time in these rooms and the first shower of the morning, delaying heating at a time when the space heating system is at its most stretched.

Multizone control is used for comparison of building fabric upgrade options, as discussed in **Appendix 4**.

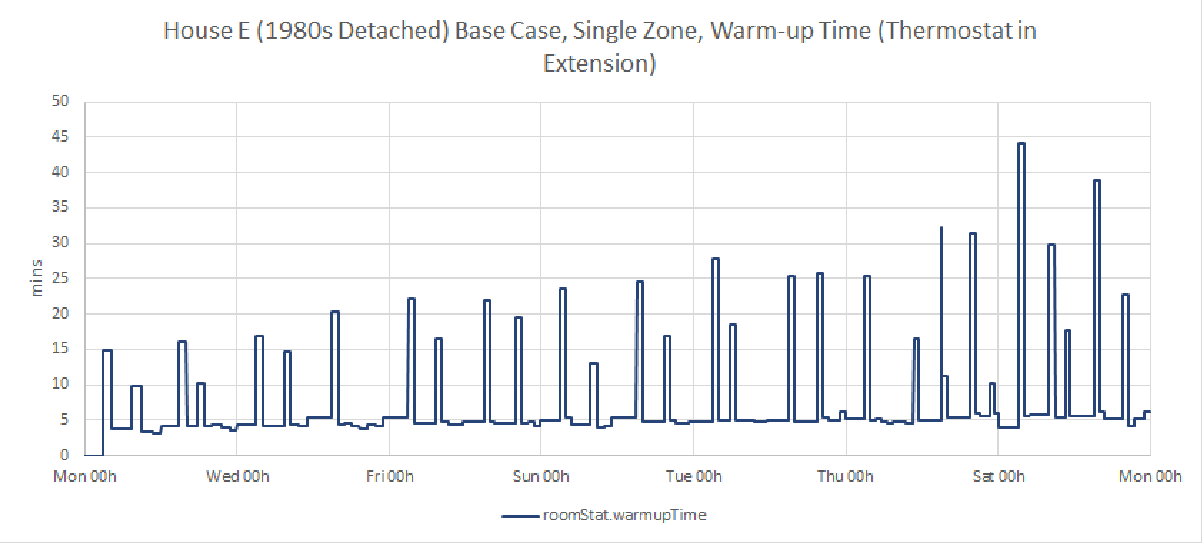

Figure A.5.5-2 – warm-up times, base case, single zone control

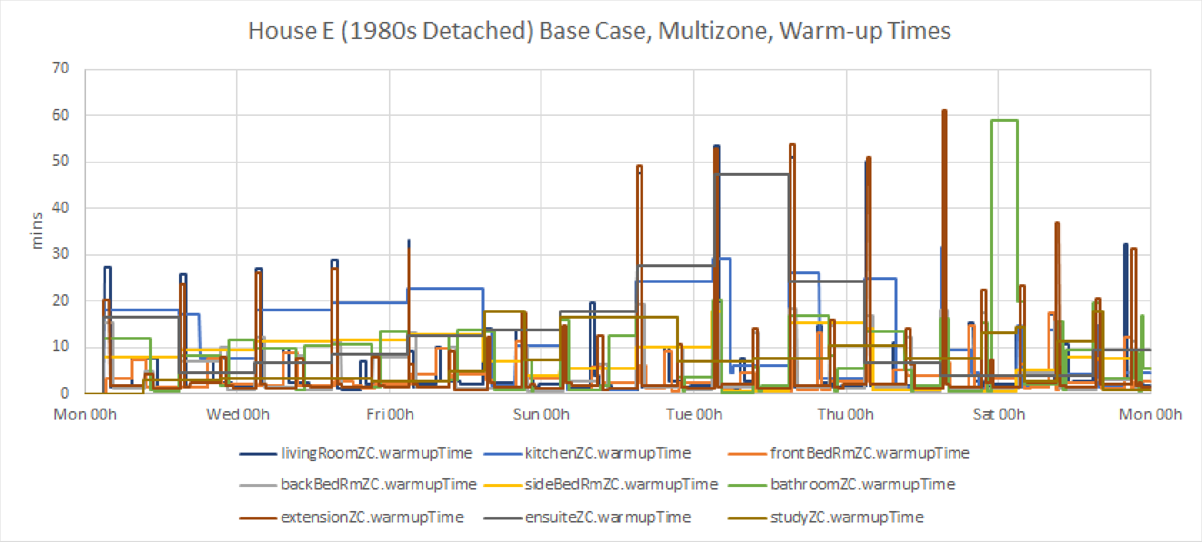

Figure A.5.5-3 – warm-up times, base case, multizone control

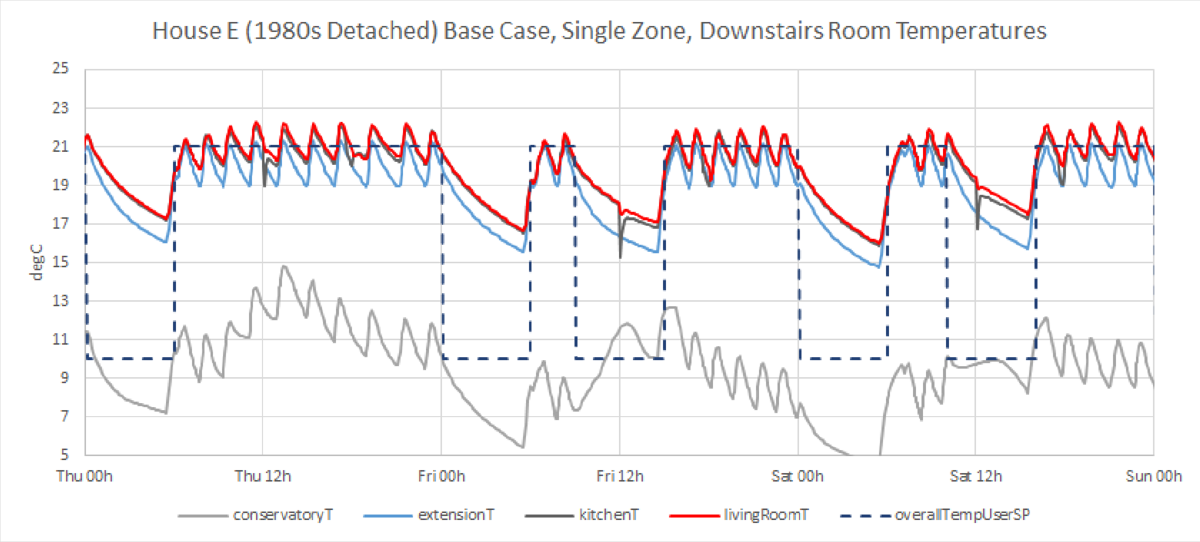

Figure A.5.5-4 –downstairs room temperatures, single zone control, base case

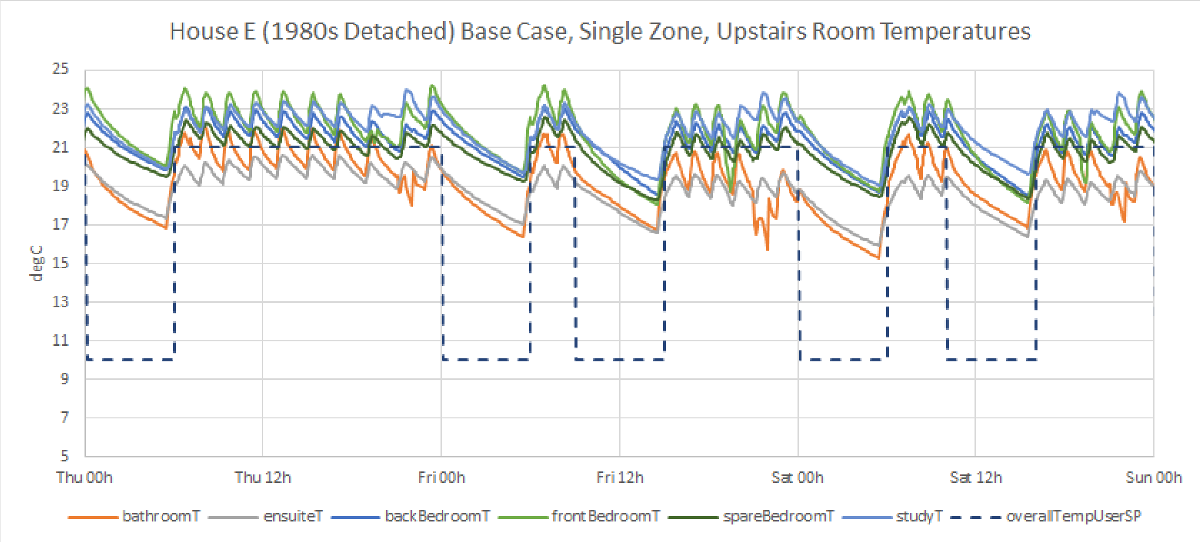

Figure A.5.5-5 –upstairs room temperatures, single zone control, base case

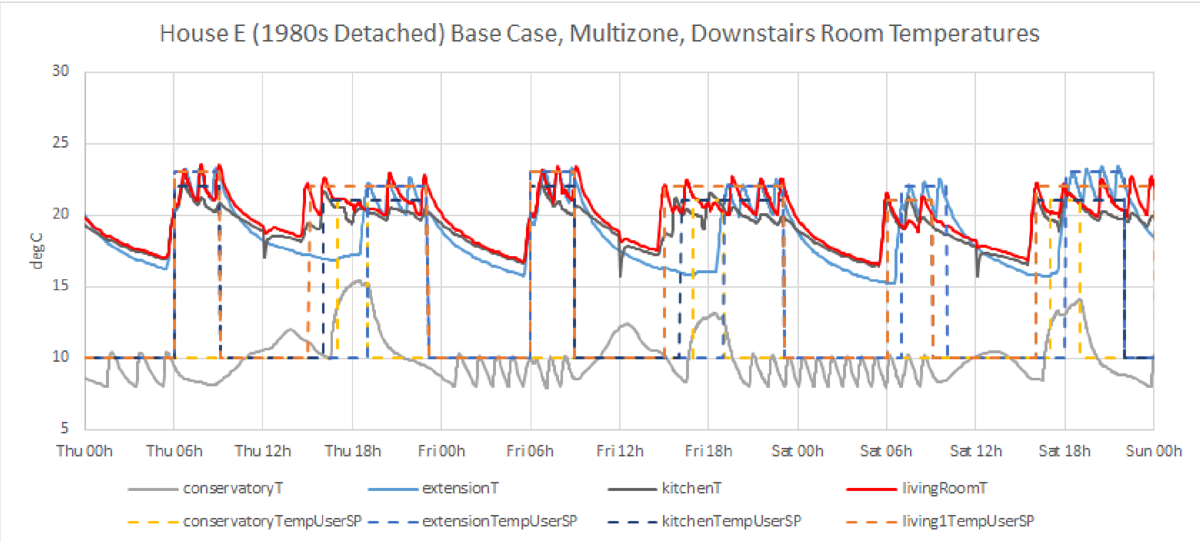

Figure A.5.5-6 – downstairs room temperatures, multizone control, base case

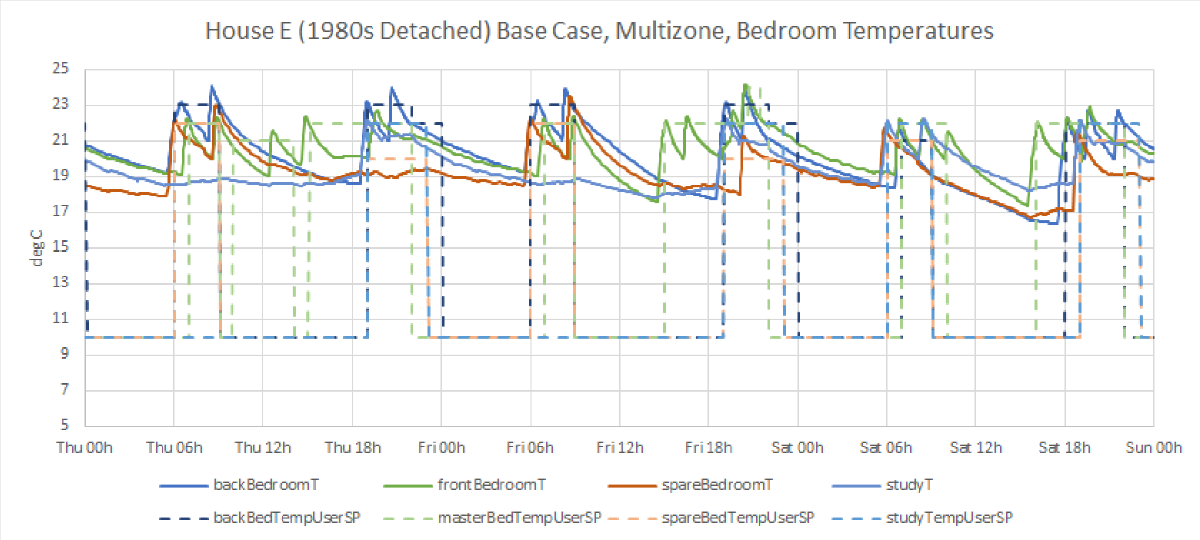

Figure A.5.5-7 – bedroom temperatures, multizone control, base case

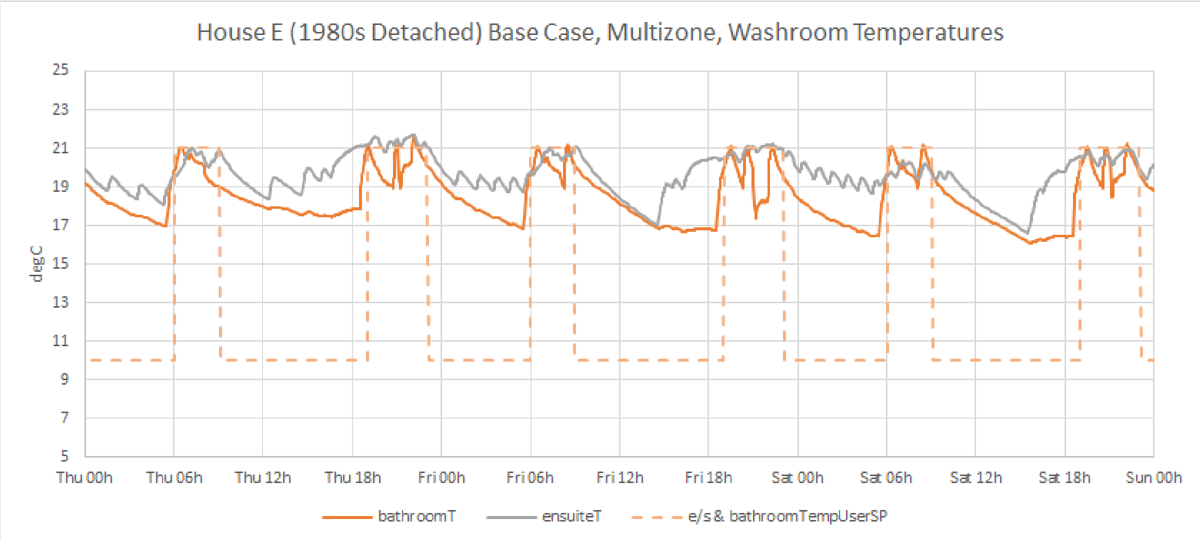

Figure A.5.5-8 – washroom temperatures, multizone control, base case

A.5.5.3. Base case annual energy consumption

The annual energy consumption has been estimated as described in the introduction to the results summaries. The multizone case is shown to use about 3% more energy over the year caused partly by the extension (location of single thermostat) benefitting from heating by the sun in the mornings (via the east facing conservatory), leading to the boiler being turned off prematurely in the single zone case between March and September.

Table A.5.5-2 - Base case estimated annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	Annual Energy Consumption, kWh	Energy Output for DHW, kWh	Energy Output for SH, kWh
Base (single zone control)	16320	2393	11927
Base (multizone control)	16774	2407	12139

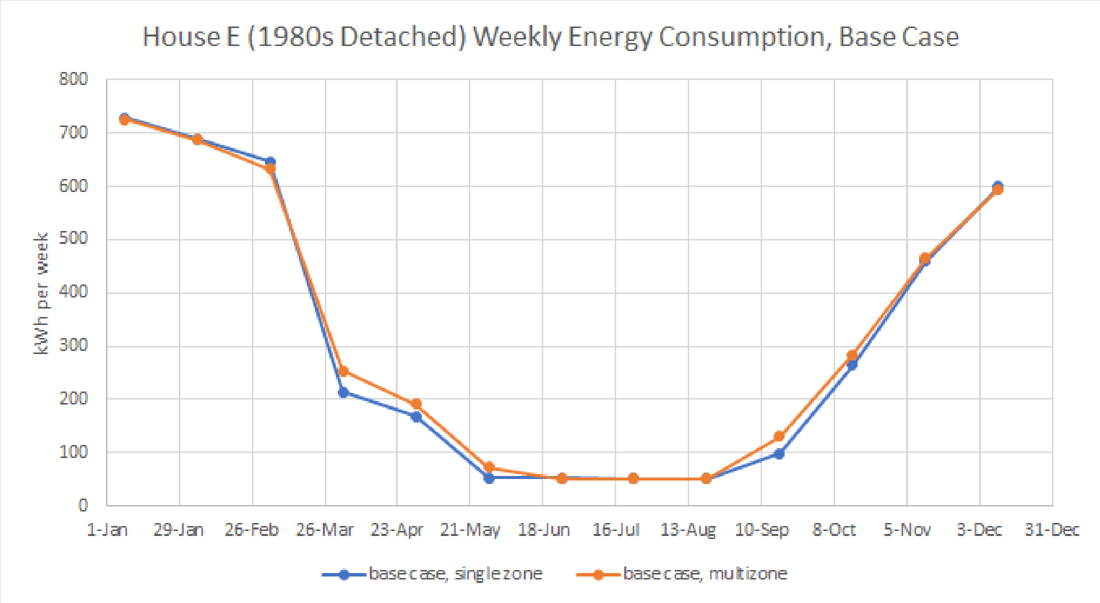

Figure A.5.5-9 - weekly energy consumption, base case

A.5.5.4. Building fabric upgrade evaluation cases

A summary of results of evaluation cases are presented below, investigating the impact of building fabric upgrades, to enable energy and comfort gains to be incorporated with practical and household issues in the decision process to choose upgrades to recommend.

There is limited scope in this house for upgrades to insulation: walls are already insulated, the solid floors have recently fitted high cost wood floor coverings, and the main loft is partly fully insulated already, and partly boarded and in use for storage. Hence the single storey extension roof is the only easily achieved possibility for increasing the insulation. However, the downstairs windows, external doors and conservatory offer significant scope for improvement, as does the heating system.

A.5.5.4.1. Building fabric evaluation cases: extension loft insulation, windows, doors, conservatory

Original loft and single storey extension loft insulation cases:

Table A.5.5-3 –Extension loft insulation upgrade results summary (mid-winter, two weeks)

Loft insulation (total)	Gas Energy Used, kWh	Energy output to SH, kWh	Fraction of Demand Time Below T Range, %						
			Living Rm	Kitchen	Front Bed	Back Bed	Side Bed	Extension	Study
100 mm (base case)	1266	1000	1.2	0.24	0.1	0.0	0.0	2.2	0.0
250 mm in extension	1256	991	1.2	0.26	0.1	0.0	0.0	1.7	0.0
250 mm in original loft	1268	985	1.0	0.20	0.1	0.1	0.0	2.0	0.0

Full (250 mm) extension loft insulation can achieve only 0.8% energy saving but with minimal disruption, assuming good access to the roof space. This extra insulation gives a negligible improvement in worst-case extension warm-up time, which are still around an hour. Insulating the main loft, which would cause more disruption and be more expensive (due to using insulated boards to retain the storage amenity) reduces heat used in the radiators by about 1.5%, and reduces warm-up times in the original bedrooms. However, with a gas boiler this saving is offset by a decrease in boiler efficiency thanks to the greater time spent with sub-minimum heat load (as the bedroom radiators turn off earlier) and with higher average return temperatures.

Window, door and conservatory upgrades: upgrading the downstairs windows (including the kitchen's patio door) was assumed to achieve an improvement in U value from 2.8 to 2.0 W/m2/K; a similar improvement was evaluated for the conservatory windows, plus an ultra-low U value option of 1.5 W/m2/K; the conservatory roof was evaluated by replacing its glazing with opaque options of either a minimum cost option (U-value of about 1.0 W/m2/K, equivalent to standard MDF-reinforced uPVC panels) or a thicker insulation (U-value of about 0.5 W/m2/K, equivalent to adding 40 mm of polyurethane); an upgrade to the front door was assumed to improve its U-value from 2.4 to 1.8 W/m2/K.

Table A.5.5-4 – window and door upgrade results summary (two weeks, mid-winter)

Case	Energy Used, kWh	Energy Output to SH, kWh	Fraction of Demand Time Below T Range, %						
			Living Rm	Kitchen	Front Bed	Back Bed	Side Bed	Extension	Study
New d/s windows	1206	943	0.8	0.2	0.1	0.0	0.0	2.4	0.0
New conservatory windows and uPVC panel roof	1281	961	1.5	0.5	0.1	0.0	0.0	2.0	0.0
New d/s + conservatory windows and uPVC panel roof	1185	922	0.9	0.3	0.2	0.0	0.0	2.0	0.0
New d/s + conservatory windows and 40 mm PU panel roof	1175	917	1.0	0.4	0.2	0.0	0.0	1.9	0.0
New d/s + conservatory windows and 40 mm PU panel roof + upgraded front door	1170	912	0.9	0.3	0.1	0.0	0.0	1.9	0.0
New d/s windows + ultra-low U conservatory windows and 40 mm PU panel roof	1189	906	1.0	0.4	0.1	0.0	0.0	1.7	0.0

Replacing the downstairs double glazing (including the back door) reduces energy consumption by about 4.8%, with a small improvement on comfort downstairs. The original conservatory frequently demands heat to try to achieve the desired temperature range, which has a tendency to slightly warm all rooms (due to small radiator flows even when "off"). The upgraded conservatory, while reducing energy use by a further 3%, allows some rooms (e.g. back bedroom) to cool slightly more before the heating is turned on, causing them to have slightly longer warm-up times. With maximum window and conservatory upgrades the conservatory temperature is no longer low enough to require heating during the night, increasing the warm-up time in some rooms to nearly an hour in the coldest weather. Note also that although the conservatory upgrades give the expected savings in energy output for space heating, the resulting increase in boiler return temperature has a noticeable effect on boiler efficiency, in some cases cancelling out the savings in energy usage. This would not be expected with an alternative heat source, such as a heat pump (for which an increased return temperature would often increase the COP). Upgrading the front door makes a small saving in energy, and a small but noticeable improvement in kitchen comfort thanks to the open kitchen door.

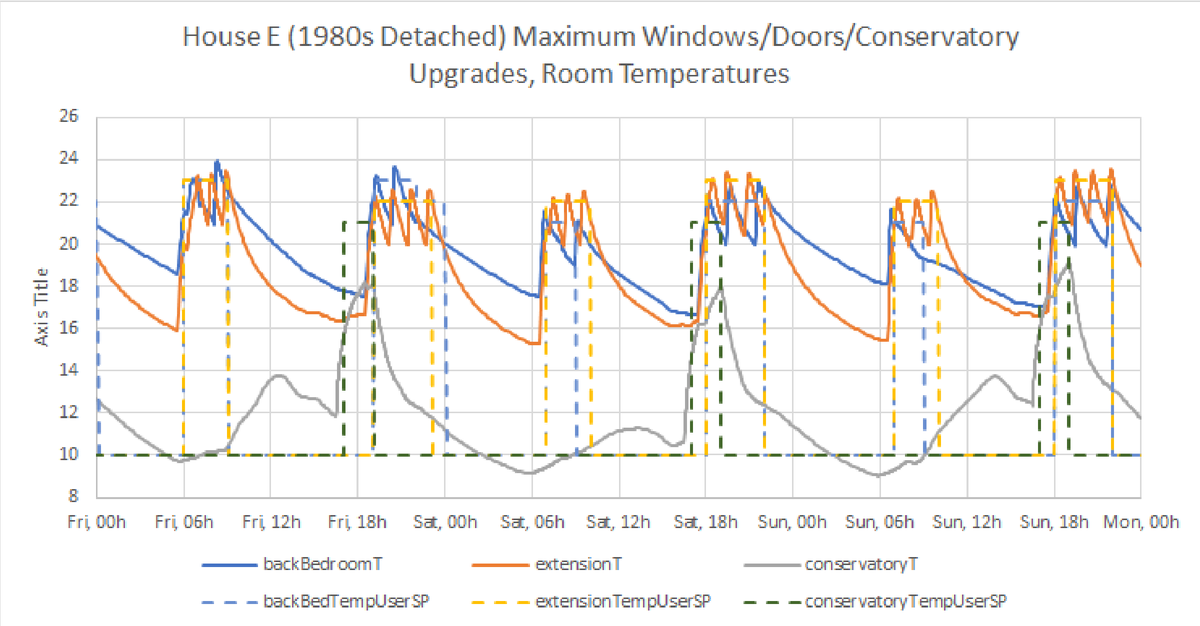

Figure A.5.5-10 – conservatory, extension and back bedroom temperatures with maximum upgrade to windows and conservatory

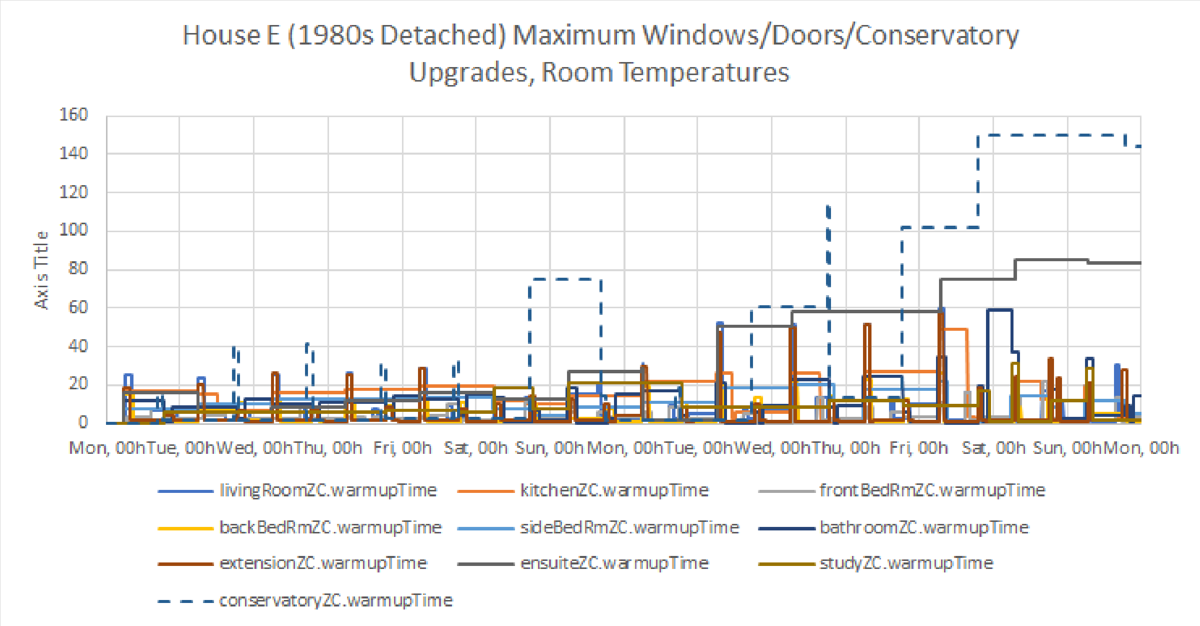

Figure A.5.5-11 - warm-up times with maximum upgrade to windows and conservatory

A.5.5.4.2. Upgraded boiler pump

As with most gas combi boilers, this house has a unit sized to provide hot water (30 kW) which gives it more than enough power to deliver space heating. However the large house and long pipe runs make it difficult for the installed water pump to supply sufficient flow rate to the radiators to deliver their potential power output. In order to reduce warm-up times, a case was run with an increased capacity pump – but still specified to be well within typical system working pressure and velocity limits.

Without any other upgrades this change significantly improves warm-up times particularly for the living room and kitchen (but not in the conservatory, which needs insulation to meet its targets), with only a 1.3% increase in gas consumption. This change will roughly double pump energy consumption, although this is small compared to gas used for heating - around 70 W to run the larger pump compared to 20 kW of gas for the boiler at full load. This change wasn't included in the combined upgrades as the aim is to replace the boiler, rather than to enhance its delivery of comfort. However, these results provide a good indication of the importance of correct sizing of all elements within the heating system.

Table A.5.5-5 – boiler pump upgrades, summary (two weeks, mid-winter)

Boiler pump nominal flow and head	Energy Used, kWh	Maximum Warm-up Time, mins						
		Living Rm	Kitchen	Front Bed	Back Bed	Side Bed	Extension	Study
16.67 l/min, 2.55 m (base case)	1266	56	31	18	19	18	59	18
23 l/min, 5 m	1282	28	22	16	16	12	53	10

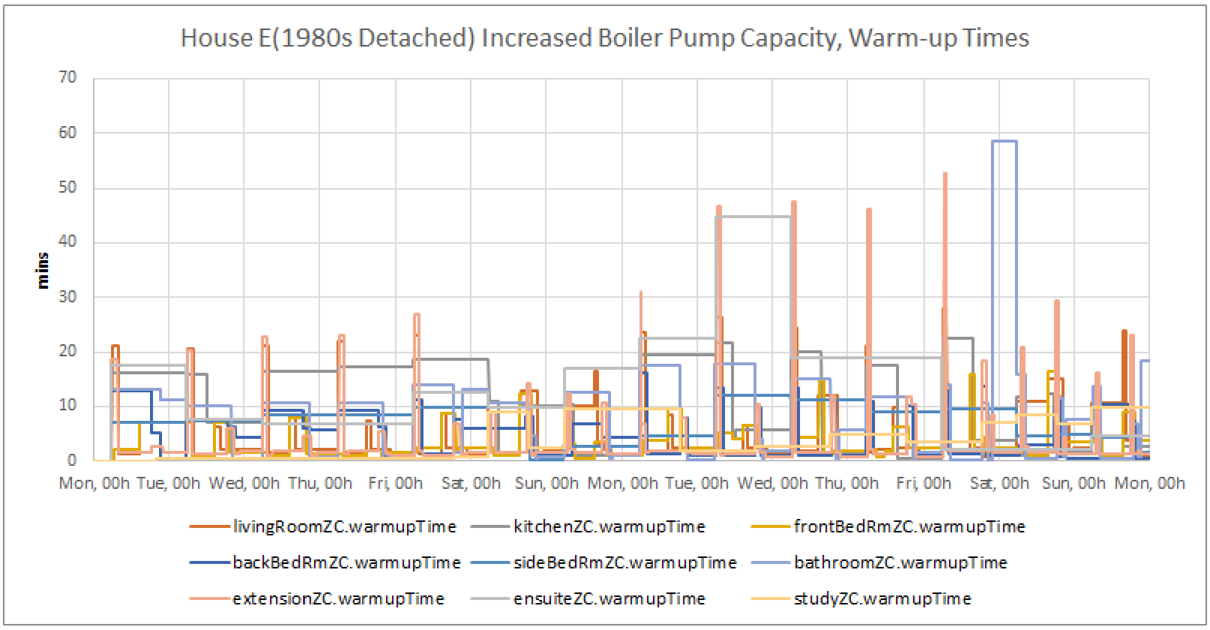

Figure A.5.5-12 - warm-up times with upgraded boiler pump

A.5.5.4.3. Possible combinations of upgrades

To combine comfort (warm-up time) improvements and energy saving, such that use of a heat-pump becomes feasible, the results above suggest that the biggest gains would be found in:

- upgrading the heating control (to multizone),
- increasing the extension roof insulation to 250 mm,
- upgrading all downstairs windows and external doors
- fitting high spec double glazing and a solid (insulated) roof to the conservatory.

This results in a 9% energy saving with respect to the base case, giving noticeably better comfort only in the extension and conservatory. The conservatory is unable to reach a comfortable temperature in the winter (less than 18 °C on most days), even with extra insulation. Hence it seems that it would be unlikely to be used for the coldest months, and could therefore be maintained at a lower temperature. This was simulated (limiting the maximum temperature setting to 15 °C), making a further energy saving of just over 3%, at the expense of a slight increase in extension warm-up time. This loss can be largely recovered by using radiator reflective foil on the extension's radiator.

The ensuite shower room has an undersized towel rail, exacerbated by the heating being on less often (thanks to better insulation in the conservatory) and a clash of space heating warm-up with the habitual morning shower time. This could be alleviated by changing the heating schedule, or by increasing the size of the towel rail. A 50% increase in rail height was simulated resulting in halving the warm-up time in this (small) room.

Table A.5.5-6 - upgraded building fabric results summary (two weeks, mid-winter)

Case	Energy Used, kWh	Fraction of Demand Time Below T Range, %						
		Living Rm	Kitchen	Front Bed	Back Bed	Side Bed	Extension	Study
Multizone, upgraded windows & doors, 250mm extension loft insulation, high spec windows and solid roof on conservatory	1149	0.9	0.3	0.1	0.0	0.0	1.1	0.0
Full upgrades as above, with conservatory heating limited to 15 °C	1109	0.8	0.3	0.2	0.0	0.0	1.6	0.0
Full upgrades as above, with conservatory heating limited to 15 °C and 1.2m ensuite towel rail	1105	0.9	0.3	0.1	0.0	0.0	1.6	0.0
Full upgrades as above, with conservatory heating limited to 15 °C, 1.2m ensuite towel rail and rad foil in extension	1105	1.1	0.3	0.1	0.0	0.0	1.0	0.0

Table A.5.5-7 - upgraded building fabric maximum warm-up time summary (two weeks, mid-winter)

Case	Energy Saving (w.r.t base), %	Warm-up Times, mins						
		Living Rm	Kitchen	Front Bed	Back Bed	Side Bed	Extension	Ensuite
Multizone, upgraded windows & doors, 250mm extension loft insulation, high spec windows and solid roof on conservatory	9.2	58.9	48.7	21.2	25.5	21.6	52.8	84.4
Full upgrades as above, with conservatory heating limited to 15 °C	12.4	57.6	47.1	21.4	25.5	22.2	54.5	86.2
Full upgrades as above, with conservatory heating limited to 15 °C and 1.2m ensuite towel rail	12.7	58.3	47.8	20.8	25.7	22.4	55.2	39.6
Full upgrades as above, with conservatory heating limited to 15 °C, 1.2m ensuite towel rail and rad foil in extension	12.8	58.6	48.3	21.1	26.1	21.6	53.4	40.6

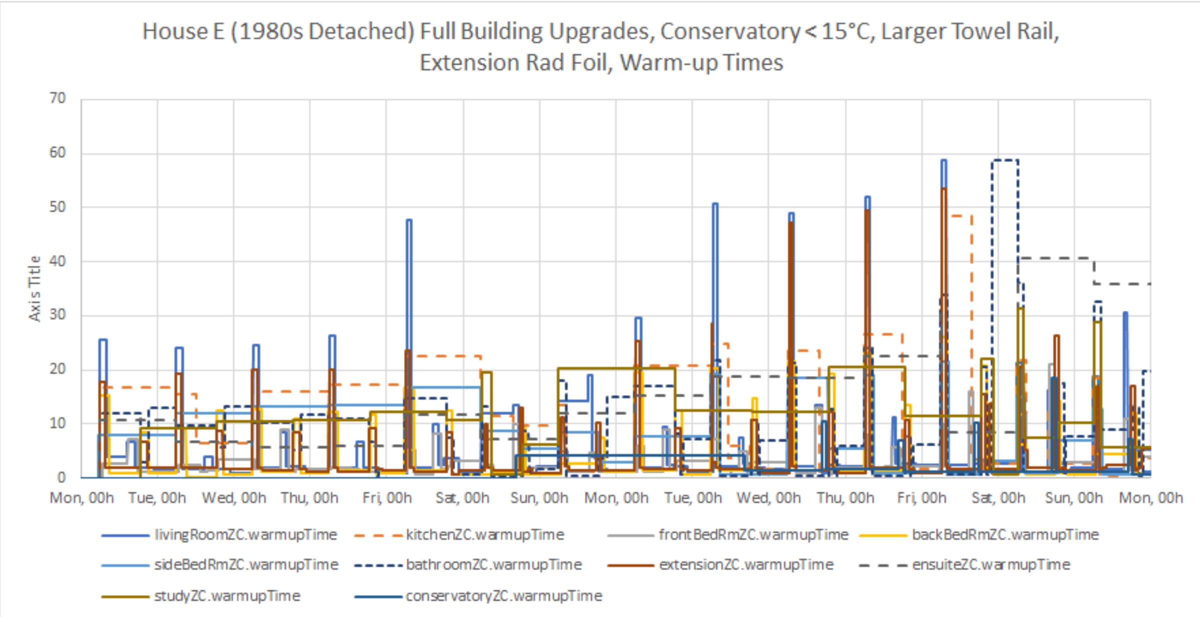

Figure A.5.5-13 - warm-up times with all building fabric upgrades and modifications, gas boiler

Annual consumption for the suggested upgraded building fabric case was estimated as for the base case, showing a saving of 8.5%, less than in mid-winter thanks to the effect of solar heating of the conservatory during spring and autumn.

Table A.5.5-8 – Proposed building fabric upgrades, annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	**Annual Energy Consumption, kWh**	**Energy Output for DHW, kWh**	**Energy Output for SH, kWh**
Full upgrades as above, with conservatory heating limited to 15 °C and 1.2m ensuite towel rail	14948	2407	10690

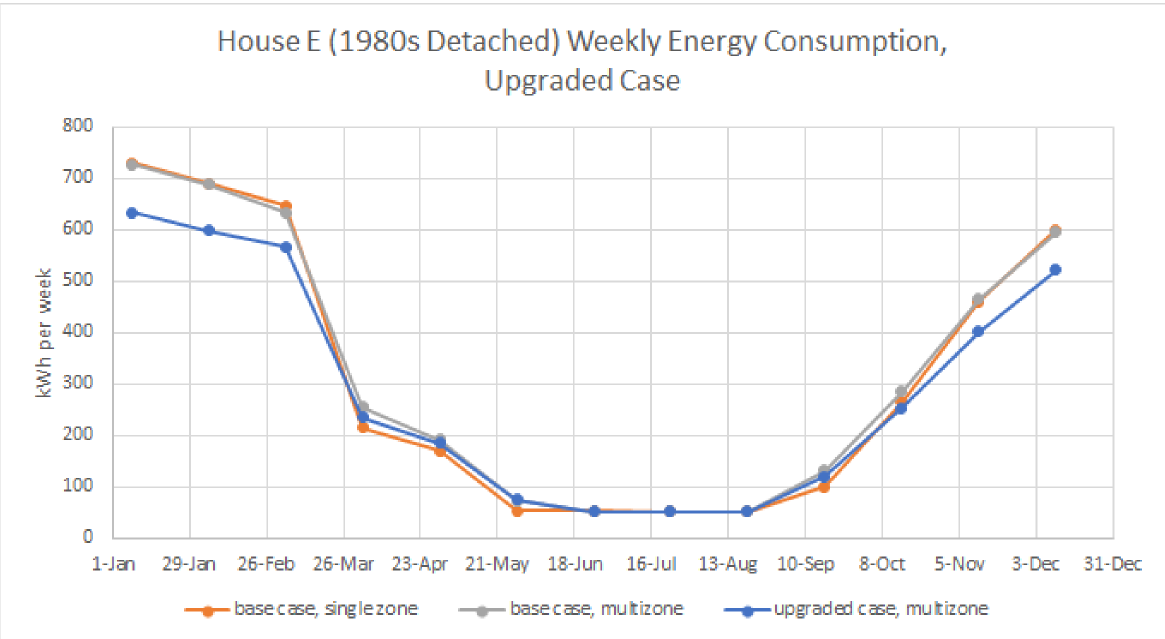

Figure A.5.5-14 - weekly energy consumption, upgraded building fabric

A.5.5.5. Air and ground source heat pumps

Using an air source heat pump as the heat source was considered technically feasible for this house. A ground source heat pump was also considered possible, thanks to the large rear garden, although access for machinery is limited. From preliminary tests, House A results and the base case simulations reported above, it was clear that using a lower heating medium temperature with no other changes would give unacceptably long warm-up times. Therefore the full upgrades proposed to building fabric and heating system were considered for the cases using the heat pumps, including ensuring the water pump provided higher flow rates to the radiators than the current boiler. Also, assuming the bulk of the heat pump equipment is mounted externally (perhaps the ASHP would fit under the utility room window, assuming sufficient air flow), the utility room should have sufficient space to reinstate a DHW cylinder. This should facilitate use of a heat pump without a supplementary water heater (other than an optional 3kW immersion heater).

A.5.5.5.1. ASHP and GSHP with building fabric upgrades

The cases using heat pumps were simulated with the following changes relative to the base case:

i. All building fabric upgrades installed as suggested in the combined case above (upgraded windows & doors, 250mm extension loft insulation, high spec windows and insulated solid roof on conservatory) together with the 15 °C limit on the conservatory maximum temperature setting, and a new 1.2 m high towel rail in the ensuite shower room.
ii. Combi boiler replaced with an 8 kW (nominal output) air or ground source heat pump with an input power limit of 3 kW, coupled with a 250 litre insulated DHW cylinder (fitted with a 3 kW immersion heater to supplement the heat pump if necessary – not used in these cases).
iii. Multizone control with lockshields even more fully opened (especially in the extension and ensuite), to increase the power output of the radiators (also assuming higher hot water pump flow rate of up to 18 l/min)
iv. Heat pump outlet temperature for SH set as a linear function of outside air temperature (rising to 55 °C at or below 5 °C outside) and increased to 5 °C above the DHW tank setpoint when higher than the SH requirement (e.g. to achieve 60 °C for 1 hour each day to guard against legionella).
v. 60 minute pre-heat times used for SH, 90 minutes for DHW tank.
vi. Temperature profile for the DHW tank adjusted to avoid clashes with SH warm-up times (by heating to 60°C at 4am), and allowed to heat both simultaneously (subject to power limits of the ASHP).

Table A.5.5-9 – heat pump results summary (two weeks, mid-winter)

Case	Energy Used, kWh	Peak Electricity Demand, SH+DHW, W	Fraction of Demand Time Below T Range, %						
			Living Rm	Kitchen	Front Bed	Back Bed	Side Bed	Extension	Study
8kW ASHP with upgrades	362	3075	0.4	0.4	0.8	0.3	0.0	6.1	1.4
8kW GSHP with upgrades	342	3069	0.4	0.4	0.9	0.1	0.0	6.3	1.3

The results indicate good comfort performance (better than the current situation, based on room temperatures during desired warm-times) can be achieved with a heat pump without excessive peak demand on the electricity grid, provided building fabric upgrades reduce heat loss from the dwelling and the radiator power dissipation is enhanced by increasing the flow of hot water to them. The warm-up times in mid-winter are, as expected, longer than the upgraded case with a gas boiler, being generally less than 60 minutes, except in the extension, ensuite and bathroom where they exceed two hours on the coldest days. Even in these rooms, during the very coldest weather, the temperatures are rarely colder than 1.5 °C below the target range by the start of the required warm-time.

The mean COP over two mid-winter weeks with upgrades is about 2.6 for the ASHP and 2.8 for the GSHP, giving an energy consumption of about 29 and 27% of that used by the single-zone base case, respectively. Note that both these COP values would be expected to be higher in warmer parts of the country (e.g. 10% higher for a 3 °C increase in mean temperature). The heating performance of the GSHP is very similar to the ASHP, thanks to using the same settings for the outlet temperature, input power limit and water flow rates. The higher COP for the GSHP does reduce the maximum warm-up times in some rooms by a few minutes.

See note in section **A.5.2.5.1** on ASHP water pump capacity.

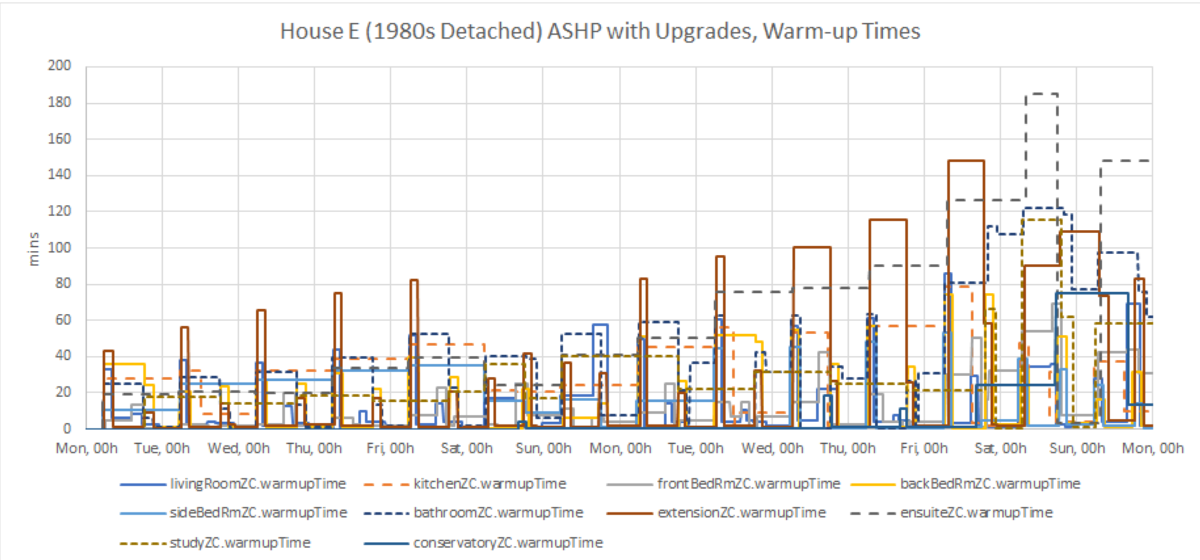

Figure A.5.5-15 - warm-up times with all building fabric upgrades and air source heat pump

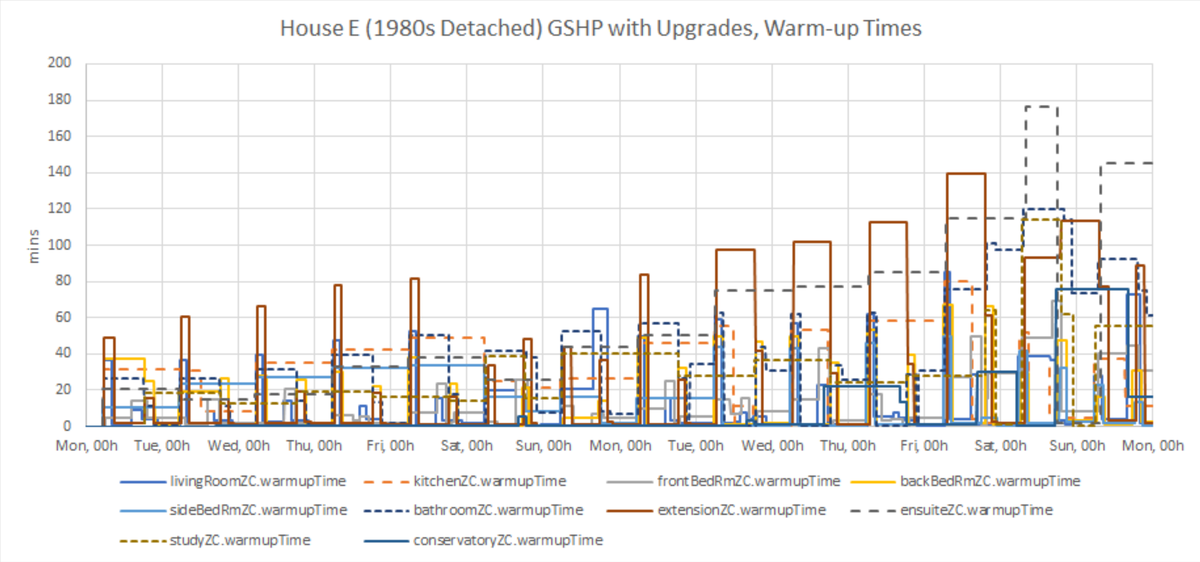

Figure A.5.5-16 - warm-up times with all building fabric upgrades and ground source heat pump

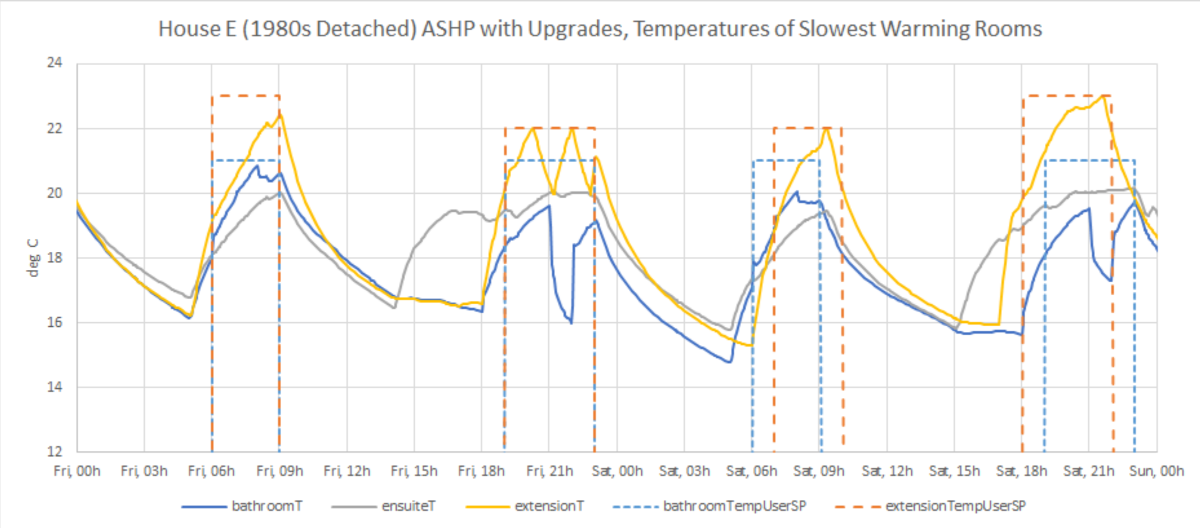

Figure A.5.5-17 – slowest warming room temperatures with all building fabric upgrades and air source heat pump

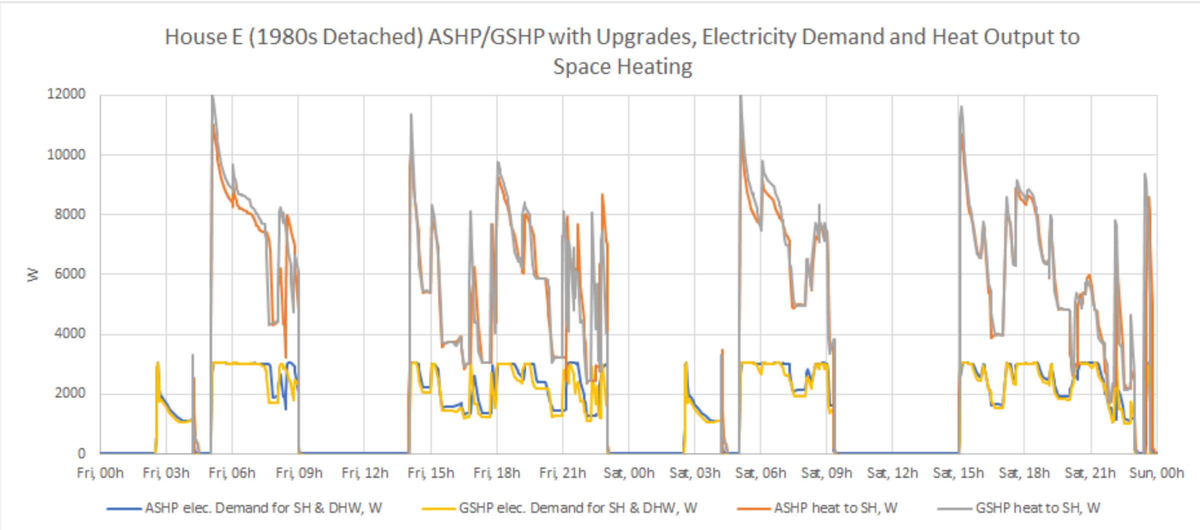

Figure A.5.5-18 – heat pump power inputs and outputs to space heating, all building fabric upgrades

Note on ground source heat pump: The difference in COP between ASHP and GSHP is relatively small, considering the large extra expense of providing the underground heat source. The average air temperature during heating is about 3.6 °C in the mid-winter Newcastle-upon-Tyne weather; the ground temperature at depths greater than about 3 m is assumed to be the close to the annual average air temperature of 9.3 °C, but at the trench depth modelled of 1-1.5 m the undisturbed temperature in January is expected to be around 7-8 °C, which would be expected to be reduced further by cooling of the ground around the tubing. Assuming an effective ground temperature of 7 °C, the datasheet COP values for the heat pumps in these conditions (with their outlet temperatures at 55 °C) would be about 2.7 (air) and 2.9 (ground), a 7% difference, which would reduce to 2.6 and 2.8 respectively when heat losses from the hot water storage and distribution are included. The difference would be larger for a lower outlet temperature (e.g. 12% at 35 °C). Furthermore, the suitability of this property for a GSHP is in doubt due to the limited access to the rear garden (the extensions reach close to the property boundaries on both sides). Also, the ground area required for a heat pump of sufficient power may not be available without unacceptable disruption to the garden. The model includes two 25 m long slinky trenches, each 1 m wide and 1 m deep (1.5 m deep was also modelled), which should be several metres apart to ensure no long-term cooling of the ground occurs. Wider but shorter trenches may also be suitable but the size of the garden may make vertical bore holes more suitable, depending on local geology and ground water characteristics. These have not been modelled here, but should be the subject of further study, as should alternative heat pump control algorithms. Due to the uncertainty regarding the possible use of a GSHP, the following analysis of annual performance is restricted to the ASHP, but should be applicable to the GSHP with a small reduction (e.g. 5-7%) in energy consumption estimates.

A.5.5.5.2. Multizone + ASHP + upgrades: annual energy consumption

The annual energy consumption of the upgraded heat pump case above has been estimated as described in the introduction to the results summaries for comparison with the combi-boiler results above. The overall energy consumption with a simple linear outlet temperature adjustment is about 30% of the base-line case (single zone control, no upgrades). The savings from changes to building fabric, control and heat source can be characterized as independent energy reduction factors, multiplying to give the overall reduced consumption. In this case, multizone control and building fabric changes together reduce annual energy consumption by a factor of 0.88, with the change from a condensing boiler (effective efficiency of 0.87) to a heat pump with an average effective COP of about 2.6, gives a reduction factor for heat source change of 0.33. The effective COP is higher than found in smaller houses due to the larger proportion of heat used for space heating (at a lower outlet temperature than for heating the hot water cylinder).

Table A.5.5-10 – Air source heat pump with upgraded building fabric: annual consumption (Newcastle-upon-Tyne, typical mean year)

Case	Annual Energy Consumption, kWh	Energy Output for DHW, kWh	Energy Output for SH, kWh
8kW ASHP 3kW input limit, multizone control + fabric upgrades	4995	2359	10607

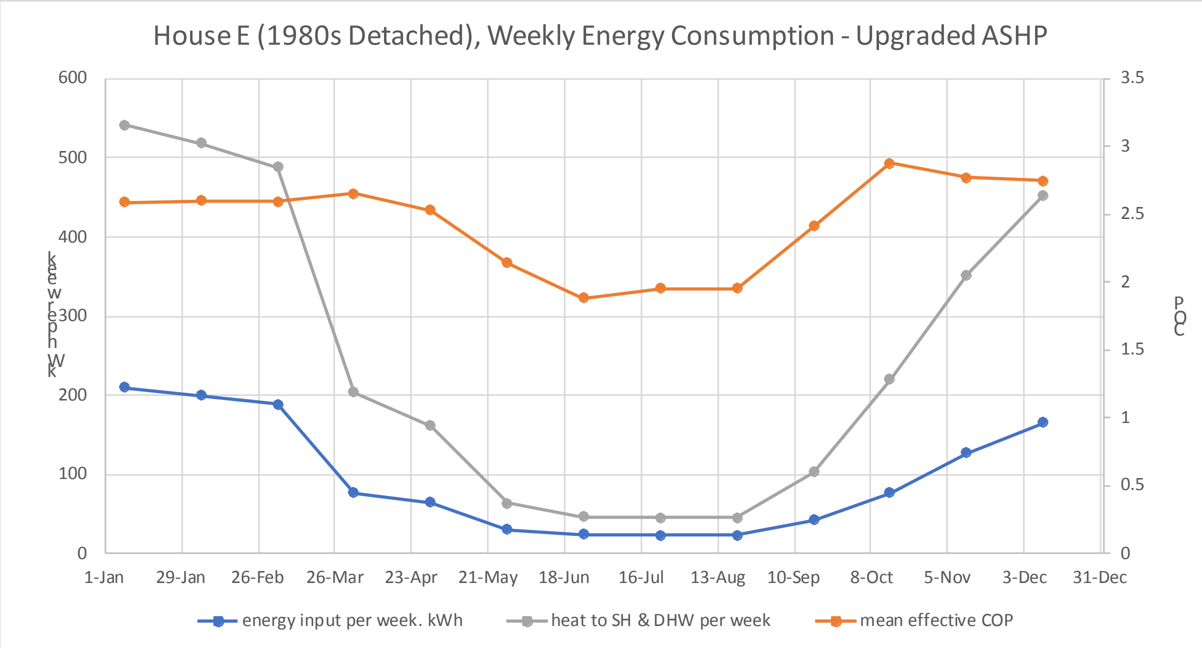

Figure A.5.5-19 – weekly energy consumption, air source heat pump with building fabric upgrades

As discussed in House B results summary (section **A.5.2.5.3**), the drop in mean weekly effective COP in summer is due largely to the increased proportion of heat lost around the DHW tank. Also discussed in House B results, the simple control logic used in this case is effective but indicates scope for improvement.

A.5.5.6. Upgrade pathway stages

The following stages in the pathway to full upgraded building fabric and heat source have been identified:

Stage 1: multizone control + limit conservatory temperature setpoint to 15 °C + increase extension loft insulation to 250 mm

Stage 2: upgrade conservatory with opaque roof insulation and high-spec windows

Stage 3: replace downstairs windows and doors, install larger towel rail in ensuite shower room

Stage 4: replace gas boiler with either an air-source (a) or ground source (b) heat pump together with 250 litre hot water cylinder.

The summary of the results for each stage in the pathway are shown in Table A.5.5-11 and Table A.5.5-12.

Table A.5.5-11 – pathway stages, summary (two weeks, mid-winter)

Case	Energy Used, kWh	Fraction of Demand Time Below T Range, %						
		Living Rm	Kitchen	Front Bed	Back Bed	Side Bed	Extension	Study
Base (single zone control)	1268	7.9	10.2	0.9	0.9	2.0	44.8	0.2
Stage 1 (MZ + extension loft insulation + 15 °C max conservatory)	1248	1.2	0.2	0.1	0.0	0.0	1.7	0.0
Stage 2 (+ upgrade conservatory)	1175	1.5	0.5	0.2	0.0	0.0	1.5	0.0
Stage 3 (+ new d/s windows & doors, larger towel rail)	1105	0.9	0.3	0.1	0.0	0.0	1.6	0.0
Stage 4a (+ ASHP)	362	0.4	0.4	0.8	0.3	0.0	6.1	1.4
Stage 4b (+ GSHP)	342	0.4	0.4	0.9	0.1	0.0	6.3	1.3

Table A.5.5-12 – selected pathway stages, estimated annual consumption for heating and hot water (Newcastle-upon-Tyne, typical mean year)

Case	Annual Energy Consumption, kWh	Energy Saving	Energy Output for DHW, kWh	Energy Output for SH, kWh
Base case	16320		2393	11927
Stage 1[1]	16100	1.3%	2400	11720
Stage 2[1]	15260	6.5%	2400	10980
Stage 3	14948	8.4%	2407	10690
Stage 4a (ASHP)	4995	70%	2359	10607
Stage 4b (GSHP) [1]	4630	72%	2359	10607

Note 1: estimated from winter results and annual results of other cases

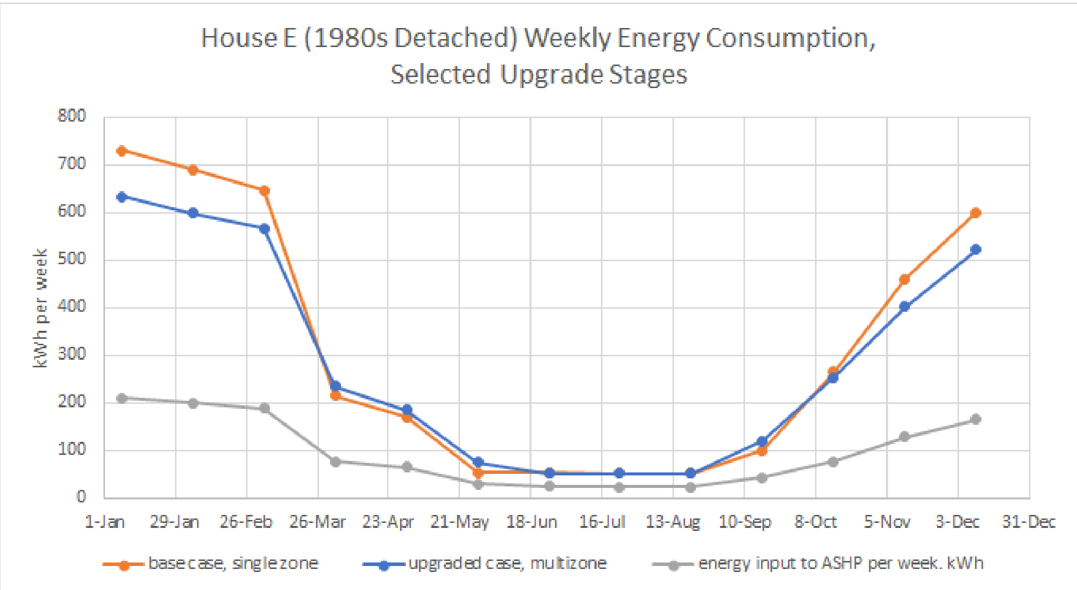

Figure A.5.5-20 – weekly energy consumption for heating and hot water, selected stages to full upgrade with air source heat pump and building fabric upgrades

Appendix 6. Thermal storage modelling methodology and results

To provide an approximate, first-pass examination of the behaviour of a storage system to facilitate demand shifting, a simple spreadsheet model was built to calculate the amount of thermal energy that would need to be stored, at any given time, throughout the year. Using the output data from the IEHeat model, with maximum time intervals of ten minutes, the storage model was used to find

The model works by calculating the heat available from the system (from the combination of storage and permitted heat pump output), moment by moment, and compares this to the heat demand in that moment derived from the IEHeat output data (a consequence of thermostat settings, weather, hot water consumption, etc). If there is a surplus of energy from the output of the heat pump against demand, this energy is stored. When demand exceeds supply, energy is taken from storage. Over the course of a given day (selected by the user), the model then calculates whether there is a shortfall in the heat available from the system at any point. Such a shortfall would imply either higher power is required from the heat pump (perhaps during the grid peak demand period), or the comfort of the occupants being sacrificed with temporarily inadequate room temperatures. The model automatically performs a sensitivity analysis over a range of heat pump power settings and storage capacities (determined by the user), showing which combinations avoid such a heating shortfall. the size of storage required to meet certain demand-shifting scenarios.

The simulation begins five hours before the start of the selected day to reduce the influence of initial conditions. Five hours before the start of a day is 19:00 on the previous day – the end of the evening peak grid demand period and hence the time when energy stored by an optimally-sized system will be closest to zero.

The storage device is modelled as a perfect repository of units of energy, with no allowances made for the effect of varying temperature of the storage material on its performance, the limit of the rate at which energy can be deposited and withdrawn, or heat losses. In this regard it is approximate, but also technology-agnostic. The requirement to put heat into storage using a higher input temperature than that at which the heat can later be extracted has not yet been incorporated into this work, and will require further detailed modelling to quantify the effect this may have on average COP.

Energy storage for DHW is modelled separately from storage for space heating, mimicking a system with a dedicated DHW cylinder. Timing of DHW heating follows the output data of IEHeat, which scheduled DHW heating to ensure it would not deprive occupants of space heating. This schedule can also be configured independently in the spreadsheet model. Alternatively, the model can represent a shared storage device for both space heating and DHW, mimicking a thermal store or equivalent.

This model can be run with results from any house and set of weather data to build a more complete picture of how storage could be implemented at scale. It can then guide targeted IEHeat simulations towards thermal storage solutions that are most likely to be of value. The model would be equally suitable for representing storage from other types of heat source, both for demand shifting and improving heating performance in other ways (e.g. by increasing the power output available for space heating or domestic hot water).

A.6.1. Model inputs and parameters

The spreadsheet model can use input from the IEHeat heat demand results from any house and weather data. Parameters in the model can be set according to scenarios of how the grid might function in a high heat pump uptake scenario. All results in this report are based on data from House C (a 1930s semi-detached house) in Newcastle weather, with the exception of results in section **A.6.2.2**, which compares results from the other houses in the Upgrade Analysis study. The IEHeat heat demand results are based on the full set of upgrades recommended in the pathways, with an air source heat pump (without the gas boiler). In the spreadsheet, the evening peak period is set as 16:00-19:00, and during this time the heat pump is set to operate at 0.6 kW (electrical input power), the minimum setting of the device modelled in this pathway. The model assumes a constant heat pump coefficient of performance (COP), which is set as 2.5 for this report, based on typical average effective values from IEHeat output data during the coldest month.

Green cell = user input

Global Parameters	
HP Power During Peak Times (input), kW	0.6
HP COP	2.5
DHW Storage Capacity, kWh	9
Initial SH Energy Storage, kWh	0
Initial DHW Energy Storage, kWh	6

Grid Peak Timing		
	Start (h)	**End (h)**
Peak period 1	16	19
Peak period 2	0	0
Peak period 3	0	0
Peak period 4	0	0

To disable a peak period, set its start and end times to the same value. To represent minutes, use decimal fractions of hours, e.g. for 03:30 type 3.5. Peak periods cannot cross midnight; one peak period must be used for before midnight and another for after.

DHW Timer		
	Start (h)	**End (h)**
Heating period 1	3	4.5
Heating period 2	13	14.5

Single Run Parameters	
HP Continuous Power (input, off-peak), kW	1.5
SH Storage Capacity, KWh	20

Storage Sensitivity Analysis		
	Min	Max
HP Continuous Power (input, off-peak) kW	0.5	3
SH Storage Capacity, kWh	0	35

Figure A.6.1-1 - Input parameters, adjustable by user

A.6.2. Model outputs

The most informative outputs generated by the spreadsheet model are: a plot of energy stored over the course of a day, indicating the timing and severity of depletions (or oversizing) in the storage system (Figure A.6.2-1), and the range of heat pump power settings and storage capacities which prevent any energy shortfall (Figure A.6.2-2).

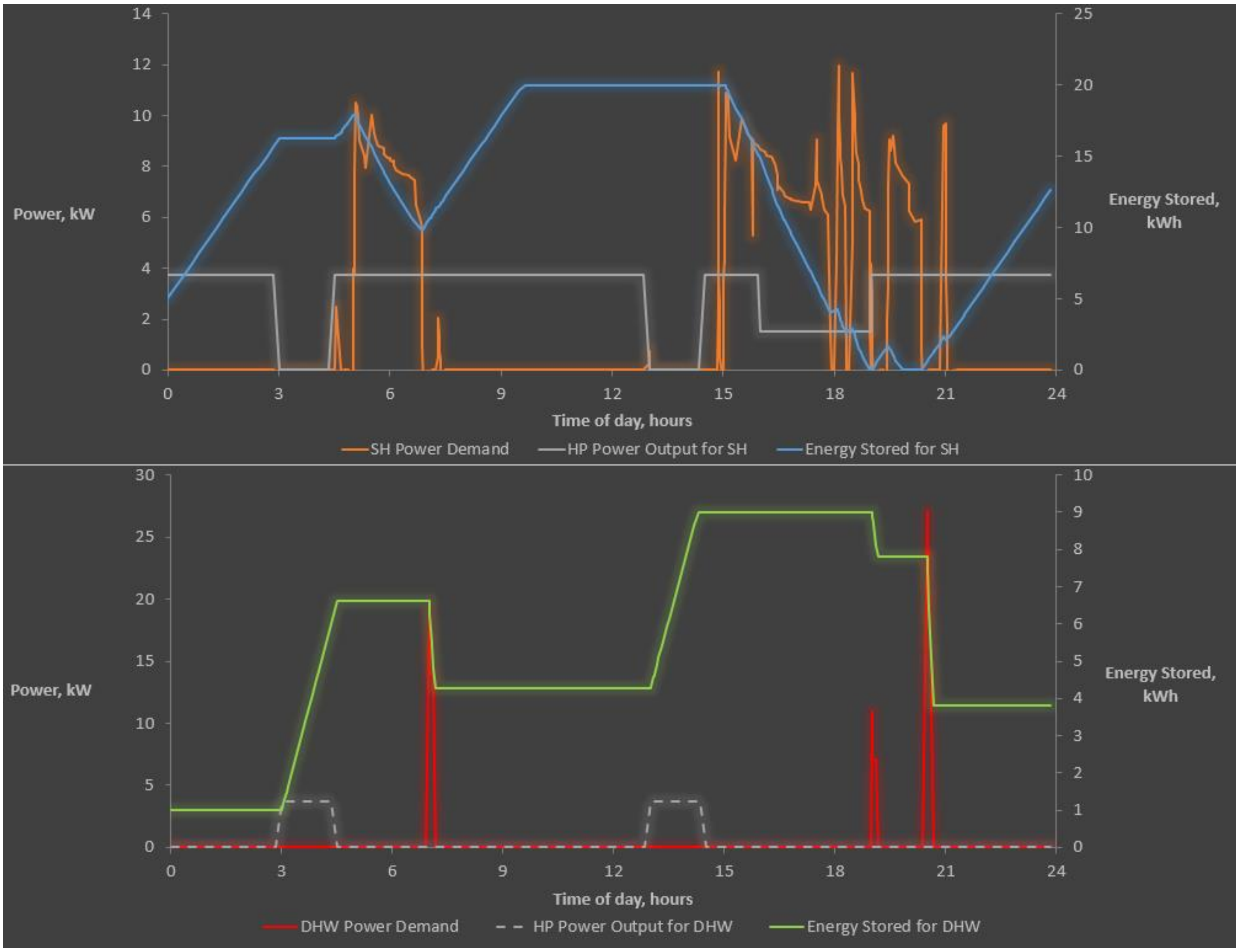

Figure A.6.2-1 - Plot of energy storage balance for space heating (upper half) and DHW (lower half). Plots produced using data from House C with full upgrades applied and stand-alone air source heat pump.

Since the energy stored for space heating (blue) falls to zero for a substantial period in the evening, it can be deduced that the selected combination of storage capacity and heat pump power is inadequate to meet demand on this day. Heat pump output to space heating (solid white) shows a step down in power during evening peak and during DHW heating periods, with steady operation otherwise. Space heating demand (orange) shows the pattern of power to be supplied to satisfy the occupants. Equivalent plots for DHW are shown in the lower half, from which it is apparent that storage capacity, as well as heat pump power and availability, are ample for the provision of DHW. Since DHW heating is carried out prior to periods of space heating demand, there is no conflict between the two. Note that the model does not reduce heat pump operation when storage is fully charged and demand is low, which is the behaviour that would occur in reality.

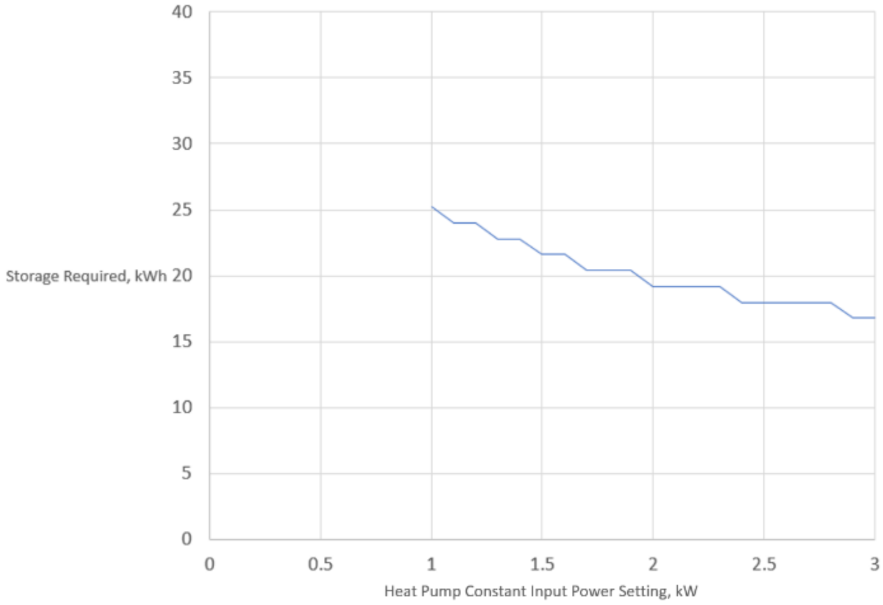

Figure A.6.2-2 - Plot of minimum storage requirement for given heat pump electrical power consumption to avoid any energy shortfall, for a user-determined range of storage capacity and power input values; where no line is shown, no solution could be found within the range. Plot produced using data from House C with full upgrades applied and stand-alone air source heat pump.

This plot is indicative of the grid load reduction possible as the capacity of storage is increased. It also shows the point at which required capacity exceeds the user-defined maximum – in this case for heat pump electrical power settings less than 1 kW.

Further to these outputs, the rate of energy transfer to and from the storage device can be interrogated (Figure A.6.2-3) to ensure that this remains within the capability of the candidate storage technologies.

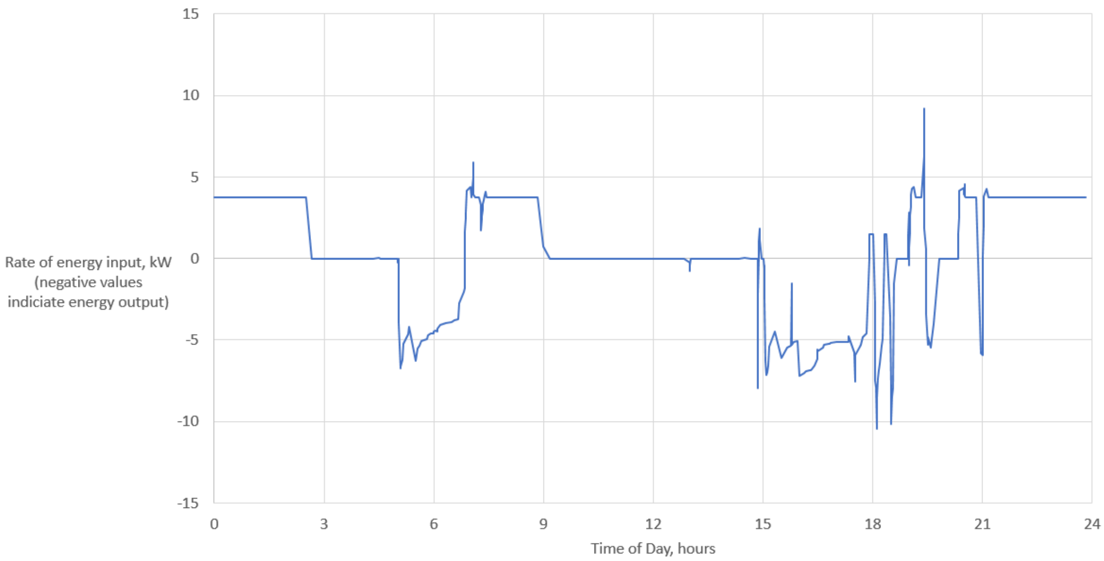

Figure A.6.2-3 – Plot showing rate of charge and discharge (heat added and removed) of storage device over the course of a day. Plot produced using data from House C with full upgrades applied and stand-alone air source heat pump

A.6.2.1. Effect of weather conditions

The storage model was run throughout the whole year to explore the impact of the seasons on the requirements for the storage system. Through inspection of these results for key archetypal days, some informative patterns emerge. Figure A.6.2-4 below shows plots from some such days, for comparison.

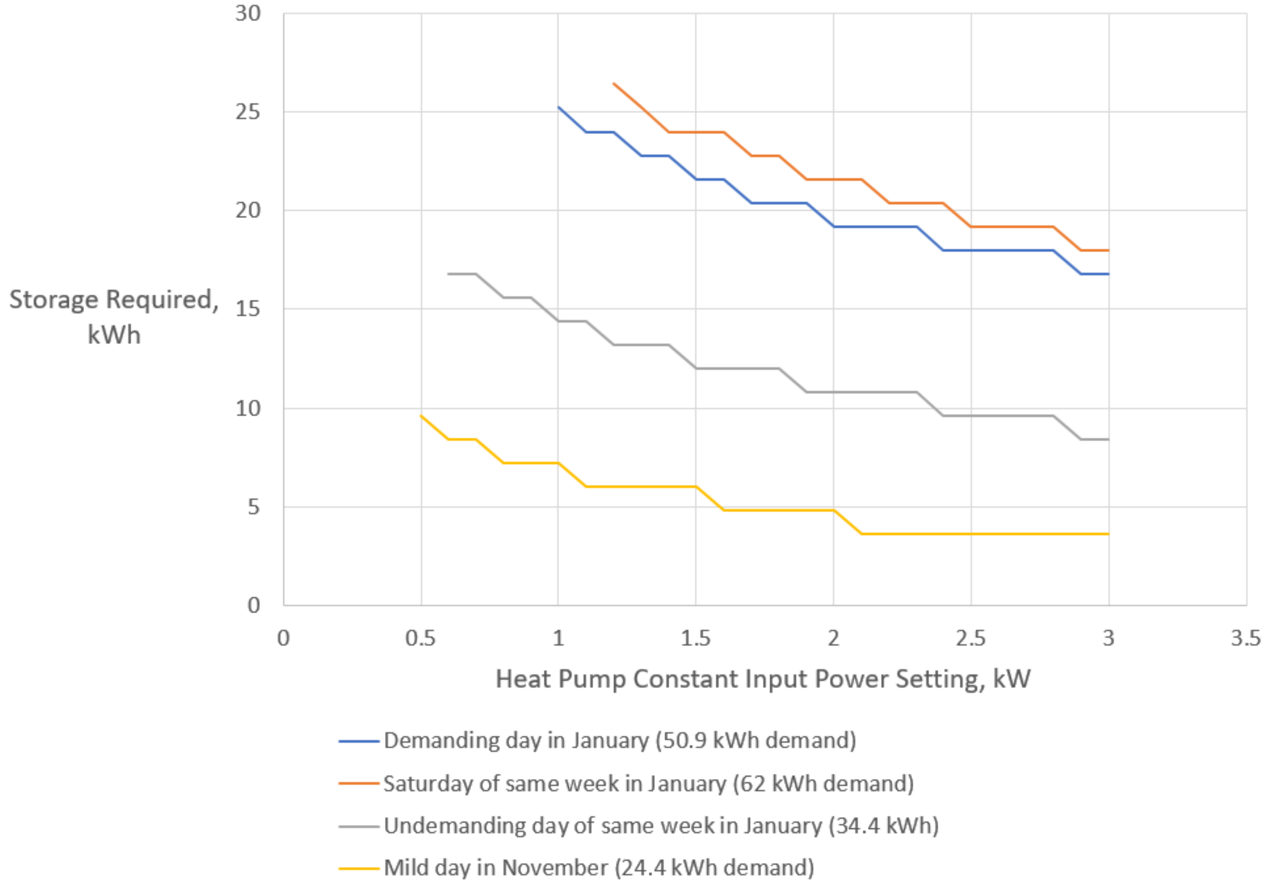

Figure A.6.2-4 – Plots showing the capacity of storage required to meet space heating demand in varying weather conditions, and with various heat pump power settings. Plots produced using data from House C with full upgrades applied and stand-alone air source heat pump.

A possible strategy would be to size storage for the most demanding winter day, however this would result in significant unused capacity for much of the heating period (see for example the difference between storage capacity requirements for the coldest day [orange line] and much of the rest of that same week [grey line]).

A.6.2.2. Results from other houses

To explore the effects of differing household situations upon storage requirements, the storage model was run with data from the other houses in this study. The plots below highlight sensitivities to the variations in heating usage patterns between houses.

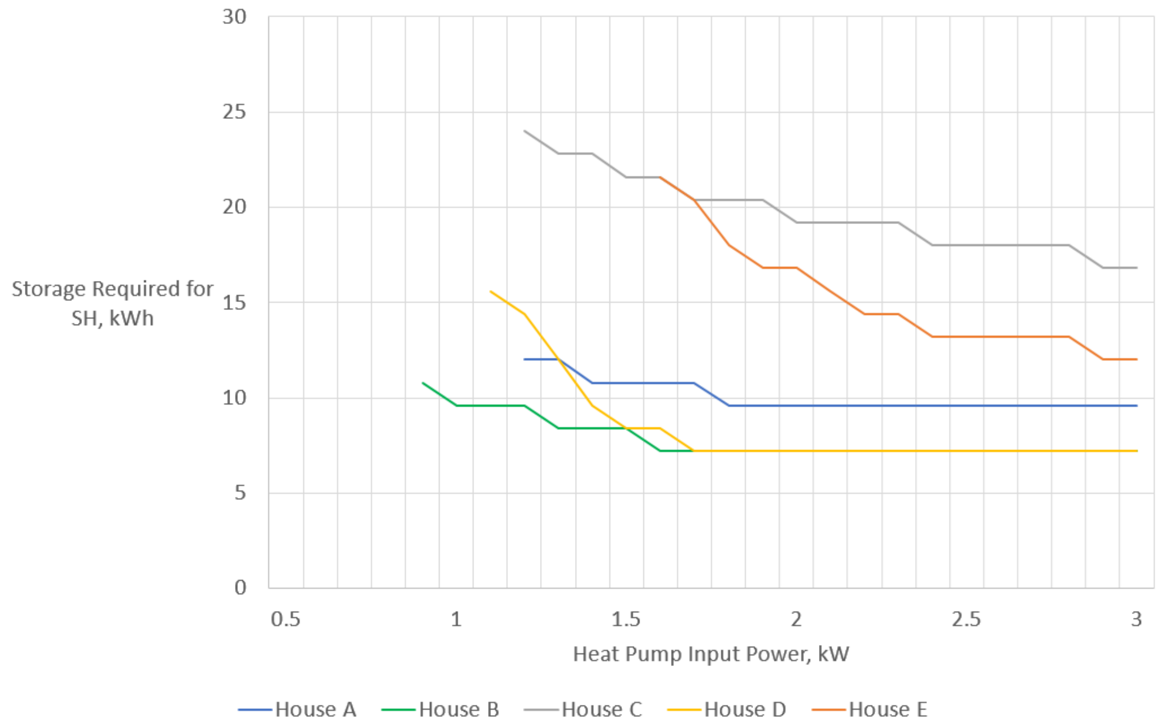

Figure A.6.2-5 – Comparison of storage requirements across all houses of the upgrade analysis (data taken from full upgrade scenario with stand-alone air source heat pumps in all cases).

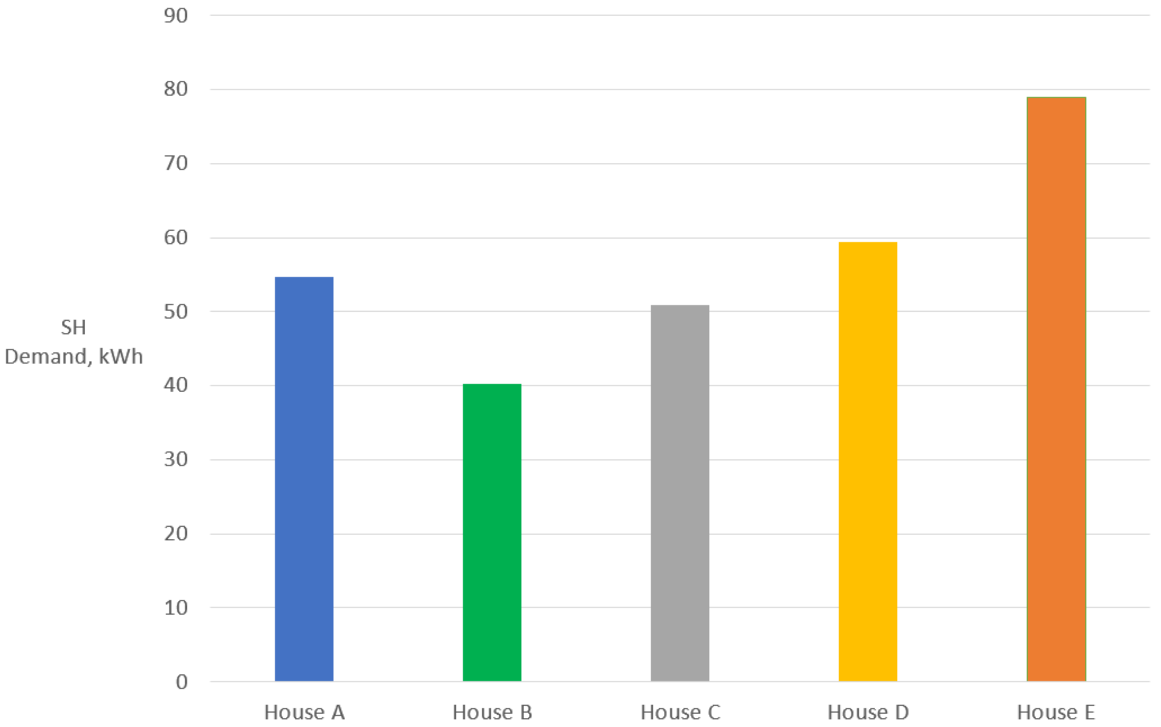

Figure A.6.2-6 – Heat demand during the cold January day used to study each house (with full upgrades)

Examining Figure A.6.2-5 & Figure A.6.2-6 together is surprising: total heat demand over the course of the day is not, as might be expected, a strong predictor of the variance in required storage capacity between houses. Figure A.6.2-7 - Figure A.6.2-9 reveal that distribution of heat demand over the day correlates with the greatest differences between houses. The houses with the largest storage requirements – C and E – have a long gap of unheated time through the day, while the others keep the house warm through the day. This gap will allow room temperatures to drop, resulting in an increase in energy required to reach desired temperatures during the evening, including the peak grid demand hours when heat pump power is reduced. This finding may be valuable to consider for the design of control strategies for systems utilising storage, as it could allow for reductions in required storage capacity through preheating of the dwelling.

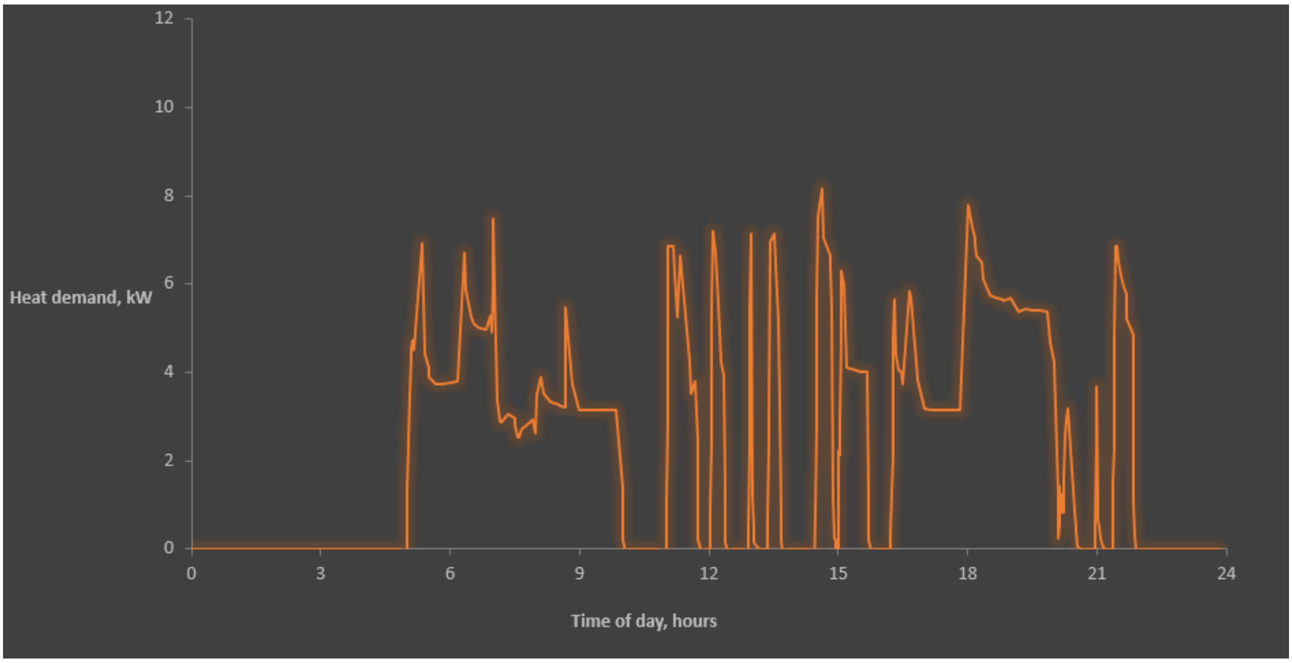

Figure A.6.2-7 – Heat demand profile for House A showing steady heating of house all day (full upgrades applied)

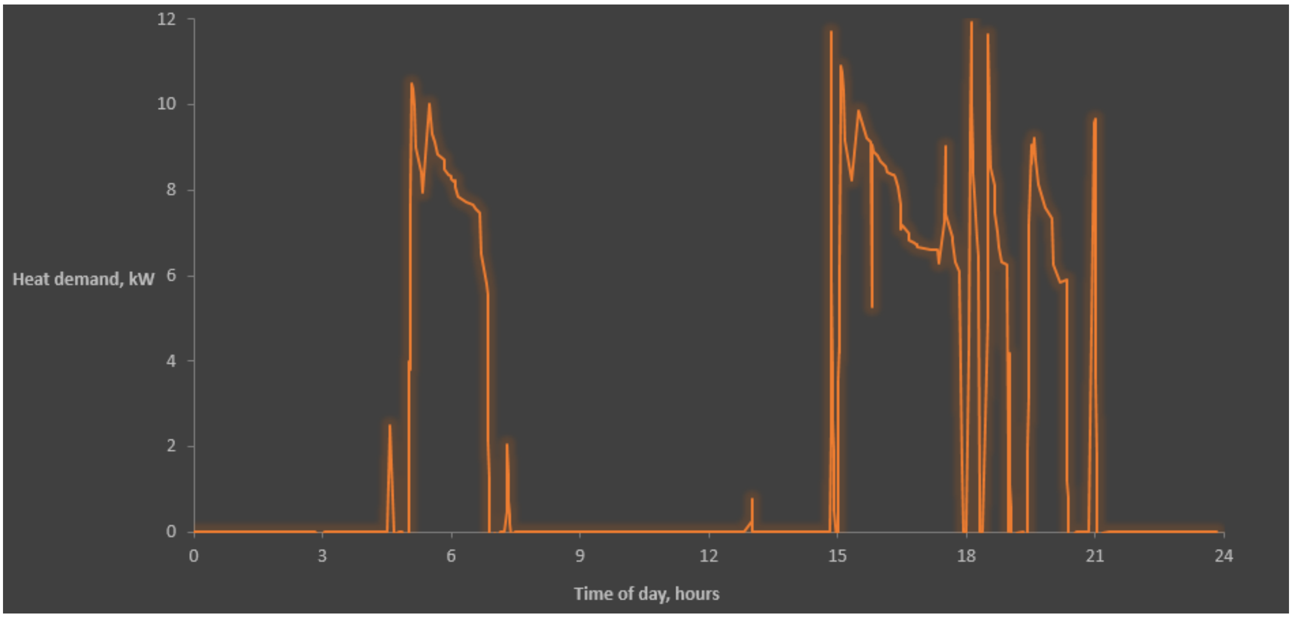

Figure A.6.2-8 – House C is heated in a large morning and late afternoon peak (full upgrades applied)

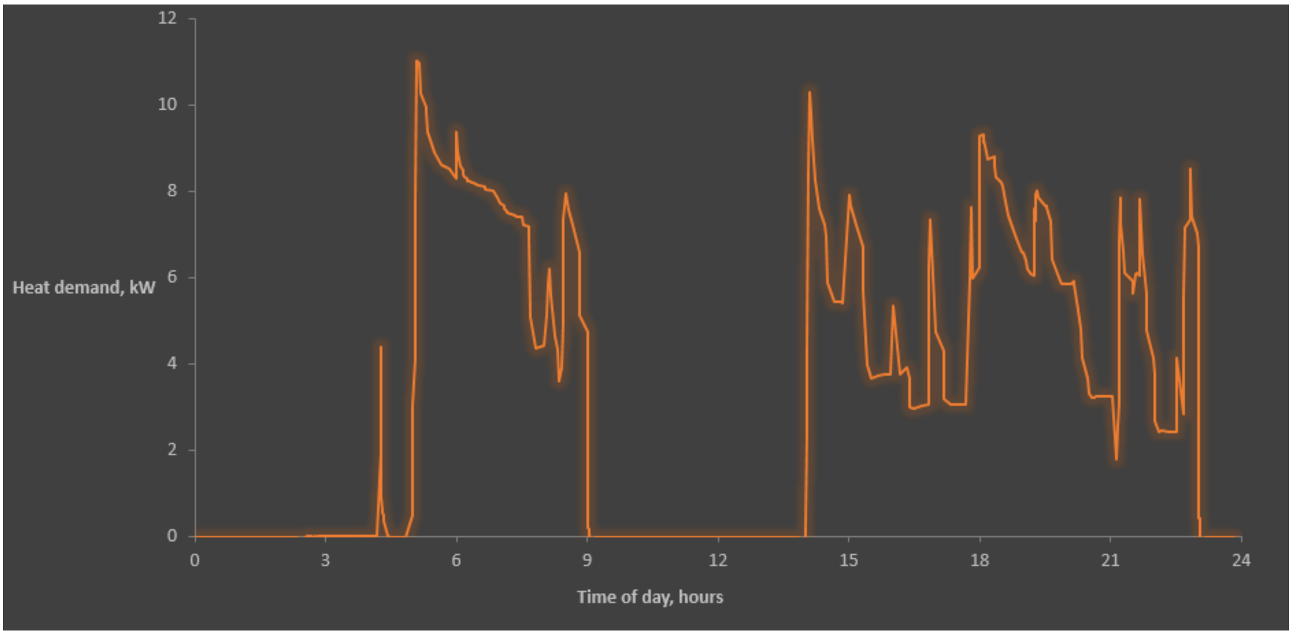

Figure A.6.2-9 – House E (full upgrades applied) is also unheated in the early part of the day, but the evening heating is more spread out than in the case of House C

A.6.2.3. Timing of peak grid demand periods

The peak price schedules below were used to test the impact of peak price signals of varying quantities, durations and timings of occurrence on storage requirements. These could be substituted with real data of typical daily electricity price profiles for future studies. All schedules were tested with data from House C with full upgrades and the stand-alone air source heat pump.

Table A.6.2-1 - Demand schedule summary

Case Number	**Peak 1 Start**	**Peak 1 End**	**Peak 2 Start**	**Peak 2 End**	**Peak 3 Start**	**Peak 3 End**	**Peak 4 Start**	**Peak 4 End**	**Heat Pump Response to Peak**
1: Evening Peak (Low)	16:00	19:00							Minimum power
2: Evening Peak (Off)	16:00	19:00							Switch off
3: Short Price Peaks (Low)	06:00	08:00	10:00	12:00	16:00	18:00	20:00	22:00	Minimum power
4: Short Price Peaks (Off)	06:00	08:00	10:00	12:00	16:00	18:00	20:00	22:00	Switch off
5: Short Price Peaks (High Coincidence)	00:00	02:00	08:00	10:00	11:00	13:00	21:30	23:30	Switch off
6: Short Price Peaks (Low Coincidence)	05:00	07:00	15:00	17:00	18:00	20:00	01:00	03:00	Switch off

7: Long Peaks (Low)	06:00	12:00	16:00	22:00					Minimum power
8: Long Peaks (Off)	06:00	12:00	16:00	22:00					Switch off

The following charts illustrate these profiles;

Case 1. Evening Peak (Low): this is the base case used throughout this report, where the heat pump power is reduced to the minimum setting for the evening grid peak period.

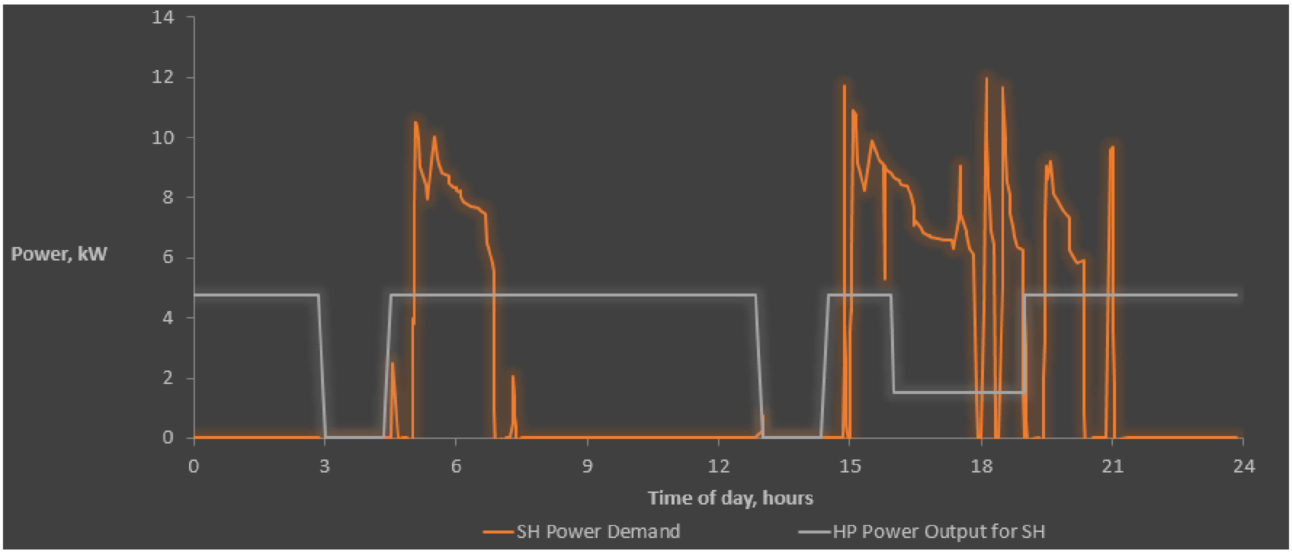

Figure A.6.2-10

Case 2. Evening Peak (Off): as case 1 but with the heat pump switched completely off for this period.

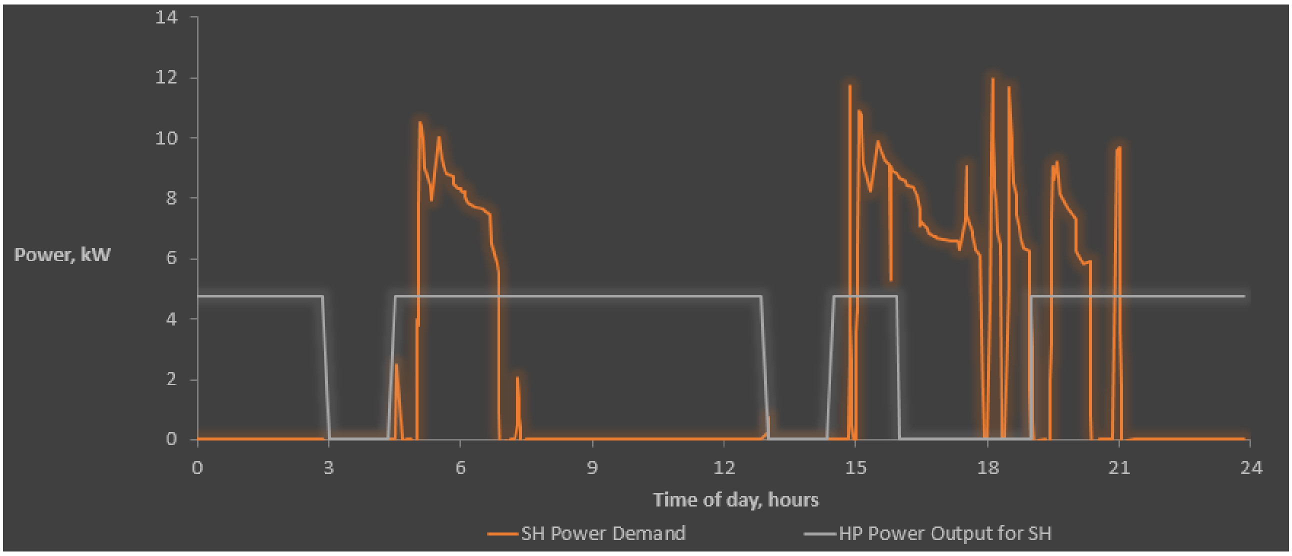

Figure A.6.2-11

Cases 3&4. Short Price Peaks: a profile intended to represent a response to variable time-of-use electricity prices. The periods of high price are short – two hours – and occur over breakfast and the time people return home, with an additional late morning and late evening peak (perhaps representing fluctuations in renewable output).

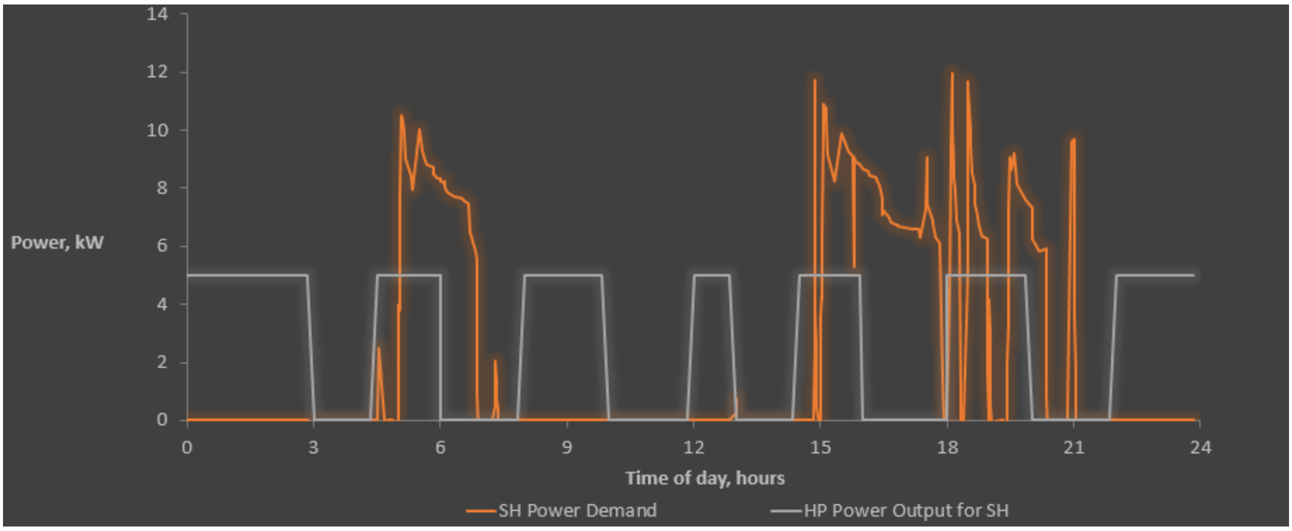

Figure A.6.2-12

Case 5. Short Price Peaks (High Coincidence): As case 4 but peak periods have high coincidence with heating demand periods (worst case).

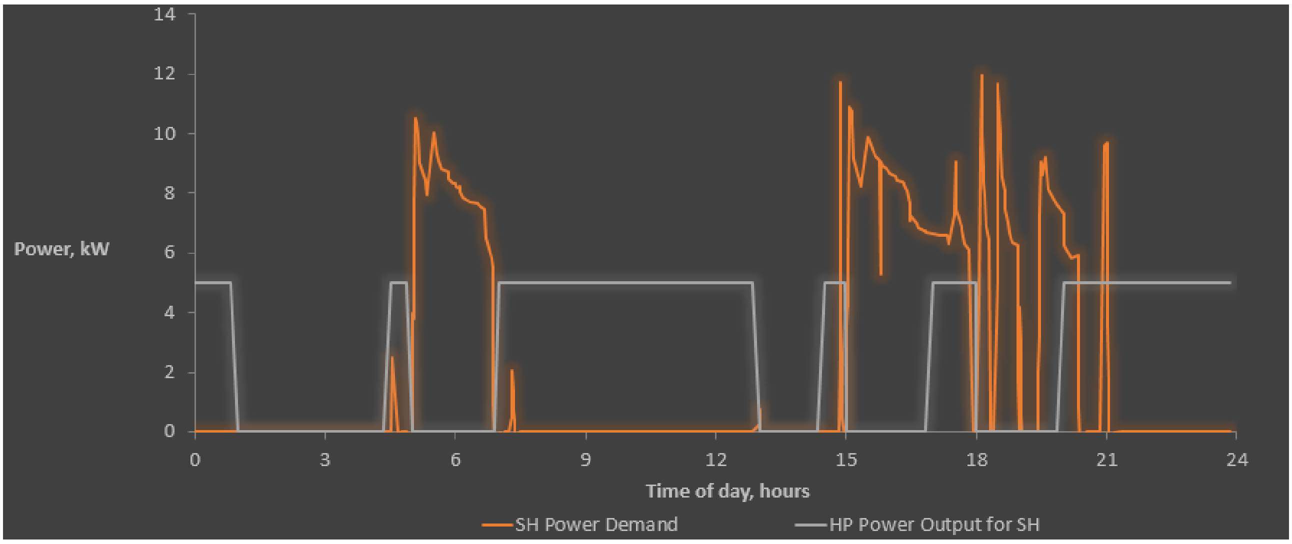

Figure A.6.2-13

Case 6. Short Price Peaks (Low Coincidence): As case 4 but peak periods do not coincide with heating demand periods (best case).

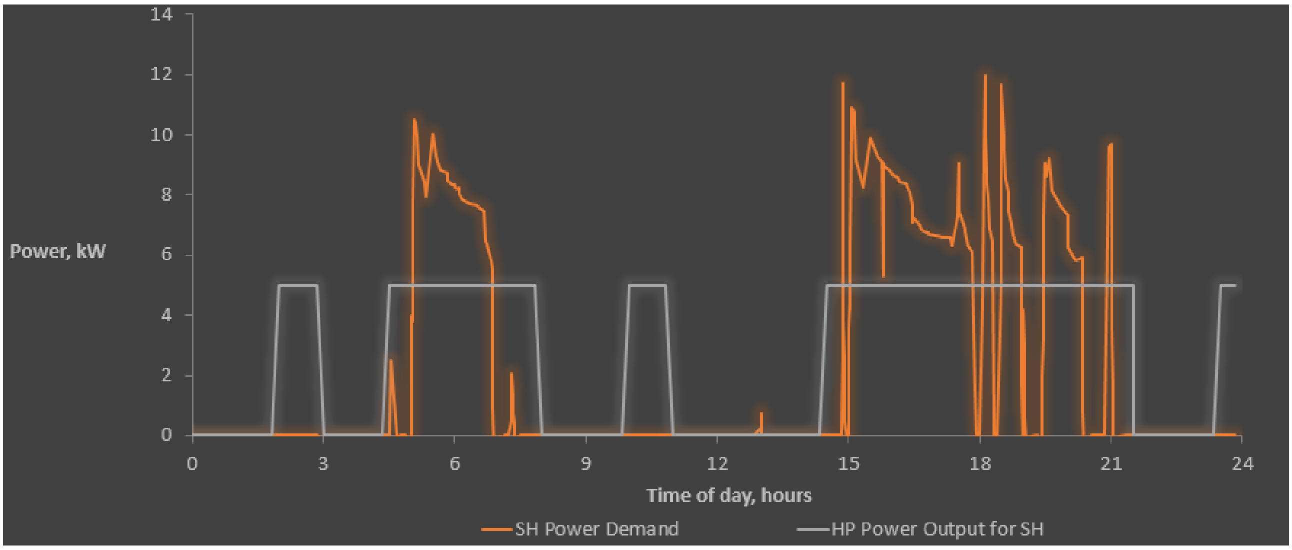

Figure A.6.2-14

Cases 7&8. Long Peaks: A tariff closer to Economy 10 than real-time pricing, with long peak periods (two blocks of six hours)

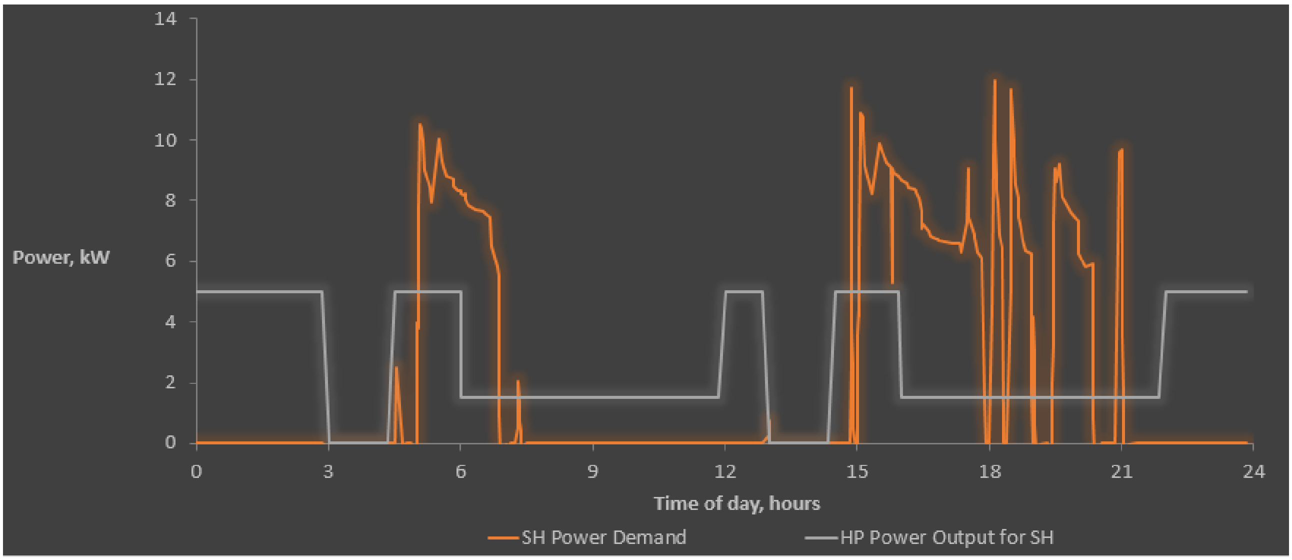

Figure A.6.2-15

The implications of these schedules for storage requirements and heat pump output can be seen in Figure A.6.2-16 below.

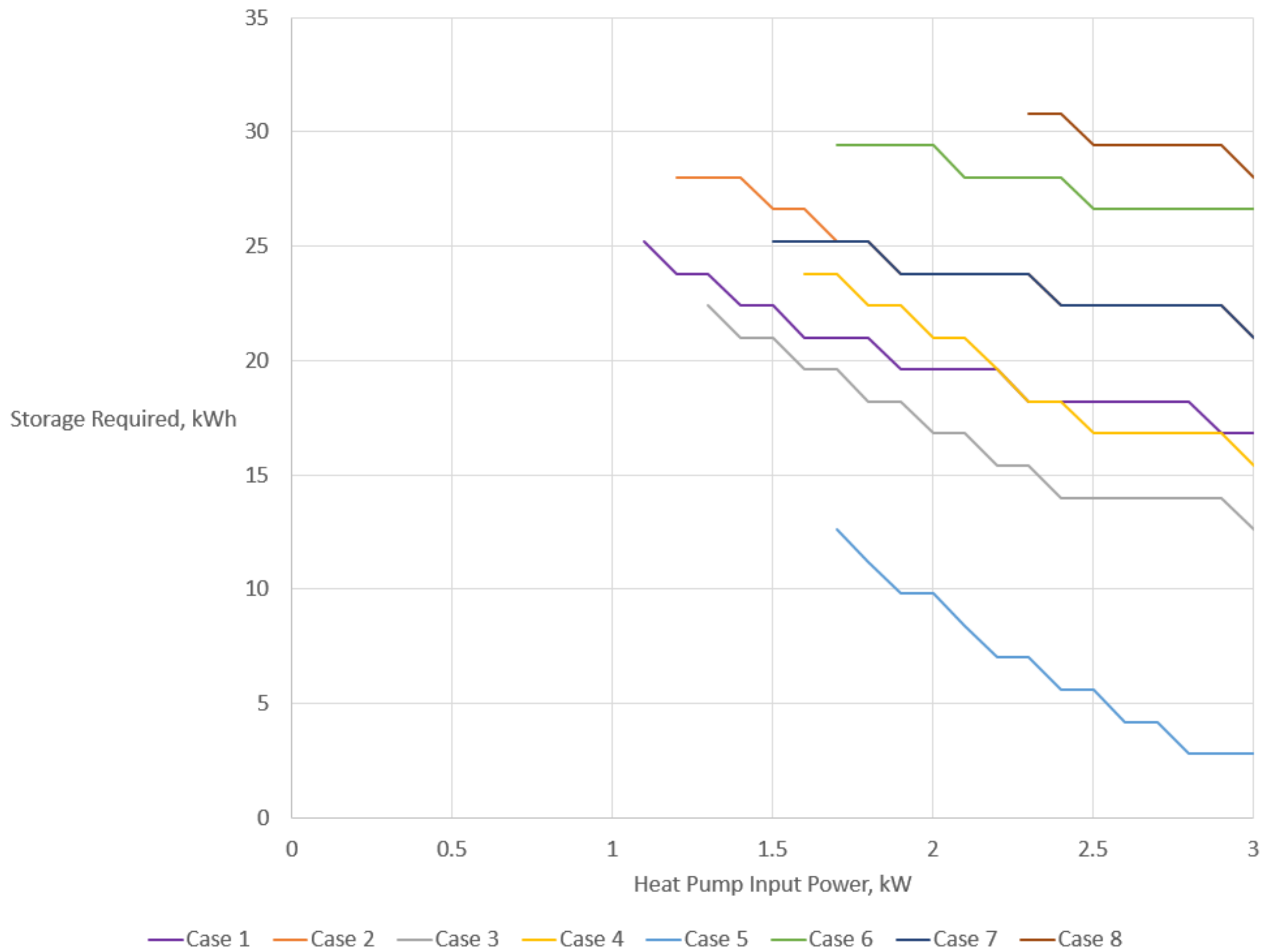

Figure A.6.2-16 – Storage capacity and heat pump electrical power requirements with various peak power down schedules (for House C with full upgrades and stand-alone air source heat pump).

Unsurprisingly, longer and more frequent power-down periods increase the storage capacity requirements of the system and require the heat pump to be run at higher power levels the rest of the time.

Through this method, the model can be used for investigation of cost or carbon optimisation strategies employing heat pump demand shifting.

A.6.3. Further work

The work carried out so far has demonstrated the method by which thermal energy storage can be modelled to allow storage sizing for the purposes of demand shifting. It has indicated that for a selection of case study houses, representative of a sizeable portion of the UK's existing building stock (after thermal efficiency upgrades), demand shifting can be achieved with viable storage device capacities, albeit larger capacities than householders are currently used to accommodating.

Incorporation into IEHeat would be the most effective next step in developing the storage model. This would overcome the limits in complexity inherent to spreadsheet modelling. The major approximations could then be more easily eliminated, such as the heat pump running when storage is full and demand is low, and the exclusion of various thermodynamic characteristics from the simulation (e.g. heat loss, heat transfer rate limitations and varying performance with temperature). It would also allow for faster modelling of multiple scenarios with fewer steps in the methodology, and greater flexibility to change the characteristics of the storage system. Modelling could be expanded to investigate the effect of geographic location on the results, to test the feasibility of storage for the range of climatic conditions which occur across the UK.

Further value could then be generated from the model through simulation of a control strategy which optimises heat pump operation for varying electricity prices throughout the day, surplus on-site generation (such as rooftop PV) and the varying carbon intensity of grid electricity. It may also be possible to enhance the COP of the heat pump by taking advantage of fluctuations of outdoor air temperature. These additions would introduce an economic optimisation element to the storage model, from which an investment case for storage could be derived. They would also ensure that the carbon reductions anticipated from heat electrification are realised to their greatest possible extent. Scale-up implications of such an approach could also be quantified to assess the implications for the electricity supply system.

In addition to dedicated thermal storage, the control strategy could utilise greater deviations from the target room temperatures, effectively recruiting the thermal mass of the building as additional storage capacity, especially when external or cavity wall insulation or peripheral solid floor insulation is in place. Studies would be required to explore the range and timing of such deviations that can be allowed without being unacceptable to the occupants.

Presently, DHW heating follows a schedule set in IEHeat to avoid clashes with periods of space heating. Being fixed, it cannot compensate for periods of demand response coinciding with DHW heating times, or with very low heat pump power settings being selected. In these cases, insufficient DHW may be produced unless the schedule is modified manually in the spreadsheet. A more sophisticated control logic should be developed to adjust DHW heating dynamically to ensure that demand is always met. For example, highest priority could be given to meeting current space heating demand, lowest priority to charging space heating storage, and charging of DHW storage in between. DHW would then be heated at every opportunity, rather than at fixed times. Additionally, space heating could be maintained at a reduced power during DHW heating.

Electric storage comes with a different set of advantages and disadvantages as discussed in section **7.2.2**. Functionality could be added to model electrochemical batteries in place of thermal storage, potentially identifying which scenarios would benefit more from which of the two options.

Appendix 7. IEHeat model verification report: matching to Salford Energy House gas combi-boiler test cases

As part of the Smart Systems and Heat Phase 1 Programme, the Integrated Electric Heat Project developed a modelling tool to evaluate the opportunities and challenges for electric heating to meet UK household requirements. To satisfy the requirements of this Upgrade Analysis Study, the tool, referred to here as "IEHeat", has been further developed into a detailed and adaptable dynamic simulation model of heating systems within dwellings. As part of this development a number of aspects of the model have been enhanced and therefore required verification against measured data. This report provides a summary of the model verification exercise that has been carried out. The aim of the verification process was to provide a justifiable and efficient basis for the modelling of five dwellings in the Upgrade Analysis, by:

- establishing confidence in the realism of the model,
- minimizing as far as practical the uncertainties in the input data, and
- performing detailed testing of the model (inherent in the verification process).

These aims were pursued by attempting to achieve a reasonable match with test data obtained from heating trials at the Salford University "Energy House". The definition of "reasonable match" is typically a matter of judgement in such a verification, since specifying criteria based on metrics can often be too stringent for some parts of the model, whereas errors elsewhere (especially of slope) may meet the criteria despite indicating significant errors in the model. Specifying measures of data fit prior to investigating the model behaviour (relative to the data) can also lead to an under-constrained optimization – i.e. one where many combinations of parameter values can meet the criteria, only one of which is a representative and useful combination for further model use. The appropriate level of matching is often specific to the use to which the model is to be put, with higher fidelity required of a tool with a broad range of applications.

The following report assumes some familiarity with the Upgrade Analysis Study and the IEHeat model and is specific to the verification exercise (i.e. this report only provides such model information as required to follow the discussion of the verification results). More details of the IEHeat model components can be found in the IEHeat Modelling Overview (**Appendix 2**).

A.7.1. Verification scope and limitations

It is important to appreciate the scope and limitations of this verification exercise. Achieving a match against a single set of test data for a single dwelling (without occupants) will give confidence in the modelling of the heat source, heat distribution (including flow distribution interactions, radiator performance and heat losses), heat transfer and capacitance within the building fabric, with closed doors and windows and the estimation of resulting energy usage for that particular case. The validity of the model for other dwellings and cases is inferred by maximizing the use of "standard" parameters for material properties, wall types, radiator powers (based on type and size) and the direct use of house geometry and heat source data-sheet values, whilst minimizing the use of "tuning" parameters (see below).

This verification has not had the opportunity to demonstrate the behaviour of the model with varying external conditions (temperature, insolation, wind, rain etc.), with occupancy effects (use of DHW, door and window opening, heat gains from people and appliances etc.), or with different heat sources (e.g. heat pump). These aspects should be the subject of further verification at a future date.

A.7.2. Modelling approach for verification

The top-level structure of the model used is shown in Figure A.7.2-1.

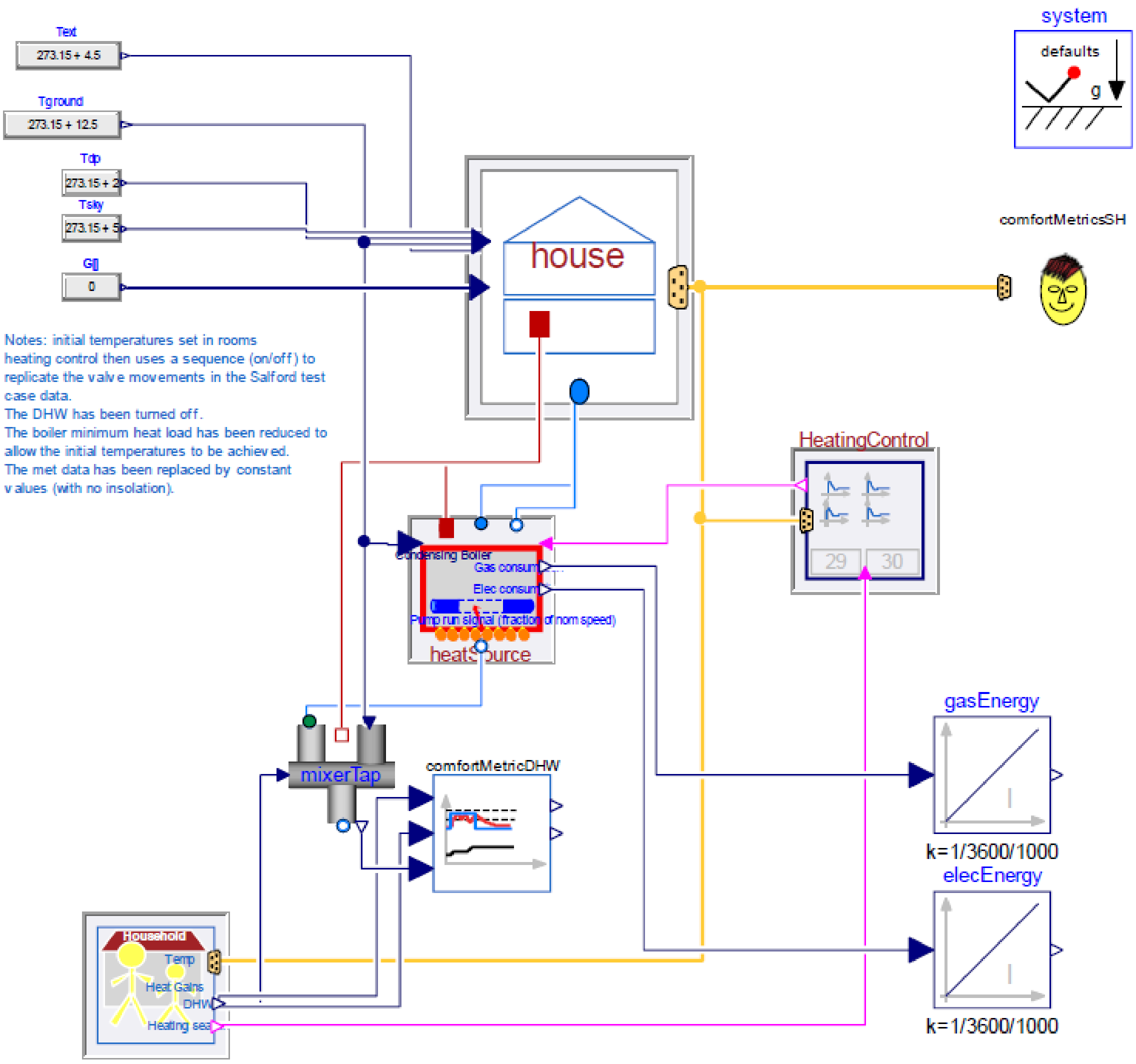

Figure A.7.2-1 IEHeat Salford Energy House model top level structure

The base IEHeat model consists of the following main components:

- house – detailed model of the rooms and heating within the house
- household – time-profiles of occupant behaviour and requirements
- heat source – a model representing a combi-boiler in the base case

- heating control
- a mixer tap to represent domestic hot water demand
- metrics – e.g. comfort, energy consumption

For the verification exercise the DHW has been switched off, the meteorological boundary conditions (e.g. external temperatures) have been replaced by constant values (to match the test data) and the household is used only to achieve the test starting conditions.

The heating control model is used to set initial room temperatures (via radiator valves), turning the boiler off about 2 hours before the start of the heating cycle for the verification test (as per the Salford house test result data), to ensure air, wall and radiator temperatures are all close to the test start conditions. During the simulation of the test the heating control model follows the sequence of radiator valve on/off movements indicated by the radiator flow data recorded at Salford.

The house model consists of a set of seven interconnected cuboid rooms representing a simplified geometry of the Salford house (Figure A.7.2-2). Each room consists of 6 faces (walls, ceiling, floor) each of which can be subdivided into segments to allow interfacing with more than one other room (e.g. the kitchen ceiling exchanges heat with both the bathroom and back bedroom). Windows and doors are incorporated in the appropriate wall segments. The rooms representing the ground floor and first floor stairs are connected by a large open "door" of negligible thermal mass.

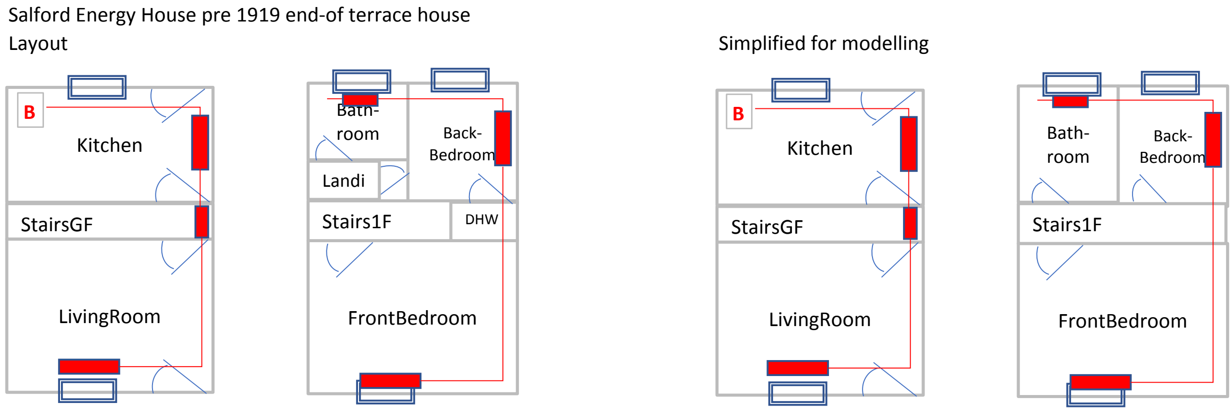

Figure A.7.2-2 Simplification of upstairs layout of Salford Energy House geometry to ease modelling

The house model structure is simplified relative to the actual house: a fully detailed representation (including the shapes of the landing, back bedroom entrance and water cylinder cupboard) would be complicated to configure, slower to run and unlikely to give much more useful results than the simplified form. However, testing the latter assertion is part of the verification process, and is discussed further below.

The air and solid contents of each room are modelled as homogenous thermal masses with heat transfer between them governed by their spatial mean temperatures. The mass and density of the solid room contents are used to calculate its volume and reduce the air volume by the same amount. This is only significant in the stairs where the air volume is significantly less than the cuboid dimensions would give. The heat transfer coefficient between air and solid contents can be adjusted to allow for uneven temperature penetration of the thermal mass of the solid contents.

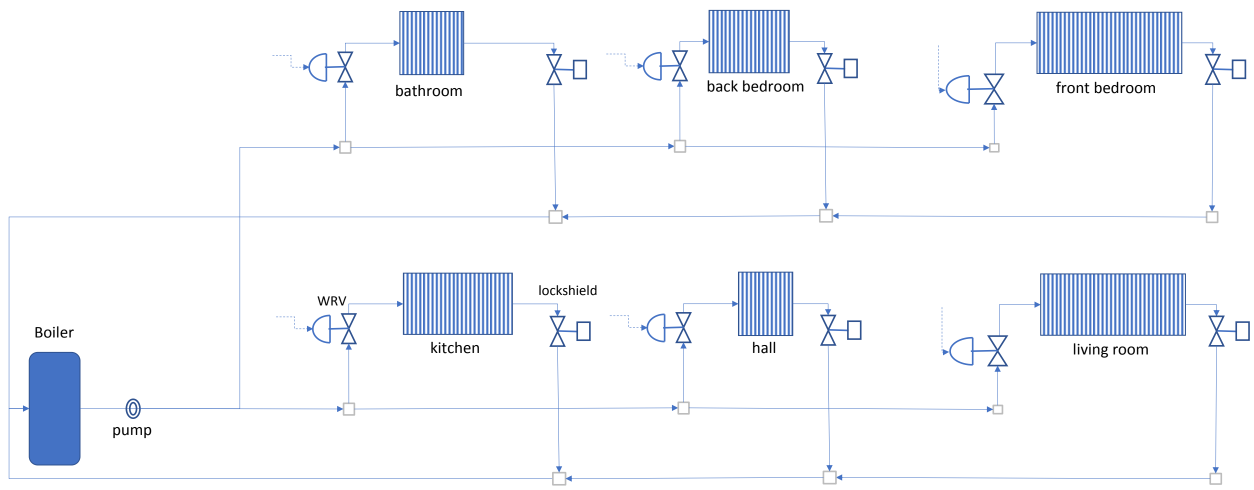

Figure A.7.2-3 Layout of space heating network

Apart from the first floor stairs/landing, each room also contains a radiator and models of the piping and valves distributing the heating water from the boiler (whose pump model forms part of the radiator piping network). The layout of radiator network is shown in Figure A.7.2-3. The stem positions of the lockshield valves and extra piping resistances (e.g. un-modelled isolation valves) can be set to represent the radiator balancing and network behaviour indicated by the test house flow data.

A.7.3. Model input data

IEHeat includes embedded material data which allows typical wall constructions to be selected from (or added to) a library when building a specific house model. Other common data used within IEHeat includes window heat transfer coefficient and transmittance, door thickness and conductivity and internal and external air boundary layer heat transfer coefficients. Much of this data is defined in the "Building and Heating System Definitions Document" from phase 1 of the Integrated Electric Heat Project or from EDF's BuildSys-Pro library (on which some of IEHeat was originally based), with some from other cross-checked publicly available sources. Part of the aim of this verification exercise was to check if the embedded data in IEHeat that was used in the model of the Salford Energy House could give satisfactory results without modification.

House-specific data was from obtained Salford University's drawings of the Energy House and from their responses to questions (mostly regarding the heating system). A summary of the data used is shown in Table A.7.3-1 to Table A.7.3-3.

Table A.7.3-1 General house data

Wall insulation	None (solid walls)
Floors (ground floor)	Suspended timber
Loft insulation	100 mm

Table A.7.3-2 Room data

Parameter		Living Room	Kitchen	Stairs GF	Stairs F1	Front Bedroom	Back Bedroom	Bathroom
Height, m		2.413	2.413	2.613	2.399	2.399	2.399	2.399
Length, m (front to back)		2.997	2.997	0.795	0.795	3.577	2.997	2.997
Width, m (left to right)		3.693	3.693	3.693	3.693	3.693	1.561	2.047
Windows	Wall	Front	Back			Front	Back	Back
	Type	SG[1]	SG[1]			SG[1]	SG[1]	SG[1]
	Width, m	1.1	1.1			1.1	0.65	1
	Height, m	1.4	1.4			1.6	1.6	1.6
Door 1[2]	Wall[3]	Front	Back	Front	Front		Front	Front
	Width, m	0.8	0.72	0.7	0.7		0.7	0.7
	Height, m	2	2	2	2		2	2
Door 2[2]	Wall[3]		Front					
	Width, m		0.7					
	Height, m		2					
Radiators	Type[4]	DPSC	DPDC	SPSC		SPSC	SPSC	DPSC
	Wall[3]	Front	Right	Right		Front	Right	Back
	TRV?	Y	Y	Y		Y	Y	Y
	Length, m	1.7	1.3	0.6		1.6	1.1	0.7
	Height, m	0.5	0.6	0.3		0.4	0.5	0.4
	Calculated nominal power, W[5]	2622	2912	376		1315	1111	883
Flow (hot) pipe from boiler or previous radiator	Length, m	6.25	3.7	3		9.2155	2.261	3
	Elevation change, m	0	0	0		0	0	2.4
	Internal Diameter, mm	13.6	13.6	13.6		20	20	20
	Insulation, mm	0	0	0		0	0	0
Return (cold) pipe to boiler or next radiator	Length, m	7.35	5	2.3		9.7155	2.661	3.7
	Elevation change, m	0	0	0		0	0	-2.4
	Internal Diameter, mm	13.6	13.6	13.6		20	20	20
	Insulation, mm	0	0	0		0	0	0

Notes: 1 – “SG” = single glazed; 2 - for internal doors, to avoid duplication, these are defined in rooms where they appear in left and front walls or ceilings; 3 - “left” and “right” are as seen when facing the front of the house; 4 - “DPDC” = double panel, double convector, “SPSC” = single panel, single convector, etc. 5 – nominal radiator output is based on a temperature difference (radiator to air) of 50 K, and is calculated from radiator type and dimensions by a correlation developed for IEHeat based on published data on commercially available radiators.

Table A.7.3-3 Boiler Parameters (from Viesmann Vitodens 200-W WB2B 26 kW Technical Data Manual)

Type	Condensing gas combi boiler
Rated output power	26 kW
Gross efficiency at 100% load	84%
Gross efficiency at 30% (minimum) load	95%
Mass (dry)	46 kg
Water volume	6 litres
Max pump head, (after allowing for losses in the boiler)	4.3 m
Nominal water flow	8.33 l/min
Head at nominal flow	3.9 m

In building the model, the room contents (solid) of the stairs was estimated to account for the volume and thermal mass of the stairs and airing cupboard. The external walls of the stairs were also modified to allow for the insulating effects of these features. Note the hot water cylinder was not modelled. Some upstairs partition walls were of lath and plaster construction, which was modelled using layer properties calculated as area or volume averages, assuming a wooden frame with 600mm pitch between verticals and three horizontals between each vertical.

A.7.4. Sources of test data

Test data was extracted from that recorded by the HEMS equipment installed in the house and by the sensors installed by Salford University. This data is presented below in comparison with the model output data. The test chosen for matching was designated "Test 3.2.2" and was performed on 1st October 2017 from 12 noon to 4pm (plus cooling thereafter). The test was performed with a constant external air temperature of 5 °C, a constant temperature of 20 °C in the adjoining space (mimicking the neighbouring house), a target temperature at the start of the test of 17 °C in all rooms and with all doors closed. This test was chosen since all rooms were being heated on a "reasonable schedule" (test procedure description) with the small bedroom set to a higher temperature than the others.

A.7.5. Review of test data

Before attempting to match the IEHeat model to the test data, it was inspected for consistency. The sets of data did not all share the same time intervals, so a number of events were identified (such as a valve opening, or the boiler turning on) from which initial measurement responses allowed the data to be synchronized. Each room had three sensors intended to measure air temperature, which were seen to give different readings. Salford University had installed a wall mounted sensor and a resistance temperature detector (RTD) mounted in a black sphere suspended in the geometric centre of the room, while the HEMS system included wall mounted temperature sensors, often located close to the Salford equivalent. Differences in location, heat transfer and thermal mass in and around the sensors contribute to these differences, with the two Salford measurements often relatively similar (typically the wall mounted sensor appearing to have longer time constants than the central RTD). Charts in Figure A.7.5-1 to Figure A.7.5-3 illustrate these differences for selected rooms (also including the HEMS temperature sensor mounted near the radiator).

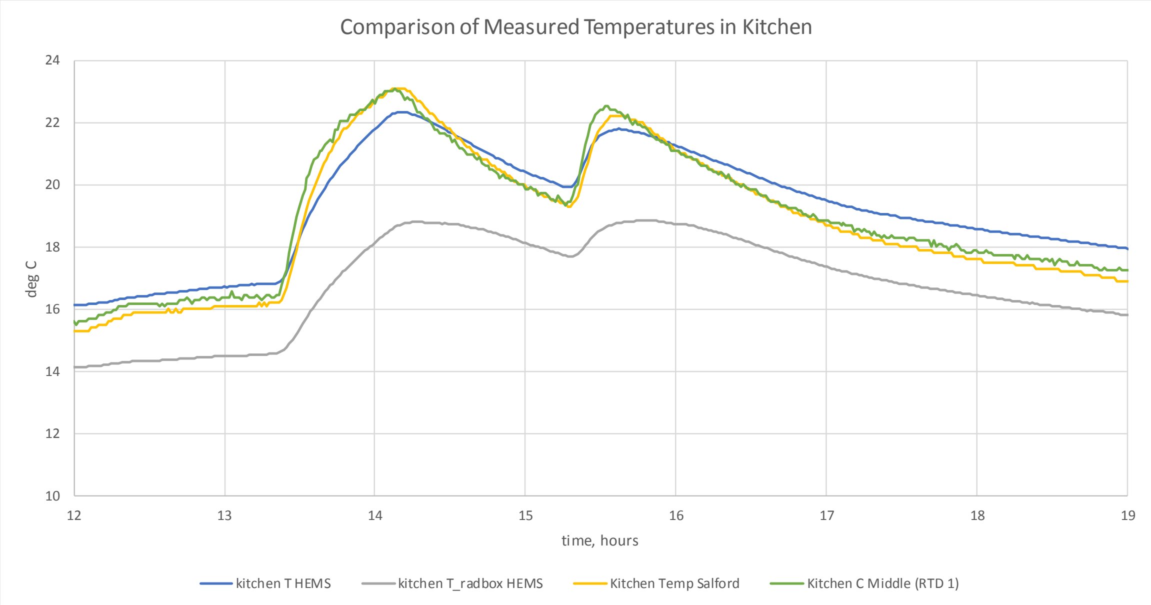

Figure A.7.5-1 Kitchen temperature measurement comparison showing influence of wall temperature on HEMS sensor

The Salford and HEMS wall mounted room temperature instruments in the living room are located close to each other on the internal wall adjoining the stairs (opposite the window), yet the Salford measurement follows quite closely their measurement in the centre of the room, whereas the HEMS measurement is 1-1.5°C lower and shows a different initial dynamic (slower rise). This difference would have a significant effect on the performance of room temperature control and occupant comfort. Investigations indicated that a match of the HEMS data could be achieved with a weighted average of modelled room (0.75) and wall (0.25) temperatures which suggests better insulation between wall and measurement device is required.

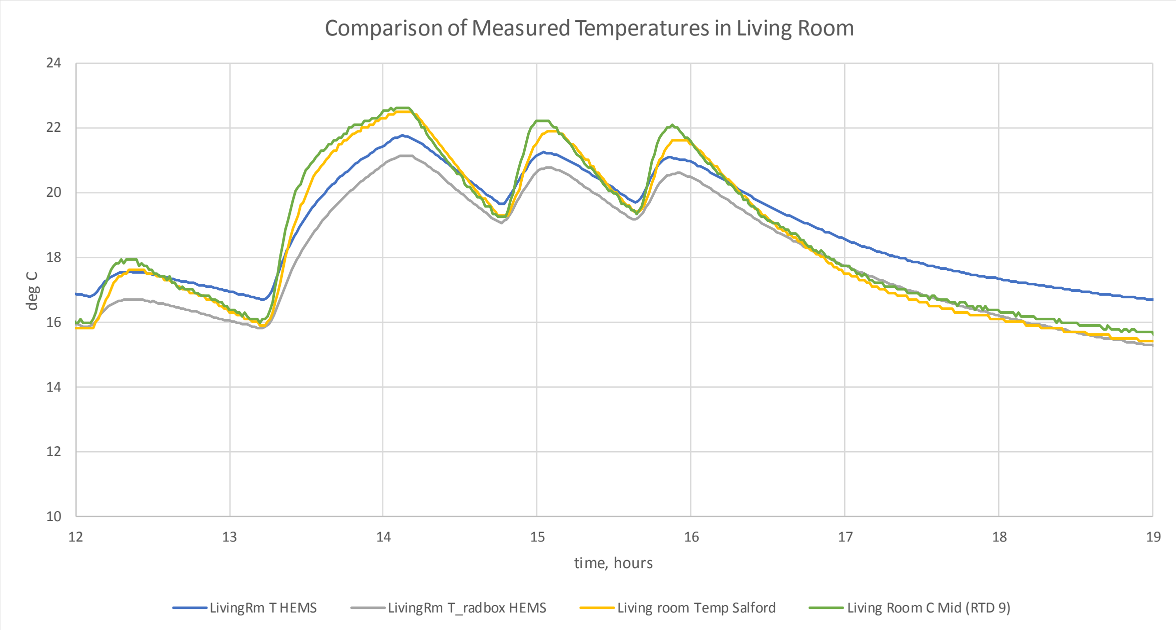

Figure A.7.5-2 Living room temperature measurement comparison showing influence of wall temperature on HEMS sensor

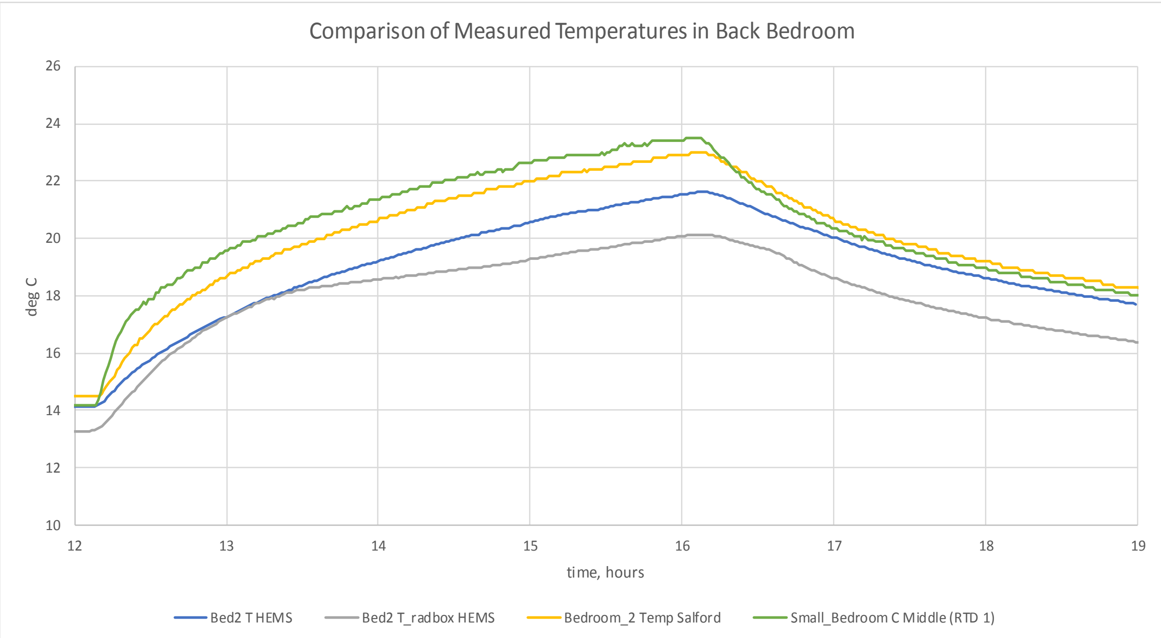

Figure A.7.5-3 Back bedroom temperature measurement comparison showing influence of wall temperature on HEMS sensor

These observations indicate the importance of selection, location and installation method of measurement devices for domestic heating control.

The Salford University central room RTD readings were used for model matching as they would be expected to most closely measure the space averaged air temperature (which is what the model predicts) – although they would not exactly measure the average temperature since radiators and windows skew the temperature distribution towards them during heating and cooling respectively.

A.7.6. Model matching methodology and findings

Having configured the model boundary conditions (external temperatures, initial air and wall temperatures, valve position changes with time, as described above), the model was run numerous times to investigate the match with the test data. Before attempting to achieve a match of room temperatures it was necessary to ensure the correct heat input was being provided by the radiators.

The first step in matching the radiator power outputs was to match the water flow rates. The flow rates were reported in the Salford data set, but to a resolution of two decimal places in units of m^3/h. With typical radiator flows between 0.01 to 0.5 m^3/h, this gave a relative signal error of up to 50% at low flow rates. However, sufficient combinations of radiator flows were available to tune the pressure drops in the distribution network to give an acceptable match of flow rates in each case (as judged by the resulting radiator power output – see below). This match was found to be possible only with the inclusion of significant pressure drops in lines that were not indicated in the data provided. For example, a resistance was identified in the common return line from the upstairs radiators (to the boiler) by matching the interactions between radiator flows: a relatively large flow resistance in a common flow path will result in the pressure drop through that pipe changing significantly when one radiator valve opens or closes. This will cause changes to outlet pressures of other radiators using same flow path, which in turn changes their water flowrates. Note that the converse is also true: minimizing pressure drops through common piping can almost eliminate these interactions between radiator operations. On inspecting photos of the boiler installation, it was noticed that a manual isolation valve was located in the upstairs return line, which could have provided the calculated resistance if it were partially closed (often the case with such screw-driver adjusted ball valves).

Note: all comparison charts below show measured data in solid lines, model predictions in dashed lines.

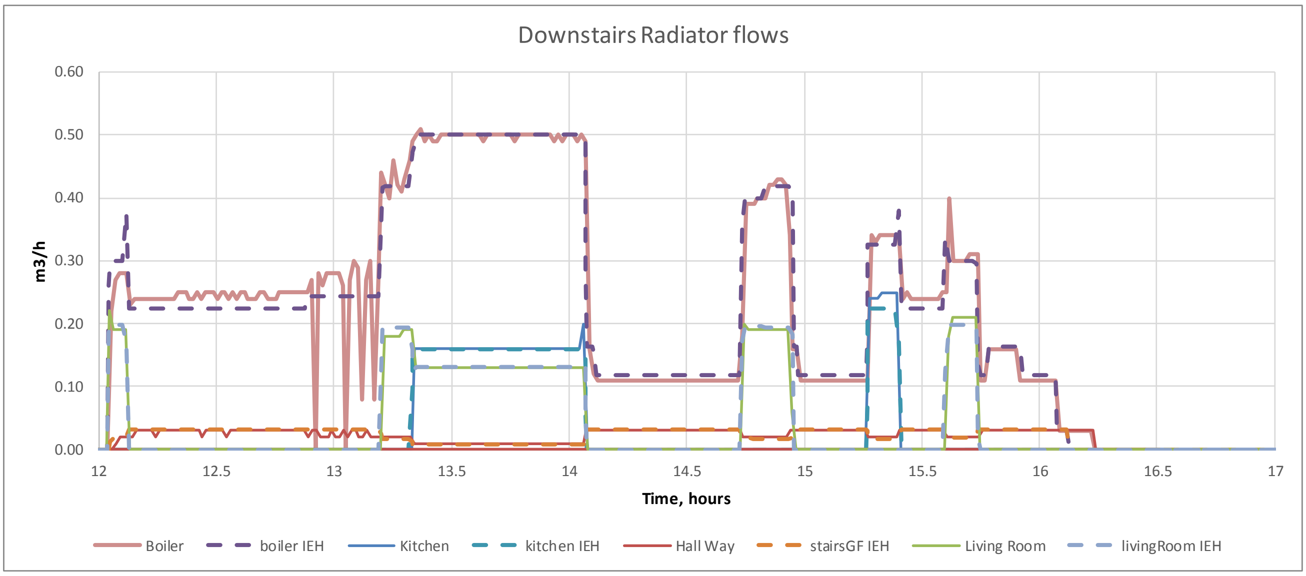

Figure A.7.6-1 Downstairs radiator flow comparison showing match with various combinations of radiators flowing

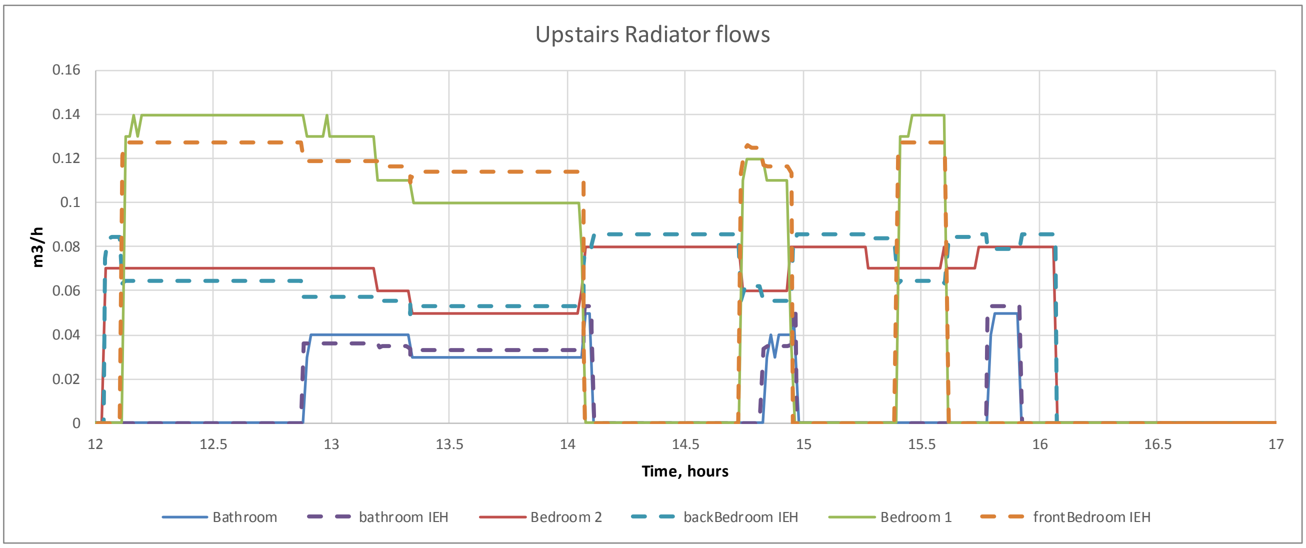

Figure A.7.6-2 Upstairs radiator flow comparison – note at lower flows (reflected in the tighter vertical scale) the measurement resolution gives greater uncertainty

With the radiator flows in good agreement with the data, and the boiler outlet temperature set correctly, the radiator power inputs were found to be in excellent agreement. These were calculated in both the Salford "heat meters" and the model as power input = mass flow * specific heat capacity * (inlet temperature – outlet temperature) = F*Cp*dT. Note that the power output is calculated rigorously in the model from heat transfer between the radiator and the air in the room. Although there is no direct measurement of radiator power output available the model calculation was found to closely match the input measurement once the initial dynamic effects of warm-up had passed.

Comparison of radiator inlet (flow) and outlet (return) temperatures also showed a good match.

In combination, these findings verified the hydraulic modelling of the radiator network, the radiator power dissipation model and the correlation between radiator type and size with nominal radiator power.

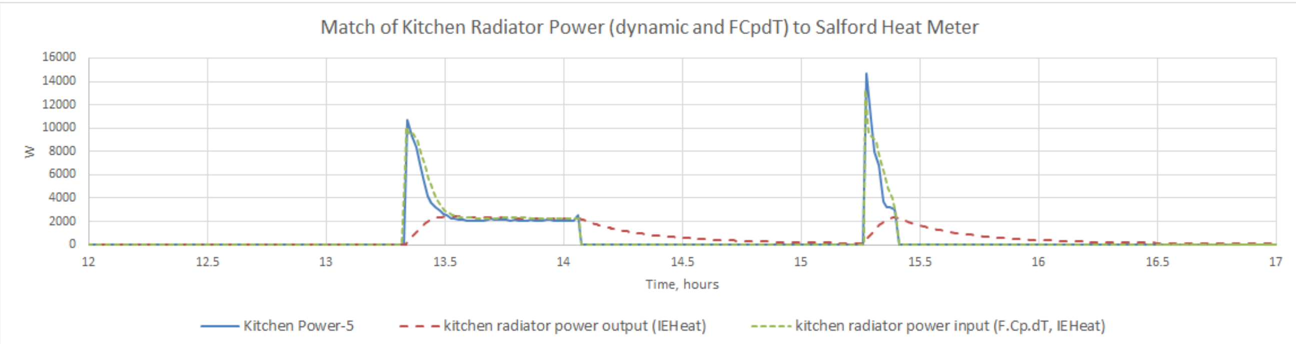

Figure A.7.6-3 Kitchen radiator power comparison, showing excellent match of input dynamics and steady output power

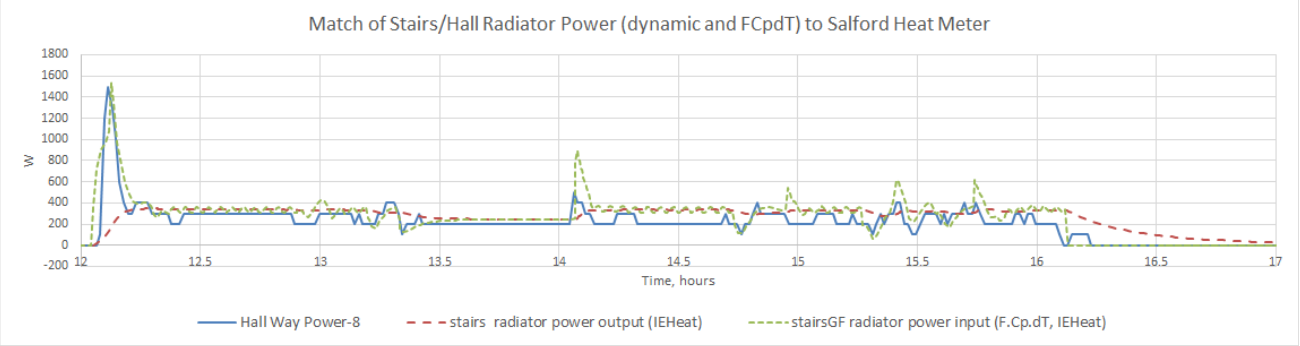

Figure A.7.6-4 Stairs radiator power comparison, showing acceptable match of input dynamics and steady output power

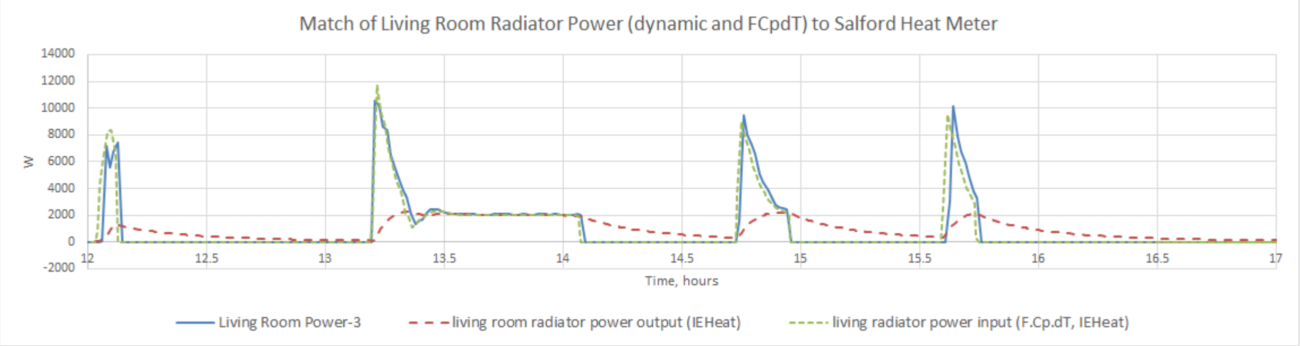

Figure A.7.6-5 Living room radiator power comparison, showing excellent match of input dynamics and steady output power

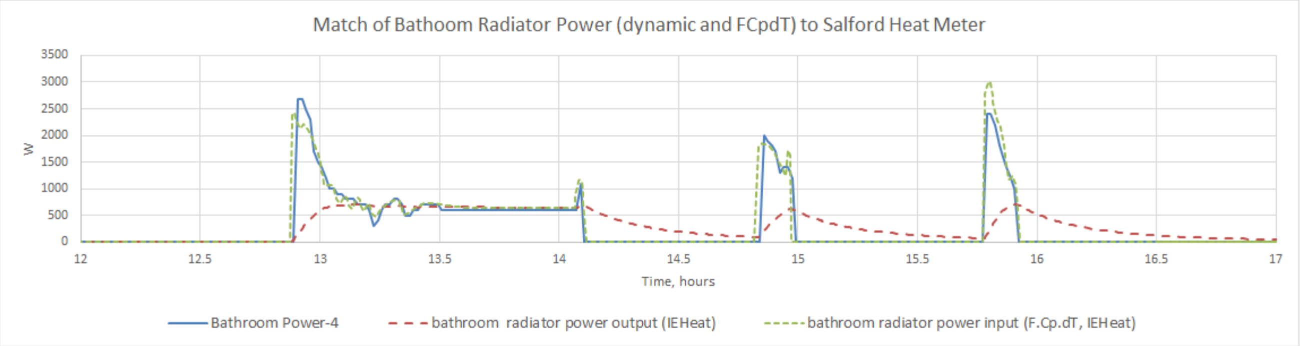

Figure A.7.6-6 Bathroom radiator power comparison, showing excellent match of input dynamics and steady output power

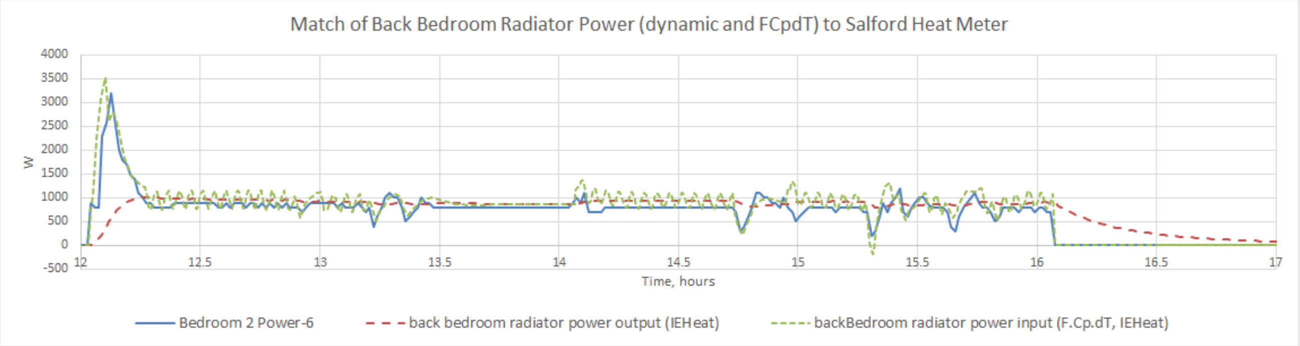

Figure A.7.6-7 Back bedroom radiator power comparison, showing excellent match of input dynamics and steady output power

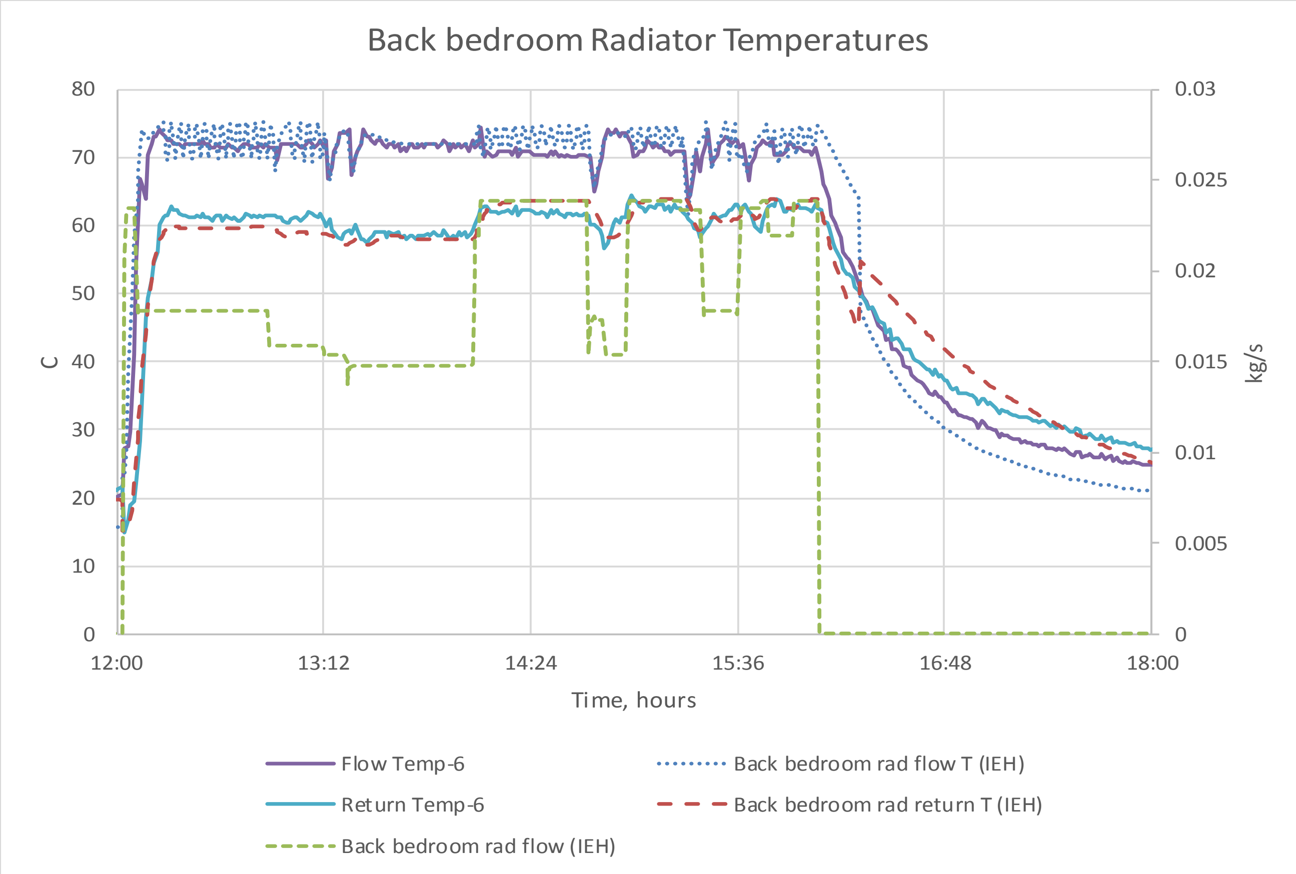

Figure A.7.6-8 Back bedroom radiator temperature comparison, showing good match while radiator operating

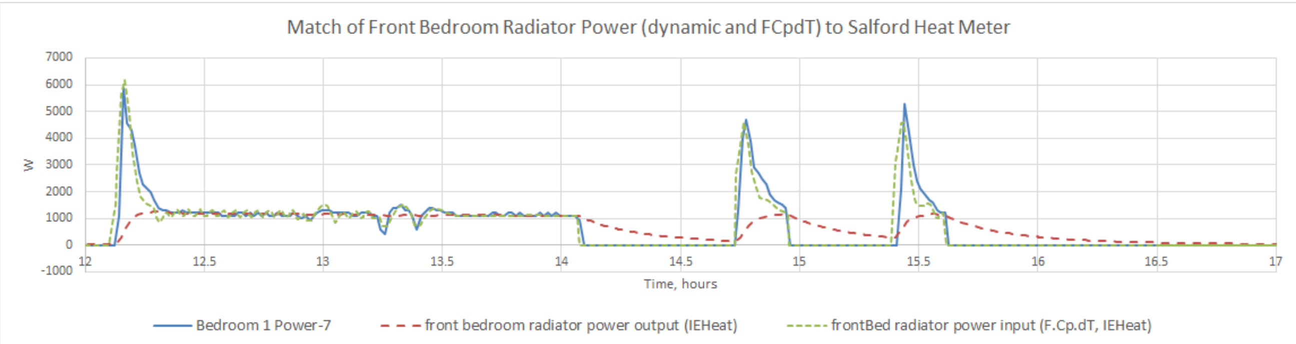

Figure A.7.6-9 Front bedroom radiator power comparison, showing excellent match of input dynamics and steady output power

Measurements of the boiler power output (using F*Cp*dT as with the radiators), and gas usage (converted to input power using the gas gross calorific value) were also compared with the model predictions. Initially the radiator network piping had been erroneously modelled as insulated: removing this insulation increased heat loss in the system by the equivalent of one medium sized radiator, but most of this heat is lost under the floors, giving a 20% drop in effective heating efficiency (gas power / radiator emitted power during desired warm times). Removing the insulation allowed the model to match the boiler output very closely, but the gas usage was still under-predicted by about 20%. Investigation revealed non-physical aspects of the heat transfer paths and thermal masses in the boiler model were responsible for most of this discrepancy. Correcting this reduced the discrepancy to less than 5%, and highlighted that the effective boiler efficiency during the 4-hour heating period was about 76% - far lower than the data sheet values – due to gas used to heat up metal in the primary heat exchanger. This heat is later released to the kitchen, but at a quality and time when it is not of benefit to the householders and therefore should not be included as useful heat in efficiency calculations (typical heat loss from boiler casings are in the order of 100 W when operating, which reduces as the internal heat exchanger cools).

Further investigation into the boiler efficiency calculations revealed scope for improvements which achieved a final match of cumulative gas consumption within 1% over 4 hours firing.

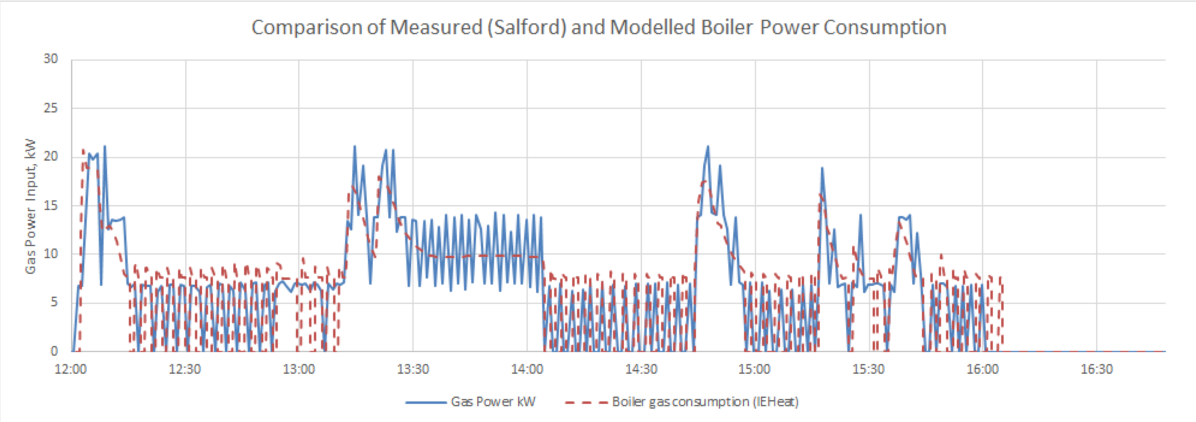

Figure A.7.6-10 Gas boiler power consumption, showing a match of both gas rate and boiler cycling, but indicating that the actual minimum load may be higher than given in the datasheet (see the boiler on/off cycles between 13:30 and 14:00)

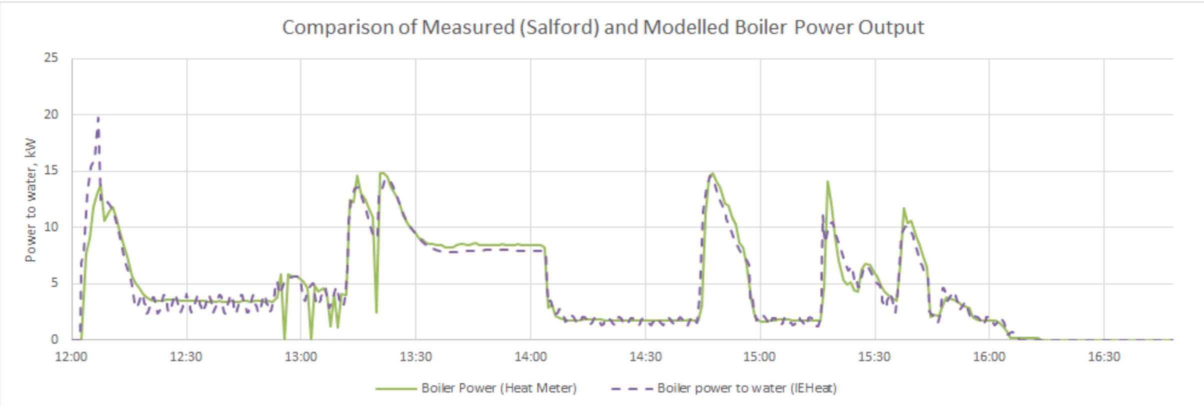

Figure A.7.6-11 Gas boiler output power (to radiator network), showing excellent match of dynamics and steady output power

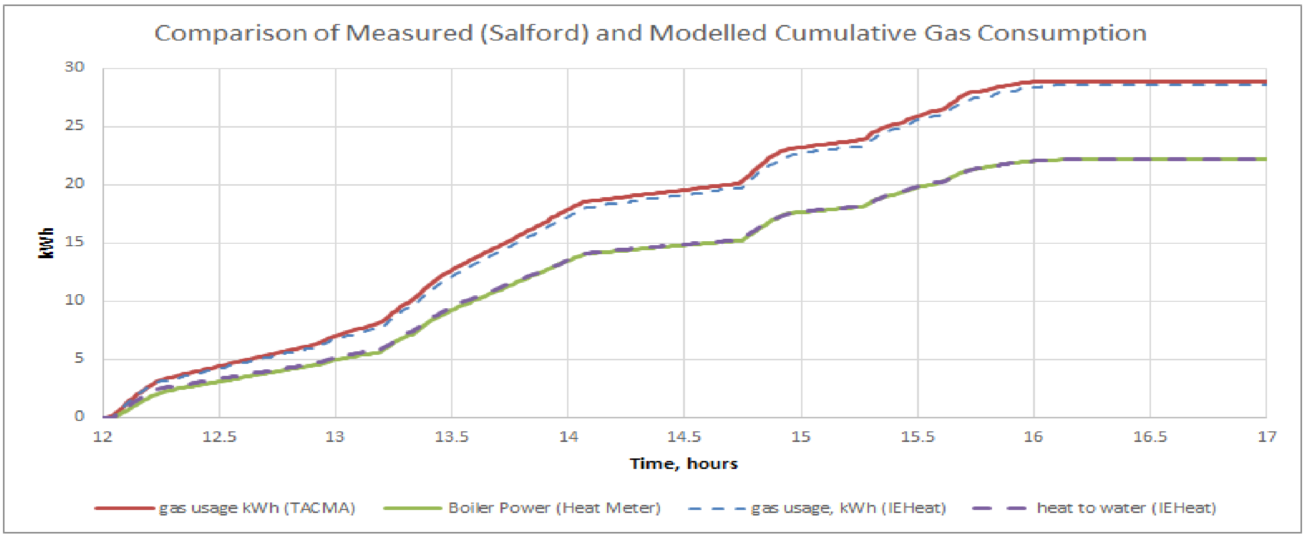

Figure A.7.6-12 Gas boiler cumulative input and output power comparison, showing excellent match over 4 hour heating cycle

A.7.7. Tuning to match room temperatures

Once a good match of heat input to the rooms had been achieved, attention was focused on finding a minimum set of tuning parameters to achieve an acceptable match of room temperatures. Ideally, it should be possible to obtain representative results from an IEHeat model from easily obtained survey data, without great sensitivity to assumed parameter values. However, while a library of typical wall constructions can be compiled with an expectation that resulting wall thermal properties will be reliably close to reality, this is not as easy to achieve with solid room contents (furniture, enclosed building features etc.) and ventilation. These two room properties are far more difficult to estimate accurately from superficial survey data (e.g. from type and age of house, dimensions of rooms, age of windows, type of furniture etc.). They are therefore considered unknowns in the IEHeat model being verified and are considered valid choices of tuning parameters. Ventilation is characterized in IEHeat by a parameter setting air changes per hour (ACH) for each room, setting the heat transfer rate between the room air and the external air temperature in relation to the volume of air in the room. Solid room contents are characterized by their combined heat capacity and heat transfer coefficient with the room air (set relative to the internal wall-air heat transfer coefficient, allowing for rate of heat penetration into the interior of the solid contents).

Initial investigations to identify discrepancies between model and measured room temperatures identified modifications necessary to the IEHeat model in the internal wall-air heat transfer coefficient and to the fraction of radiator power emitted that is absorbed first by the adjacent wall. The internal wall-air heat transfer coefficient was initially fixed at a default value higher (by a factor of approximately 2) than those typically found in literature surveyed[49] and was independent of temperature difference (convection effects) and

[49] Such as "Convective heat transfer coefficients in a full-scale room with and without furniture", Petter Wallenten, Lund Institute of Technology, 2001

orientation. These shortcomings were addressed and sensitivity cases run to assess the remaining assumptions (see section below). The new default values for this variable were used for the final match without further need for tuning.

The fraction of radiator power absorbed by the adjacent wall is difficult to measure or estimate with confidence, However it was found that acceptable results could be achieved in this verification study by assuming the following crude estimates, based on radiator type and proximity to a window (to allow for greater heat losses through the window due to elevated temperatures above the radiator):

Table A.7.7-1 - Fraction of radiator power adsorbed by adjacent wall

Radiator type	No window on wall	Window above radiator
Double panel, single convector	0.15	0.25
Single panel, single convector	0.25	0.4

It was not necessary in this study to further adjust these fractions, though in some models it could be appropriate to tune them to particular circumstances (e.g. radiators with shelves fitted above or boxed in etc.).

A trial and error process was used to achieve the match of room temperatures shown in the charts below, using the values tabulated below. Over the 6 hour heating/cooling cycle the model predicted spatial mean air temperatures within 0.5°C of the central room RTD measurement, with the difference less than 0.25°C for over 70% of that time. This demonstrated that not only were extreme temperatures well matched by the model, but also the dynamic shape of the trends was well matched, and confirmed that this match could be achieved by adjusting only a very small set of tuning parameters. It should be noted that the parameters for room contents mass and ventilation obtained may not be typical of occupied houses, due to the nature of the test house environment.

Table A.7.7-2 Ventilation and room contents parameters to achieve final match

Room	Air changes per hour, $m^3/m^3/hr$	Solid contents mass kg	Contents heat transfer factor[1]
Kitchen	1.25	332 [2]	8
Living room	0.5	111 [2]	3
Front bedroom	1.25	357 [2]	8
Back bedroom	0.8	164 [2]	8
Stairs	0.05	100 [3]	2
Landing	0.05	100 [4]	2
Bathroom	0.2	120 [5]	12

Notes: 1 - heat transfer rate to solid contents = contents heat transfer factor * horizontal wall-air heat transfer coefficient * room floor area * (air temperature – solid contents temperature); 2 – density 510 kg/m^3, specific heat capacity 1400 J/K/kg; 3 – stairs density calculated to occupy 50% of volume; 4 – airing cupboard density calculated to occupy 33% of volume; 5 – density 2500 kg/m^3, specific heat capacity 1000 J/K/kg

The quality of match achieved far exceeded expectations at the start of the exercise, albeit in a controlled environment with fixed external conditions, no wind or insolation, and no occupant activity to disturb the thermal behaviour of the house. The deviations between the modelled and measured temperatures may be in part a result of the comparison of spatially averaged room temperatures with a fixed position measurement. In reality the room air is unlikely to be well mixed such that the central RTD will tend to measure slightly less than average when heating (the spatial mean will be nearer radiator when it is on) and maybe slightly more than the mean when cooling (the mean will be closer to coldest wall or window). IEHeat does not currently model temperature distribution, but considering its impact on thermal comfort an approximate method is being considered for future inclusion.

The largest deviation is seen in the stairs, where the likely causes include the location of the measurement (on the wall with the back bedroom near the top of the stairs, close to the airing cupboard) the omission of the hot water cylinder in the airing cupboard (which had been heated a few hours before this test data was recorded) and the simplifications to the landing geometry. However, the geometry simplifications have not been seen to affect any other room temperatures, or the interactions transmitted via the heating system. The approach to modelling houses with the cuboid rooms provided by IEHeat and the simplifications used here therefore appear to be valid.

The match achieved and the small set of tuning parameters required confirm the validity of IEHeat for use in evaluating building fabric and heating system changes required by the Upgrade Analysis study.

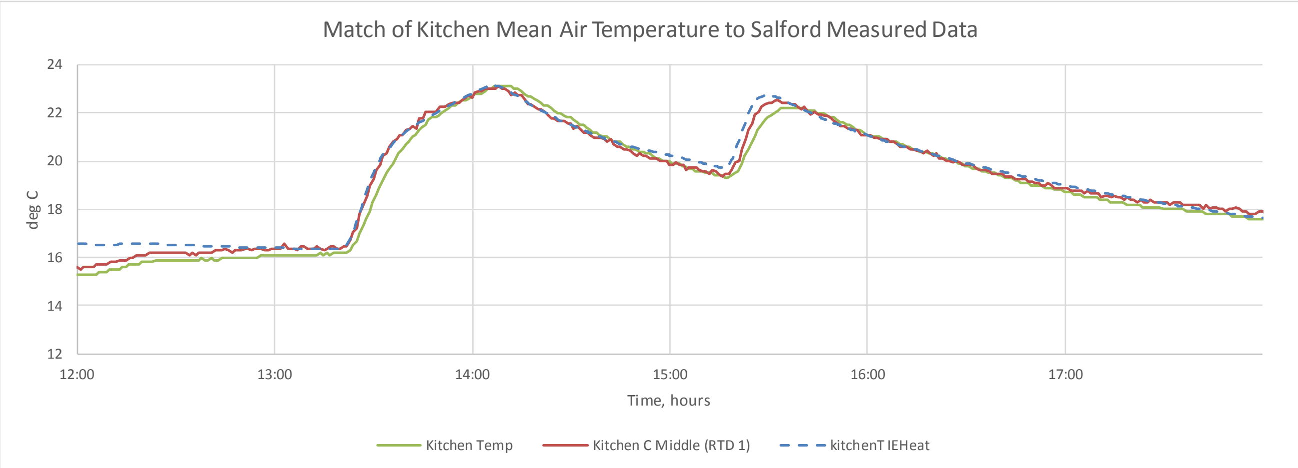

Figure A.7.7-1 Kitchen temperature comparison, showing good match with central RTD measurement

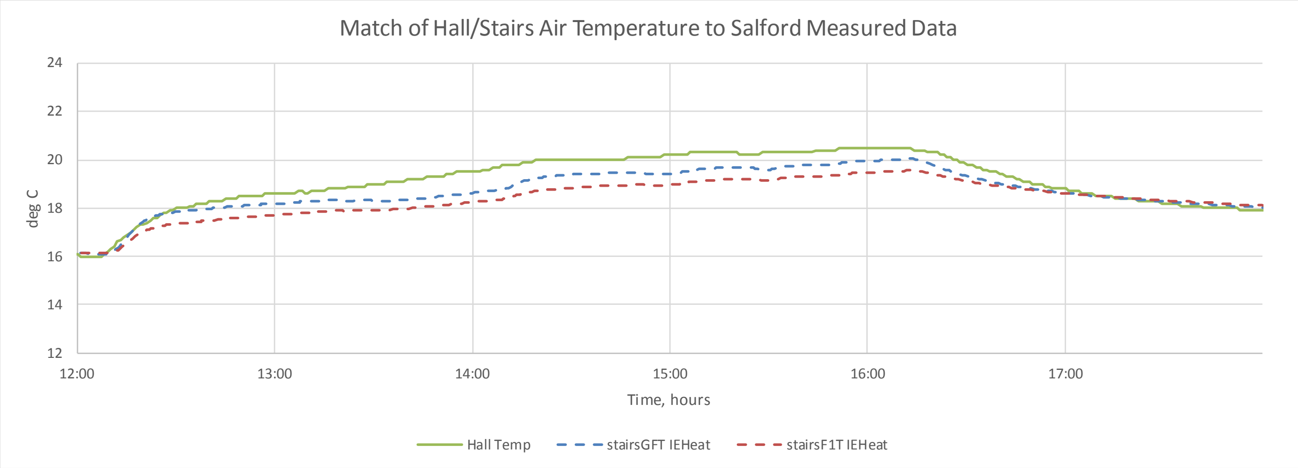

Figure A.7.7-2 Stairs temperature comparison, indicating possible errors from geometry simplifications or hot water cylinder omission

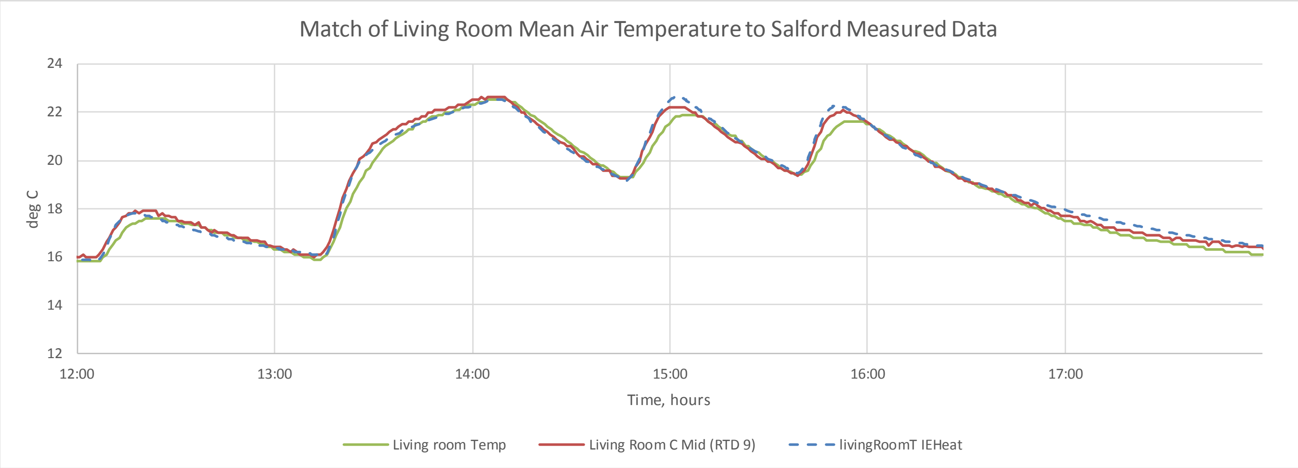

Figure A.7.7-3 Living room temperature comparison, showing good match with central RTD measurement

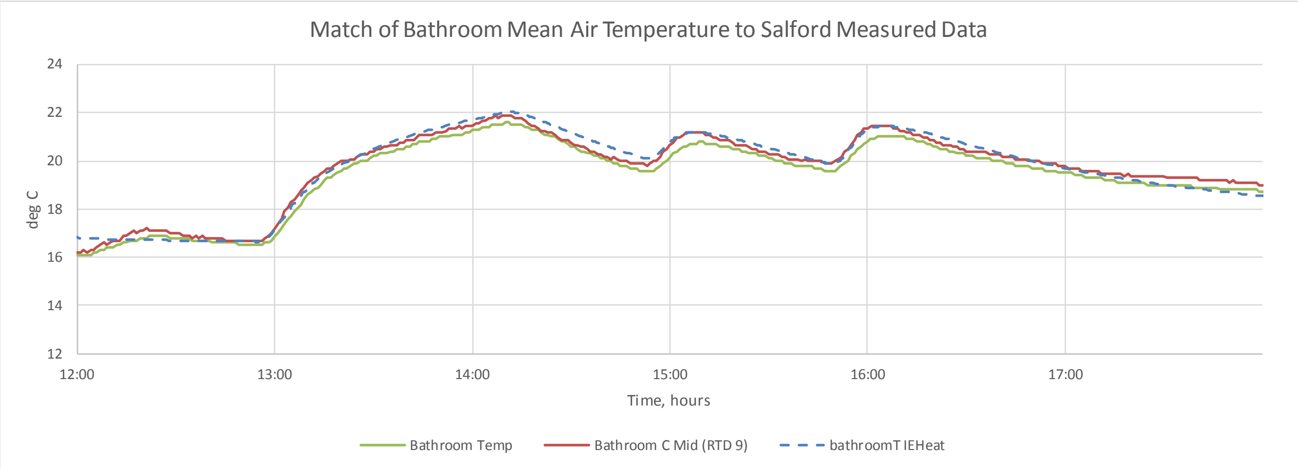

Figure A.7.7-4 Bathroom temperature comparison, showing good match with central RTD measurement

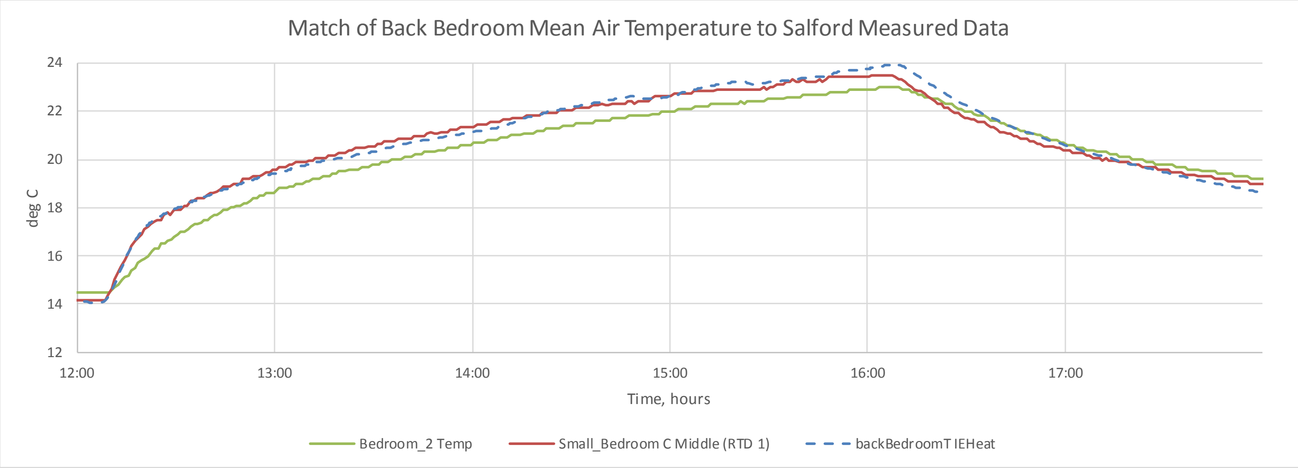

Figure A.7.7-5 Back bedroom temperature, showing slight overshoot compared with central RTD measurement

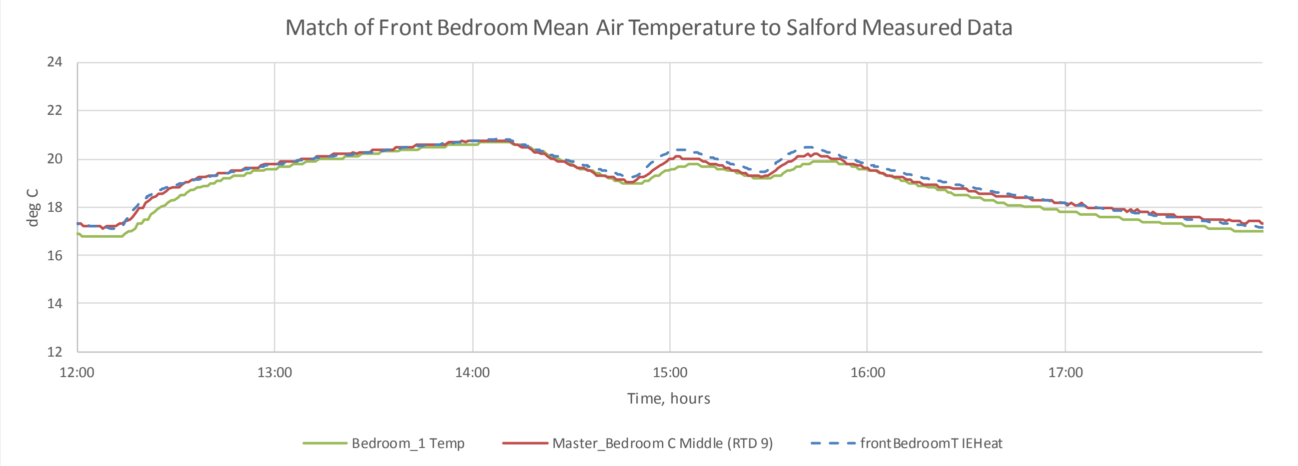

Figure A.7.7-6 Front bedroom temperature comparison, showing good match with central RTD measurement

A.7.8. Sensitivity checks on tuning parameters

A sensitivity analysis was performed on the parameters initially considered for tuning. This was to identify any parameters that have a significant effect on results, such that further work to obtain reliable values can be defined, and to establish if the matching problem was fully constrained (i.e. only one set of tuning values would produce a good solution).

The parameters investigated were as follows, with ranges set to reflect typical valid extremes:

1. External air changes per hour ("airChanges" varied from 0.25 to 1.0)
2. Solid room contents mass per unit floor area ("contentsMassPerArea" varied from 15 to 35 kg/m^2 for back bedroom, 70-150 kg for bathroom)
3. Solid room contents heat transfer factor ("contentsHTCfactor" varied from 2 to 12)
4. Internal wall-air heat transfer coefficient (SHTC)

   Vertical SHTC = hs_int*abs(Tsurface-Tbulk_air)^0.2 for large temperature differences

   Horizontal SHTC = 1.3 * vertical SHTC

   "hs_int" varied from 2.7 to 3.3 W/m^2/$K^{1.2}$
5. Fraction of radiator power absorbed by adjacent walls ("fracWall" varied from 0.1 to 0.35)

Simulations were run with each of the parameters varied individually, set to a low range, mid-range (default) and high range value (the other parameters being set to their mid-range values). The charts below show results for the back bedroom (single, long heating cycle) and for the bathroom (showing the effect of multiple shorter cycles).

Steady state conditions are not reached during these room heating cases (as is often true in reality) which means the peak temperatures are determined by the shape (slopes) of the heating and cooling curves. Hence comparisons purely of peak temperatures is not sufficient to interpret these results. Looking at the rate of rise and fall of temperatures reveals the different effects of each of the sensitivity parameters:

1. Increasing air changes per hour slows the rise and speeds the fall of room temperature (by increasing the overall heat loss from the room in cold weather)
2. Increasing the mass of solid room contents tends to slow both the rise and fall of air temperature (by increasing the total thermal capacity of the room)
3. Decreasing the heat transfer factor to solid room contents delays the effect of the increase of thermal capacity, allowing the room temperature to rise rapidly initially, before the solid contents temperature "catches-up" (this could have significant impact on room temperature control).
4. Increasing the internal wall-air heat transfer coefficient causes a relatively small decrease in the rate of rise of room temperature and increase in the rate of temperature fall.
5. Increasing the fraction of radiator power absorbed by adjacent walls reduces the rate of rise of air temperature with very little effect on the cooling rate (similar to decreasing the power emitted by the radiator) – this asymmetric effect allows isolation of the effect of this parameter, hence the confidence gained in the "default values".

It can be seen that each tuning parameter has a different impact on the shape of the heating and cooling curves, such that each combination of parameters will produce a unique curve shape.

Most charts below show only relatively small effects on absolute room temperatures, but it should be recognized that the test has reduced the variables to which the house is subjected (no weather variations, no insolation, known heating system operation etc.) such that it should be possible to identify sources of even small discrepancies between the model and the test data. Furthermore, as mentioned above, matching the shapes of the curves gives confidence that a unique solution has been found. It should also be noted that relatively small changes in temperature and rise/fall curves can have a large cumulative effect on energy consumption when the temperature is controlled (especially with typical on/off control cycles) as can be seen in the results for the bathroom.

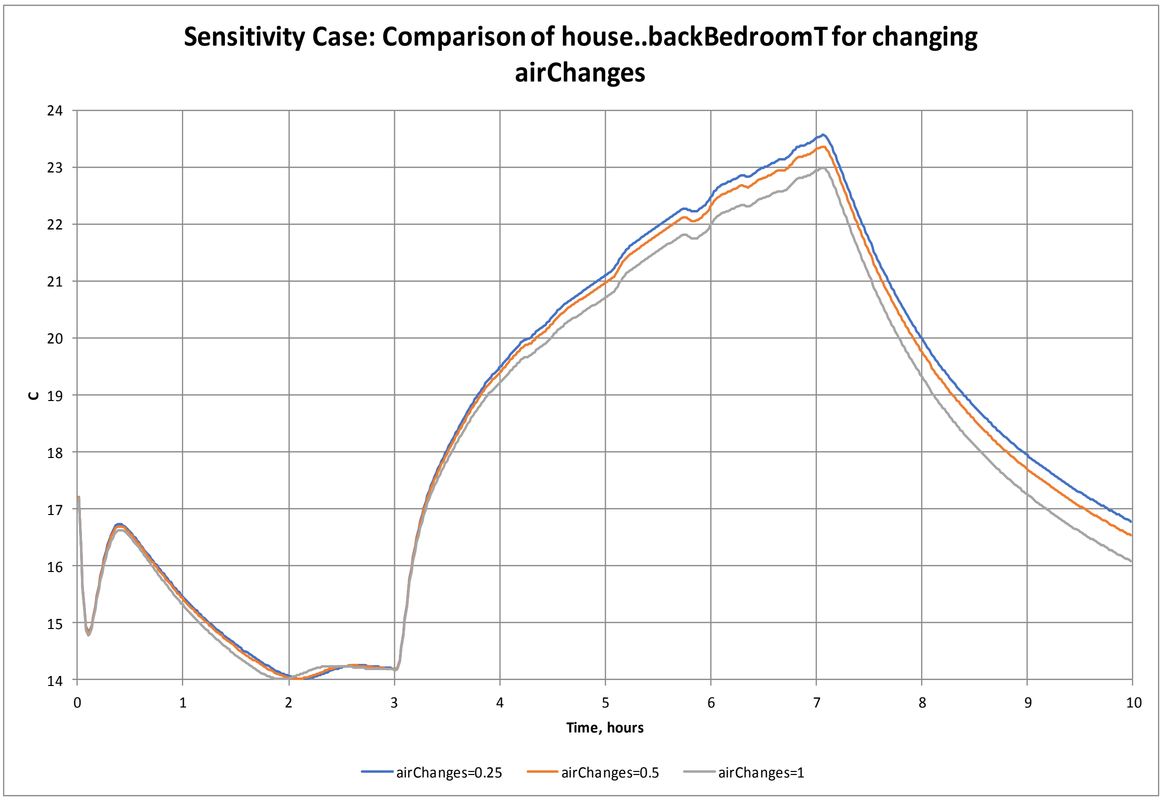

Figure A.7.8-1 Back bedroom sensitivity to ventilation from outside over a single long heating/cooling cycle

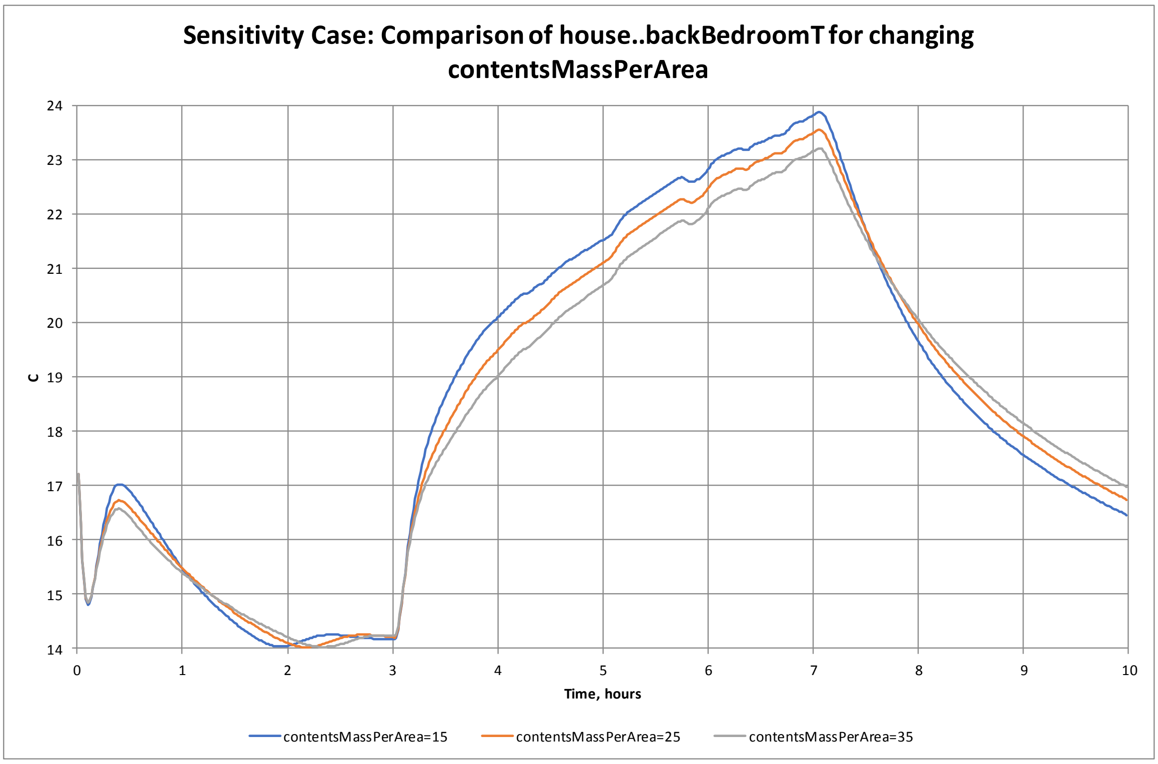

Figure A.7.8-2 Back bedroom sensitivity to mass of solid contents over a single long heating/cooling cycle

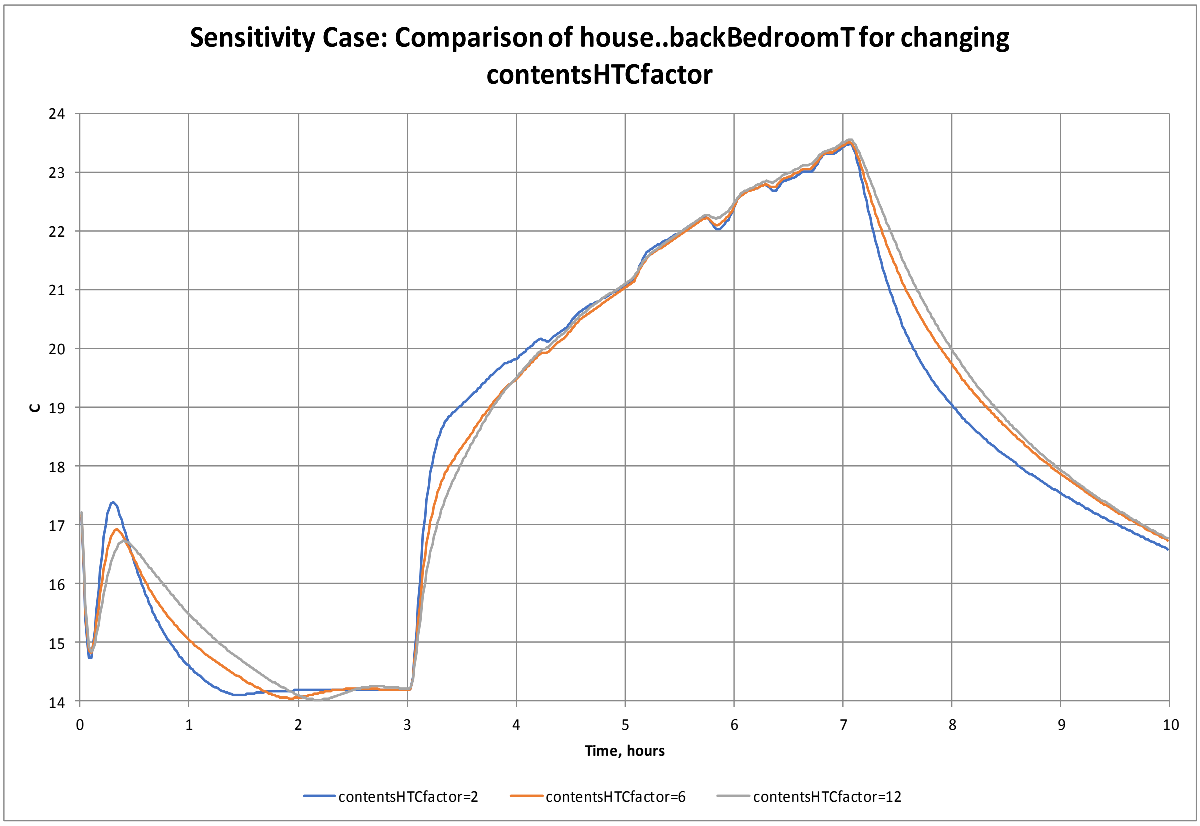

Figure A.7.8-3 Back bedroom sensitivity to heat transfer to solid contents over a single long heating/cooling cycle

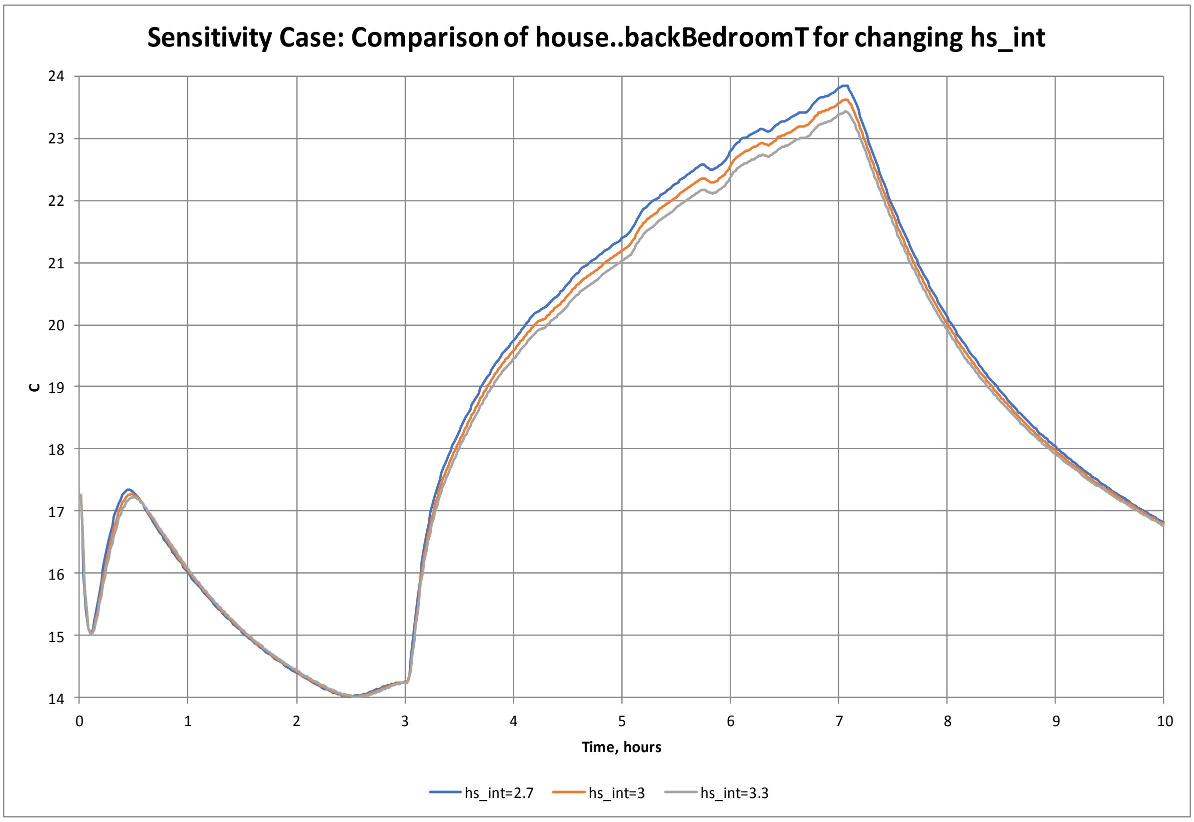

Figure A.7.8-4 Back bedroom sensitivity to internal wall-air heat transfer coefficient over a single long heating/cooling cycle

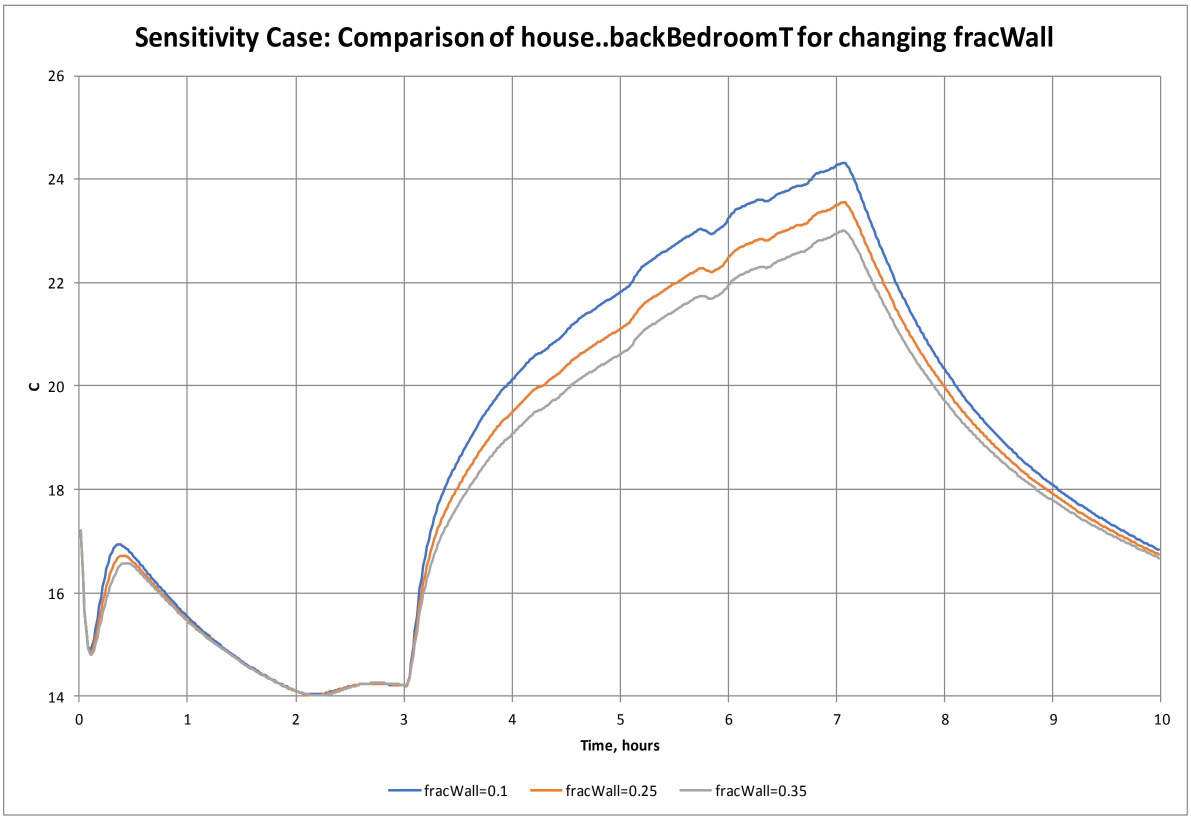

Figure A.7.8-5 Back bedroom sensitivity to fraction of radiator power absorbed by adjacent wall over a single long heating/cooling cycle

The cumulative effect of slope differences over repeated heat/cool cycles (see results for the bathroom in charts shown in Figure A.7.8-6 to Figure A.7.8-10) is different for each variable – some diverge (e.g. air changes, radiator power), whereas others converge towards the same cooling curve (e.g. heat absorbed by room contents).

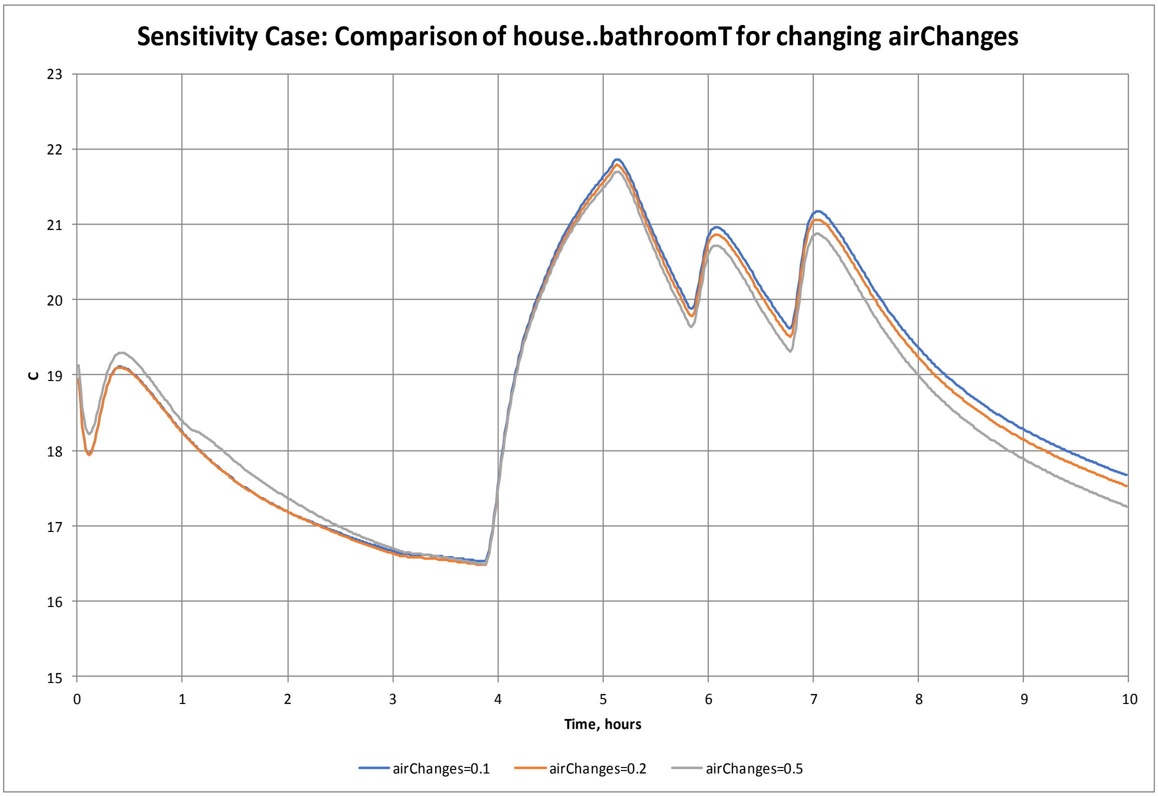

Figure A.7.8-6 Bathroom sensitivity to ventilation from outside over a number of heating/cooling cycles

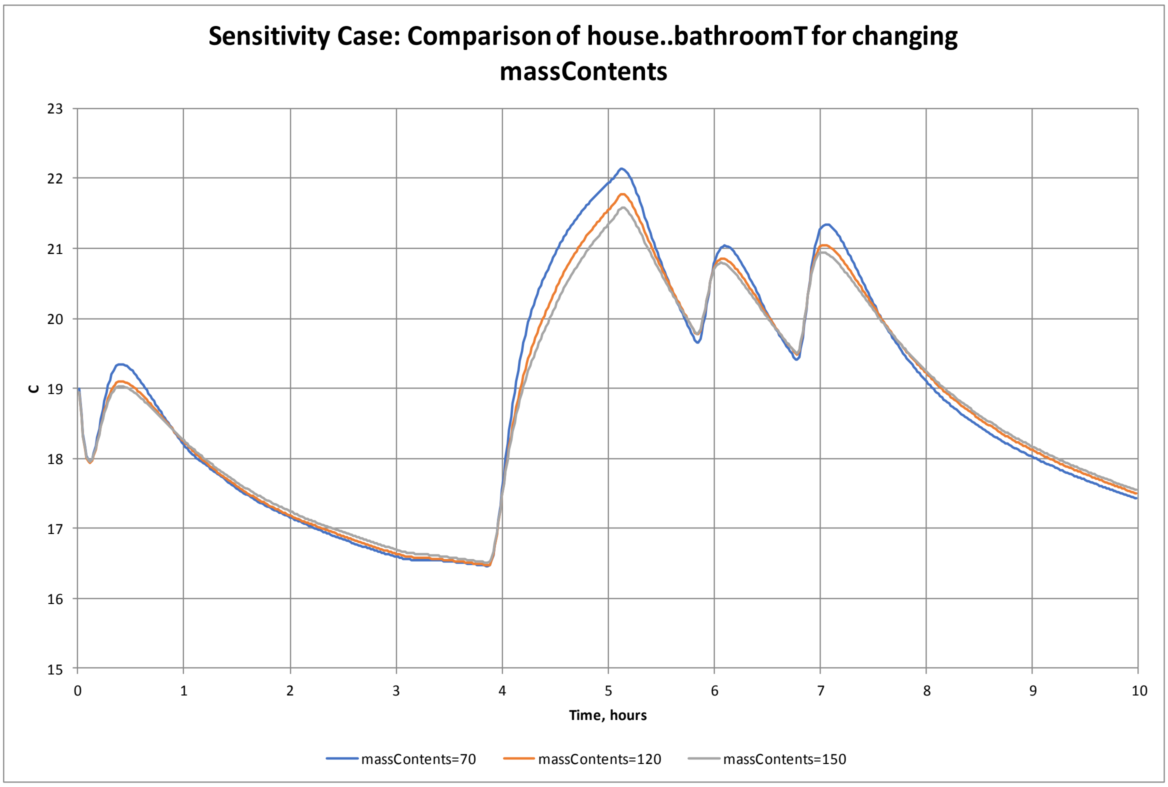

Figure A.7.8-7 Bathroom sensitivity to mass of solid contents over a number of heating/cooling cycles

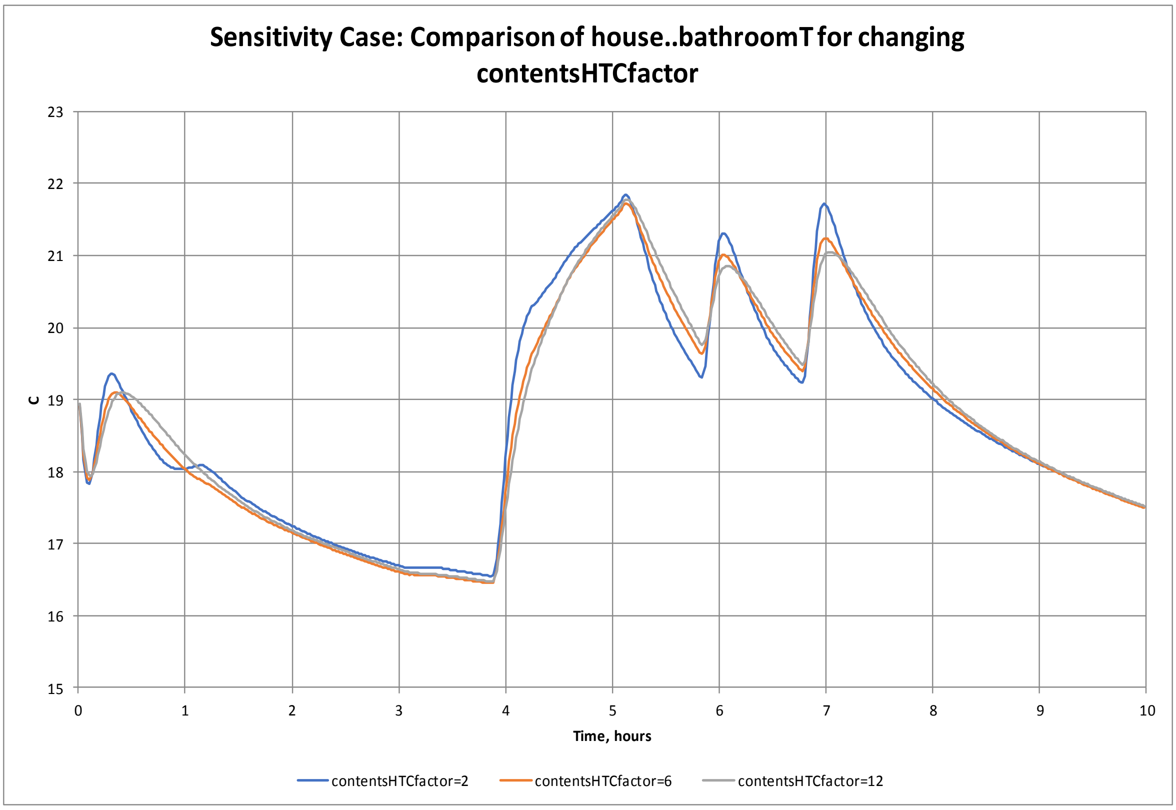

Figure A.7.8-8 Bathroom sensitivity to heat transfer to solid contents over a number of heating/cooling cycles

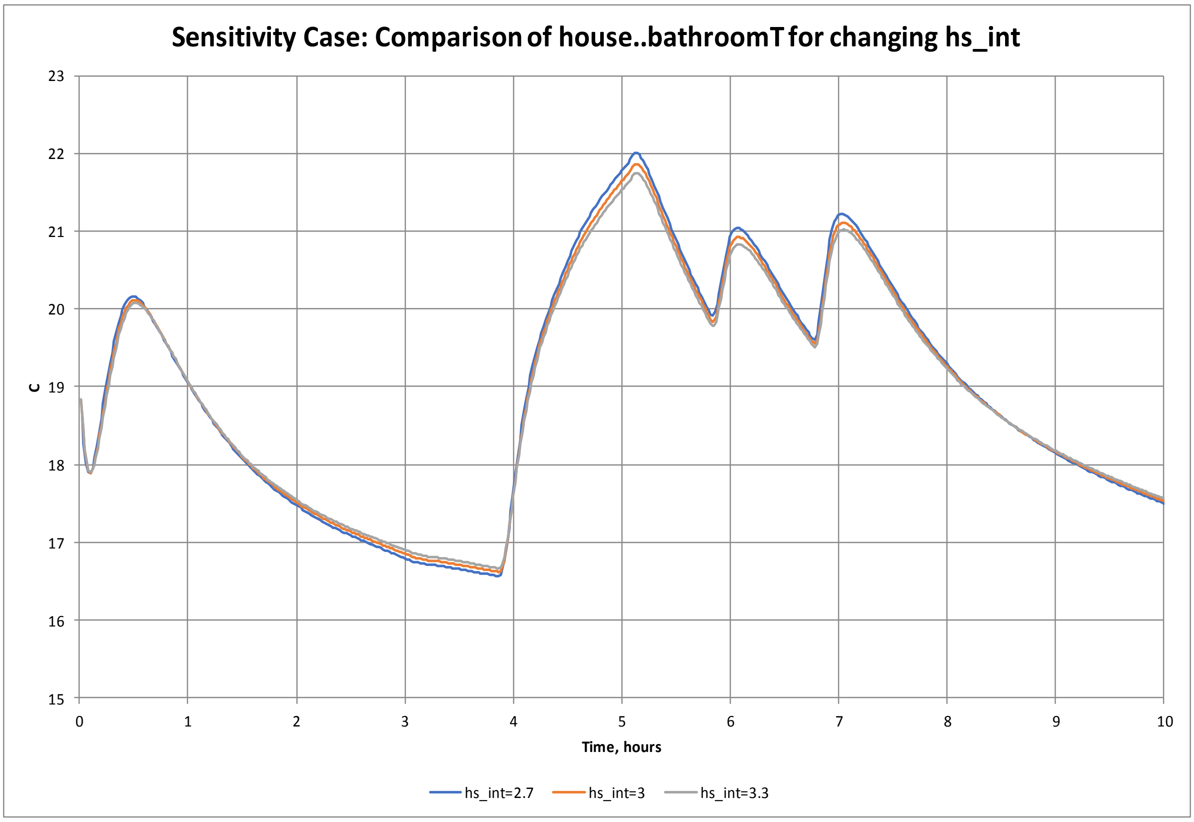

Figure A.7.8-9 Bathroom sensitivity to internal wall-air heat transfer coefficient over a number of heating/cooling cycles

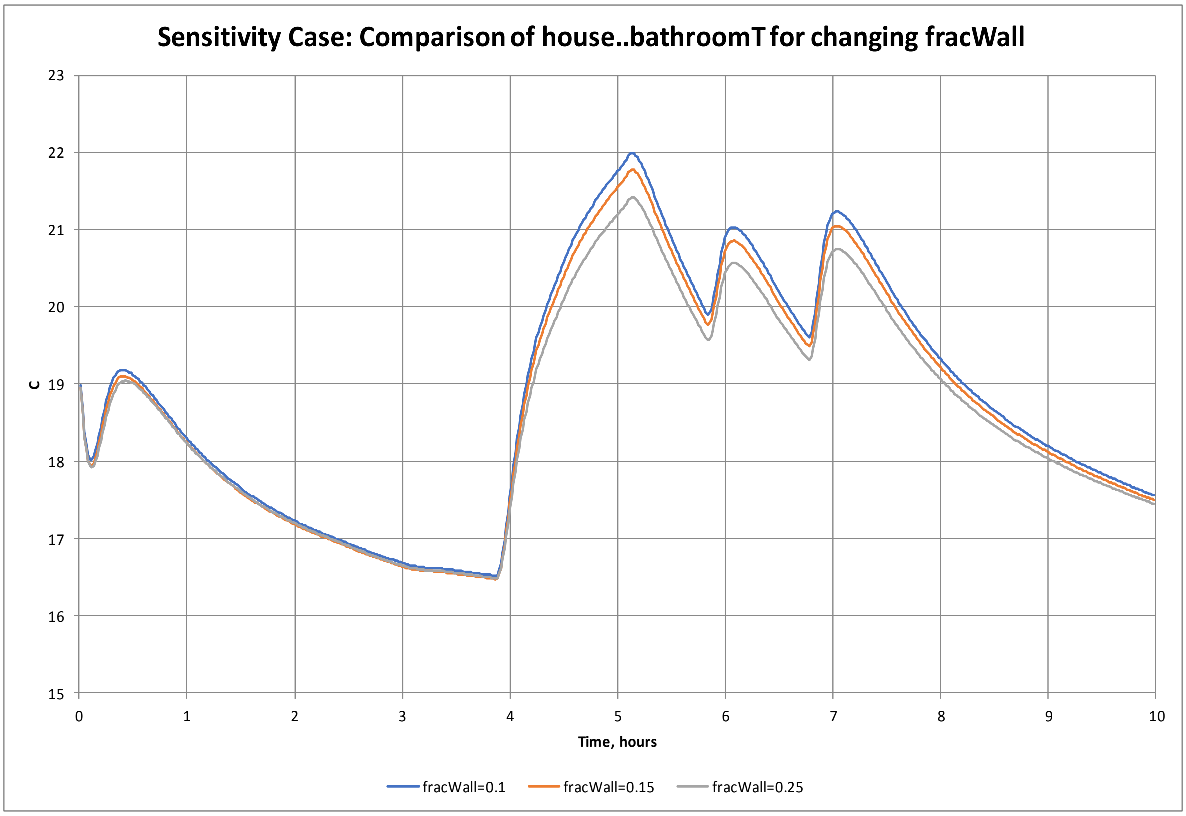

Figure A.7.8-10 Bathroom sensitivity to fraction of radiator power absorbed by adjacent wall over a number of heating/cooling cycles

A.7.9. Use of tuning parameters in other house models

Accurate data about ventilation and room contents will rarely be available for models of houses built from survey data. The sensitivity cases above indicate that these parameters can have a noticeable impact on warm-up times, while ventilation will also affect energy consumption. Peak temperatures will only be affected in cases where warm-up is too slow to reach the control setpoint before the heating cycle finishes.

When using IEHeat to make comparisons between heating performance with and without modifications to a dwelling, the choice of values for these parameters is not critical since they will have little or no impact on the differences observed between cases. The values chosen should be within credible ranges and it may be sensible to adjust the ventilation when making changes to building fabric that would reduce it (e.g. new windows or doors, suspended floor insulation etc.).

Typical values for air changes per hour can be found in published literature and can be estimated based on room type, building type and age, number of external walls, floor type, window or door age, type and size, etc. Values of air changes per hour between 0.1 and 1.5 would cover most situations in domestic dwellings.

Estimates of room contents mass can be made from the room type and usage, and typically ranges from 20 to 40 kg/m^2 [50] although special consideration should be made for kitchens and bathrooms and where this is being used to model internal features such as stairs and built-in cupboards. IEHeat now includes defaults for the room contents' heat transfer factors for different room types taken from the results of this work.

If absolute values of energy consumption, for example, are important (rather than just comparing differences) then tuning these parameters to match measured data or occupant experiences is recommended. If this is not possible then sensitivity analyses should be performed to evaluate the impact of the estimates made for these parameters.

A.7.10. Conclusions

This model verification exercise has achieved the following:

- The model components forming the IEHeat tool-kit have been tested in a full house context and improved
- Using the IEHeat tool-kit to build a model of a multizone house has been proven, with geometric simplifications having minimal impact on results (but these must be carefully chosen and considered when drawing conclusions from model results)
- It has been demonstrated that IEHeat can be tuned to match reality very accurately (albeit to only one house under a single set of test conditions)
    - Particular insights have been gained into the behaviour and set-up of radiator networks and the influence of common line pressure drops on radiator interactions
    - Results have illustrated the importance of air changes and solid room contents' properties to room temperature dynamics
- Tuning has been reduced to minimum set of parameters
    - Data available from surveys and built-in data (e.g. material properties, radiator power-size relationship) have been shown to be reliable for this case, with no indication that they may not be equally applicable to other housing archetypes
- Confidence has been gained in IEHeat's capability to generate sufficiently representative results, including interactions between components, especially for comparative evaluations of models of the same house with various upgrade options.

It is recommended that further verification exercises should be conducted as part of the future development of IEHeat.

[50] Hicham Johra, Per Heiselberg (2017) *Influence of internal thermal mass on the indoor thermal dynamics and integration of phase change materials in furniture for building energy storage: A review.* Renewable and Sustainable Energy Reviews 69 pp19-32

Appendix 8. Survey questions

In the course of conducting the Upgrade Analysis study, the following guidance has been developed identifying information that is important in the assessment of whether a technology is suitable for particular home. This section includes some technologies that were not evaluated for the pathways in this study (see section **4.1**).

For each technology that could form part of an upgrade pathway for a dwelling, the following list of information required from a survey will allow an assessment of whether that technology will be suitable for installation in that dwelling. Note that the survey will also involve producing a detailed plan and providing an overall description of the dwelling and its surroundings. If the dwelling has been modified (extended) then the survey should provide separate answers for each part of the building where necessary.

A.8.1. Air source heat pump

Outside the property

1) Identify all possible locations for a ASHP unit given the following criteria[51]:

    - A flat surface is required for the stable positioning of the ASHP (if a flat surface is not available, can the outside space be levelled to create a flat surface? – details)
    - Space must allow a unit to be installed approximately 1 m wide x 1 m high x 0.6 m deep (depending on size of the house), with space around it for air to flow and to allow installation and maintenance of a heat pump (approx. 2 m^3 of space)
    - The location must not block access routes (for cars on driveways, for wheelie bins, for people accessing back garden)
    - The location will ideally be close to the location where the boiler is installed (to make use of existing pipework to the radiator system. If it cannot be located close to the house, it must be possible to run pipework between the heat pump and the house (to the location of the boiler)
    - Take into account flood risk height requirement (see below).

2) Is there space for a van to access the property? – parking for a van?
3) Is there external access to the site of installation?
4) Are there existing sources of noise pollution at the site of installation?
5) Would the site of installation comply with criteria for permitted development?
6) Would the site of location have any visual or practical impacts on the use of that location?

Inside the property

7) Does the property have an existing wet radiator system? If so, provide details of number, size, type of radiators and type of control valves (if any), and mark on plan approximate piping routes and diameters.

[51] if on front 'in view of the highway', or within 1 m of neighbouring property, this would require planning permission to be sought, otherwise could be permitted development, https://www.planningportal.co.uk/info/200130/common_projects/27/heat_pumps/2

8) Where is the boiler located currently?
9) Age/make/model of boiler
10) Is there currently a hot water tank in the property? Where is that located? What is its size, material and level of insulation?
11) Is there space for the internal unit near the outside unit?
12) Are there features that aren't captured here which would mean installations would be more costly than usual

Desk top survey

13) Is the property in a flood risk location? (if so, ASHP unit should be mounted at height of 0.5 m above flood risk level)

Additional secondary survey

14) Perform pull out wall test (for if proposing wall mounted).

A.8.2. Ground source heat pump

Outside the property

Include outside areas in 'floor plan' including items / plant types in the garden

15) Area and description of land to front of the house – could a vertical or horizontal GSHP be installed here?
16) Area and description of land to rear of the house - could a vertical or horizontal GSHP be installed here?
17) Can you see neighbouring gardens/front of house? Are they similar or different – if different, a brief description of in what way
18) What type of road is outside?
19) Is there space for drilling/trenching machinery to access the garden
    - Is there any access route to the garden which is 2 m wide? (suitable for a drilling machine)
    - Is there any access route to the garden which is 1 m wide? (sufficient for narrower trenching or mini drilling machine)
    - Is the ground sufficient to take the load of a drilling or trenching machine?
    - Is there space for storing the dug-out earth?
    - Are there gate posts which could be removed to allow wider access?
    - Are there any man holes and indications of existing drainage, utilities or services runs?

Inside the property

20) Power into house – electricity system:
    - Has the consumer unit got additional capacity for additional electrical loads?
    - Where is the gas meter? Where is the electricity meter?
    - Where do the services (electrical, gas supply) come into the house?
    - Drain locations
21) Does the property have an existing wet radiator system? If so, provide details of number, size, type of radiators and type of control valves (if any), and mark on plan approximate piping routes and diameters.
22) Does the property have any underfloor heating systems?
23) Where is the boiler located currently?

24) Is there currently a hot water tank in the property? Where is that located? What is its size, material and level of insulation?
25) Is there space for an internal heat exchanger unit near the outside unit? [Approx 1 m^3 – just bigger than a condensing gas boiler + access] – or in a nearby outbuilding?

Desktop

26) Geological maps – ground type, water table, risk of cross-connecting different layers via bore-hole?
27) Is the land around the house large enough to lay horizontal or vertical pipes?
    - What is the width/length of garden?
    - What is the width/length of drive way / front of house? Include in the floor plan
    - What is the laying of the garden/driveway? (i.e. lawns, flower beds, trees, paving type or tarmac)

A.8.3. Hybrid Heat Pump

Outside the property

- As ASHP

Inside the property

28) Is there space near the existing boiler for a hydro box (about the size of a big toaster / small microwave)
29) Is there space around the existing boiler for pipework and valves to tie-in the heat pump?

A.8.4. Biomass Boiler

Outside the property

30) Is there a shed in the garden?
    - How big is it?
    - What is it filled with?
    - How much space is in it?
31) Is there a garage?
    - How big is it?
    - What is it filled with?
    - How much space is in it?
32) Is there space for a new fuel store in the garden?
    - How much space would be available?
33) Is there access to the shed/garage (i.e. for delivery of fuel)?
34) Can requirement of chimney be met?

Desktop

35) Are there local restrictions on solid fuel burners (e.g. on air quality grounds)?

A.8.5. High power radiators

Inside the property

In each room:

36) Size and type are each of the radiators / towel rails etc?
37) Location of radiators in rooms (description) (including towel rails and other wet system heat emitters)
38) Would larger radiators fit in the same location?
    - are the radiators closely surrounded by furniture, pictures, window sills etc?
    - How much larger? – what space (height/length/depth) would be available?
39) Is there furniture in front of existing radiators?
40) Distance of closest mains socket to each radiator
    - Is there a mains socket within 3 m?
41) Estimated age of radiators?
    - If the heating system was replaced, would you recommend the radiators be replaced?
42) Mark on plan approximate piping routes and pipe diameters. Are pipes concealed in walls or under floor boards?

A.8.6. Underfloor heating

Inside the property

43) What type of floor does each room have? (suspended timber, suspended concrete, solid concrete etc)
44) What is the state of each room? Sparsely filled --- Cluttered
45) How much furniture is in each room?
    - Sparsely filled --- full
    - Does any of the furniture appear to be high value / Antique furniture?
    - How much fitted furniture is in each room?
    - Would you expect that a household could clear the room themselves or would additional movers be recommended?
46) What is the floor covering?
    - Detailed description
47) Skirting board type – expensive to replace? Ornate?
48) Would raising the floor height be practical, and if so, by how much? – considering room height, resulting door heights, removal of skirting boards, relocation of electric sockets
49) Is there space for a manifold in a cupboard near the heating system installation?
50) What is the existing pipework routing for the wet radiator system? Could the new piping for the UFH system use the same routes?

Desktop

51) What zone locations would be allocated when fitting underfloor heating networks?

A.8.7. Cavity wall insulation

Outside the property

52) What type of wall construction does the property have? (including evidence for this if estimated?) If not the same on all walls, be clear of the construction of each wall
53) Is there evidence of cavity wall insulation already? If so, what and where?
54) Is access available to all external walls?

Further survey

Thermal imaging to see how well insulated.

Desktop

55) Is the property in a location that is likely to experience wind driven rain? If so, which wall is likely to be most susceptible?

A.8.8. External wall insulation

Outside the property

56) Are there any issues for erecting scaffolding?
57) What is the finish of each wall currently?
58) Are there any specific planning restrictions on the house?
59) What fixtures are on or close to each wall which would need to be moved and replaced?
60) Are there climbing plants on the walls?
61) Is there space to park a van?
62) Critical areas for thermal bridging
63) Surface covering of adjacent ground
64) Eaves depth
65) Where space around house is narrow, how wide is this space currently? (i.e. how wide is the access path around the side of the house?) – include in floor plan.

Desktop

66) How much space Is there for build-up (to 200 mm) to be added to each wall?
67) Is there space for 600 mm of scaffolding at each surface?

A.8.9. Internal wall insulation

Outside the property

68) Is there space to park a van?

Inside the property

69) What is the state of each room? Sparsely filled --- Cluttered
70) How much furniture is in each room?
71) How much fitted furniture is in each room?
72) What is the floor covering? Type, quality, edge conditions?
73) How intricate are external wall features?

74) How many pictures etc are fixed to the external walls?
75) What is the floor area of each room?
76) Are their radiators on external walls?
77) Are their electrical sockets on external walls?
78) Are there obvious reasons that space could not be lost from any external walls? What would be the limit?
79) Wall covering – wall paper?
80) Lime plaster or gypsum plaster
81) Are utilities boxed in running along external walls (i.e. would services need to be moved?)
82) Is there evidence of damp? Where, what evidence?
83) Is there evidence of condensation? Where, what evidence?

A.8.10. Floor insulation

Outside the property

84) Is there space to park a van?
85) Are there visible air bricks?
    - How many vents?
    - Where are they located?
86) Is there clear access to the ground adjacent to external walls (to allow insulating trenches to be installed, approximately 300 mm wide from the base of the walls)?

Inside the property

87) Is there floor insulation already?
88) What type of floor does each room have? (suspended timber, suspended concrete, solid concrete etc)
89) What is the state of each room? Sparsely filled --- Cluttered
90) How much furniture is in each room?
91) How much fitted furniture is in each room?
92) What is the floor covering? (how susceptible to damage?) – how new? cost to replace?

Later survey

93) Floor joist depth.

A.8.11. Roof insulation

Outside the property

94) Is there space to park a van?
95) Is there space for scaffolding up to the roof (if no internal access, e.g. flat roofs)?

Inside the property

96) Is there a roof on the property?
97) How much insulation is there already?
98) Where is the insulation? Joist or rafters?
99) Is there a loft?

If there is a loft…

100) Is there an access route to the loft?
101) Size of loft: height / form
102) Is the loft used for storage? How much stuff? (lots, some, none)
103) Are the items being stored susceptible to damage from being cold/damp?
104) How much headroom does the loft have?
105) If there is already some insulation, do the edges (golden triangle?) correctly allow ventilation?
106) Is the roof lining made from sarking felt or a breathable alternative?
107) Would you consider the loft to be suitable to be converted to a living space in the future?
108) Is there a water tank in the loft (or equivalent)?
109) Is the loft boarded?

If no loft…(assuming there is a room in the roof space / flat roof)

110) On what time scale is the roof likely to be replaced?
    - i.e. What material is it? Quality of the roof. Is it obvious when it was last replaced? Are there any roof related damp problems existing?
111) Max / min height of room in roof (to be marked on floor plan)
    - i.e. of areas which are used space
112) Is there a dormer window?

A.8.12. Windows/doors

Outside the property

113) What type of glazing does the dwelling have at present? How old (if judgement can be made)?
114) Is there space for a van?
115) Description of existing windows
    - What material are the existing window frames made from?
    - What appearance do the windows have? (i.e. from colour of frame to whether the double glazing is leaking moisture with internal condensation)
116) Description of existing external doors
    - What material are the existing external doors made from?
    - What appearance do the external doors have?
117) Are there potential security issues with the existing windows or doors?

Inside the property

118) How much disruption would be caused by clearing the area around each window in each room? (easy/no disruption ---rooms are cluttered=high disruption)

119) Intricacy of framing around windows internally – would it require much work to make good following installation?
120) Gap between glazing panes
121) Are they original or replacement windows?
122) Would replacing a glazed door with one with less glazing cause unacceptable reduction in light?

A.8.13. Ventilation

(incl. MVHR, single room heat recovery, positive input ventilation, natural ventilation/passive stack)

Inside the property

123) Are means of ventilation currently visible? Windows open, trickle vents, extractor fans?
124) Is there a location available for a large heat exchanger unit?
  - Needs to be easily accessible. Potentially in loft (if warm loft)
  - Needs to be close to existing or suitable location for new hole in wall for incoming/outgoing air

125) Location of all existing 110 mm through the wall vent holes
126) Is loft space available above a central point in the house e.g. top of the stairs?
127) Does the house have fireplaces? In which rooms? Are they open or closed?

Desktop

128) Is there an obvious route for ducting between rooms? – from floor plans
  - Sucking in air from bathroom/kitchen, outputting warm air to living areas

129) Does the house have a chimney? Which rooms does it go through?

A.8.14. Heat network / district heating

Applies in urban areas which may be suitable for heat networks in future.

Outside the property

130) Distance from street to front of the house [m]?
131) Distance from pathways at back of house if applicable (if there is an obvious route that a heat pipe could be laid)
132) Is there an obvious path for pipes between street and front of house? (i.e. ground that will not be too negatively affected by digging a trench?
133) Would planning permission be required to build localised generation (i.e. on roof of flats)?
134) Who is presumed to own the land between the building and the street (particularly for flats)

Inside the property

135) Does the dwelling already have a wet radiator system? Give details (see above)
136) How far is the existing boiler from the likely location of a heat interface unit?
137) Are there suitable pipe routes to connect the HIU with the existing piping?

Local to the property

138) If property is a flat/multiple occupancy building: is there space/a recommended available route for the main riser?

Desktop

139) Type of location (Local density of houses): urban, suburban, rural

A.8.15. Thermal storage

Inside the property

140) Does the property currently have a hot water tank?

If so,

141) Is there evidence that the tank still being used for hot water?
142) What are the dimensions of the tank? (diameter, height, state whether this is inclusive of insulation of not)
143) Where is it located (mark on floor plan)?
144) Size of location (i.e. dimensions of cupboard)
145) What else is in the cupboard? (i.e. is it full of other stuff or would there be room for a larger tank in the same location?
146) Of what material is the tank made (e.g. copper, stainless steel)?
147) Is the tank insulated? How thick is the insulation? What type of insulation (foam / jacket etc)
148) What controls does the tank have?
149) How is the water heated? E.g. is there an internal coil fed by a gas boiler or immersion heater etc?

If not,

150) Does the dwelling have a cupboard which looks as if it previously housed a hot water tank? If so:
- Where is it located (mark on floor plan)?
- Size of location (i.e. dimensions of cupboard)
- What is currently kept in the cupboard?

151) Does the house have an under stairs cupboard? Or small toilet room?
152) Are there other spaces in the property which could house hot water storage?
- Where are they?
- How big is the space? (what size of tank could it contain)
- What is there currently?
- How would it affect the aesthetics of the location?

A.8.16. Solar PV / Thermal

Outside the property

153) Does the property have a roof (and freehold to the roof)?

If yes:

154) Surface area of most south facing roof surface(s) (estimate)
    - If most south facing roof surfaces are split, please give details of different sections
155) What proportion of the roof does this represent? (or what is total surface area of roof (estimate)?
156) Orientation of this part of the roof
157) Pitch of this part of the roof (estimate)
158) Estimated shading of this part of the roof
159) Is this part of the roof street facing or otherwise visible by local residents etc.?
160) Material of roof covering
161) Are there any reasons to expect that the roof might not be suitable for solar panels? If so, please explain
162) In what time scale is it expected that the roof might be replaced?
163) For PV: are there spaces for inverters, cable runs, tie-in with existing consumer unit (typically needs a 16A supply slot to connect into)?
    a. Can they fit into loft space?
    b. Is consumer unit on external wall (i.e. allowing cable runs between inverter and consumer unit?
    c. Is there space for the generation meter near the consumer unit and existing meter?

Inside the property

164) For thermal: is there space for the expansion tanks and pump near to the roof? (i.e. in loft or in room in roof)

Local to the property

165) Do other properties nearby/on the same street have solar PV or solar thermal?

Appendix 9. Technology suitability summaries

For each house the information gathered from surveys was combined with the "pastiche" of householder requirements to assess the suitability for each upgrade technology. The following tables are colour categorised as follows: red = not suitable, orange = possible but not practical, yellow = practical, green = easy, no colour = no category assigned at this stage. This assessment is a filtering exercise prior to quantitative analysis by simulation, and does not consider effectiveness.

Table 8-1 House A (1950s semi-detached) technology suitability

Technologies		Building related criteria	Household related criteria
Heat generation	**ASHP**	*One of EPN recommended technologies* • The best location for an ASHP would be on the front of the house under the bay window, with partial removal of the hedge; this would allow for routing of pipes through the external wall directly into the WC/utility where the boiler is currently located. However, as this would be visible from the 'highway', it would require planning permission. • A visual blocker could be used to mitigate the visual impact of installing the unit on the front of the house. • There is room for the internal unit in place of the boiler in the downstairs WC/utility room but it would be visually on display like the boiler is currently and may be objectionable to some. The internal unit could be located more subtly out of view with the movement of furniture in the WC/utility room.	• The householders are sensitive to aesthetics and think it's important for technologies to *"look really cool"*. Would prefer technologies to "*look really super modern"*. This has implications on the heat pump as both the internal and external units may have to be visible rather than hidden out of sight. • Responsiveness of heating system is important - if it doesn't heat up quickly, the householders are likely to improvise by using secondary heating. This may compromise on the low carbon intentions of the upgrade pathway
	GSHP	• The back yard is just large enough for vertical borehole installation, however access to back garden would require rebuilding fence all along beside back garden. Land is owned by the council, therefore negotiation would be needed to understand the house's potential for this. • A more suitable location for a GSHP would be at the front, where there is sufficient ground area to install boreholes in the front lawn.	• The householders are sensitive to aesthetics and think it's important for technologies to *"look really cool"*. Would prefer technologies to "*look really super modern"*. This has implications on the heat pump as both the internal and external

		• The lawn extends across 4 neighbouring houses and therefore an option for reducing the cost of installation is for all houses to dig boreholes in their gardens at the same time or for one GSHP to be shared between them. • For external installation in the front garden, the internal unit could be located in the WC/utility room in place of the boiler or less conspicuously with the re-arrangement of furniture (as for the ASHP)	units may have to be visible rather than hidden out of sight. • Responsiveness of heating system is important - if it doesn't heat up quickly, the householders are likely to improvise by using secondary heating. This may compromise on the low carbon intentions of upgrade pathway
	Hybrid Heat Pump	*One of EPN recommended technologies* • If a heat pump were installed, there is sufficient space in the WC/utility room for this to be installed alongside the existing boiler above the sink or for a larger single hybrid heat pump unit to be installed. • It would be visually obvious in downstairs WC / utility room and may require moving furniture around.	• Householders are sensitive to aesthetics and think it's important for technologies to *"look really cool"*. Would prefer technologies to "*look really super modern"*. This has implications on the heat pump as both the internal and external units may have to be visible rather than hidden out of sight.
	Biomass Boiler	• There is already a shed which could house a biomass boiler and store fuel, however, the shed would no longer be available for storage as is its current usage. • There is potential that in the long term outside space could be used. • Delivery of fuel would be restricted to the rear garden as access route is only 1.27m wide.	• Household's priority for convenience is not compatible with a biomass boiler. Control over cost is also a priority, and this is uncertain over future years with biomass.
	Solar thermal	• *This is possible, in conjunction with hot water tank/thermal store. Half the roof faces SW.*	• Household has high hot water demand throughout the year • Technologies which require little regular interaction are likely to be acceptable to householders, especially if they can see that they are making money from the investment. • Availability of data on performance would also be of interest.
	District heat network	• Not identified as an appropriate geographical location for a heat network • Heat exchanger could be located in WC/utility room and could feed straight in to existing hot water system.	• Technologies which require little regular interaction are likely to be acceptable to household.

		• Pipe to house could be buried under lawn therefore avoiding long term aesthetic change. • Local area not suitable for district heat network, (however a local network with nearby houses sharing a large GSHP or similar technology may be more likely).	
Heat emission	**High power radiators**	• There is sufficient space for the installation of larger radiators in all rooms of the house apart from the living room	• Householders may be reluctant to install new, larger radiators due to the aesthetics, unless they can be designed in such a way that "*look really cool/super modern*"
	Underfloor heating	• Due to the solid floor, underfloor heating would be possible but not practical. Height in the downstairs rooms and extension is limited, so a reduction is likely to be quite noticable to the household. • The solid ground floor could be dug out, but this would cause significant disruption to the household during installation.	• Technologies which require little regular interaction but will deliver benefits against the household's priorities of comfort and convenience are likely to be acceptable to household. • Responsiveness of heating system is important - if it doesn't heat up quickly, the householders are likely to improvise by using secondary heating which may compromise on the low carbon intentions of upgrade pathway
Building fabric	**CWI/SWI**	• Although the large gable end cavity wall has been insulated before, survey showed fewer holes than expected and therefore there is uncertainty about whether it is fully and comprehensively insulated. It is SE facing and therefore may be less likely to experience wind driven rain. Front and back walls have no sign of insulation. • If the tiling on the front of the house means cavity wall insulation is not viable, the front wall would require external wall insulation which would need to fill the gap between blockwork and the tiling with tiles replaced afterwards. • Hedge by front would need to be removed to allow for scaffolding.	• Technologies which require little regular interaction but will deliver benefits against the household's priorities of comfort and convenience are likely to be acceptable to household. • If interventions are high cost and unlikely to give a financial return when the house is sold, the current householders are unlikely to be willing to make the investment.
	Floor insulation	• Due to the solid floor, underfloor heating would be possible but not practical. Height in the downstairs rooms and extension is limited, so a reduction is likely to be quite noticable to the household.	• Technologies which require little regular interaction but will deliver benefits against the household's priorities of comfort and

		• The solid ground floor could be dug out, but this would cause significant disruption to the household during installation.	convenience are likely to be acceptable to household.
	Roof insulation	• The loft currently has insulation between the joists (75mm), but it is not as thick as regulation standard therefore there could be benefit from increasing this insulation depth. • The loft is currently very full and therefore a large number of stored items would need to be moved to allow for insulation.	• Technologies which require little regular interaction but will deliver benefits against the household's priorities of comfort and convenience are likely to be acceptable to household.
	Windows	• Apart from the rear extension, all windows are double glazed, but with pre-2002 glazing.	• Technologies which require little regular interaction but will deliver benefits against the household's priorities of comfort and convenience are likely to be acceptable to household. • If interventions are high cost and unlikely to give a financial return when the house is sold, the current householders are unlikely to be willing to make the investment.
	Ventilation	• Extractor fan in kitchen and bathroom are adequate; heat recovery could be added.	• *Householders regularly open windows for ventilation and value fresh air in bedroom while asleep, even when it is cold outside*
Heat storage	**Hot water cylinder**	• There are cupboards on the first floor landing (1.2m x 7.9m and 9.5m x 7.9m) and an understairs cupboard (10.5m x 5.7m) that could be used for thermal store/hot water tank. • With movement of furniture, thermal storage could also be located in the WC/utility room.	• Householders have a large hotwater demand, especially on a Sunday with daughter's preference for a 40 minute hot shower.
Heating control	**Multizone heating control**	• All radiators have a TRV, but due to the age of the radiators, these do not have the standard 30mm threaded base to be compatible with the connector of a modern radiator valve and therefore a wet install procedure would be required (involving draining the radiator circuit and new valves put in place on each radiator).	• Householders have significant frustrations with existing control and are excited about the opportunities which a modern controller could provide.

Table 8-2 House B (1920s mid-terrace) technology suitability

Technologies		Building related criteria	Household related criteria
Heat generation	**ASHP**	• An ASHP could be located at the rear of the house on the kitchen side wall. There is sufficient space that the external unit would need to be located under a window, but may benefit from additional investigation relating to the drains and airbricks around that location. • This location is close to the existing boiler and therefore could be plugged into the existing radiator pipes. • There is not currently space in the kitchen for the heat exchanger unit, but this could be located in the upper floor bathroom which is where the boiler is currently, or in the shed.	• The occupant wouldn't be happy with something that looks 'ugly' or 'clunky'; external unit may need to be hidden by garden trellis or similar. • Investment case would be weak if occupant decides to move after around 5 years. This could be addressed with a finance model which ties the investment to the house or some external party.
	GSHP	• Back garden is barely large enough for GSHP, though there is an access route to the back garden which is large enough for a small drill rig (1.8m wide). • Garden is laid with grass lawn so it would be possible to make good following drilling without permanent damage. • Burying pipes to lead to house would require lifting concrete slabs and making good after. • Internal heat exchanger unit would need to be located in shed (currently filled with tools), or in bathroom cupboard (meaning pipe run would be 13m horizontal +3m vertical).	• The occupant wouldn't be happy with something that looks 'ugly' or 'clunky'. • Investment case would be weak if occupant decides to move after around 5 years. This could be addressed with a finance model which ties the investment to the house or some external party.
	Hybrid Heat Pump	• Limited space currently for ASHP internal unit in addition to existing boiler. • Would have to rearrange furniture in the kitchen to fit internal unit in addition to boiler as well as hydrobox unless these units could be stored in the shed or similar external location (sufficient outside area to facilitate this).	• The occupant wouldn't be happy with something that looks 'ugly' or 'clunky'; external unit may need to be hidden by garden trellis or similar. • Investment case would be weak if occupant decides to move after around 5 years. This could be addressed with a finance model which ties the investment to the house or some external party.

	Biomass boiler	• There is already a shed which could house a biomass boiler and store fuel, however, the shed would no longer be available for storage as is its current usage. • Delivery of fuel would also be restricted to the rear garden as access route is only 1.8m wide.	• Would appeal to owner's interest in environmental issues. • Provides assurance that comfort can be rapidly achieved for guests.
	Solar thermal / PV	• Rear pitch of roof has south-west orientation. Slates are in good condition; 20 m^2 circa for the main roof, plus 9 m^2 for the rear wing. • Erecting scaffolding to access this part of the roof is likely to present difficulties.	• The occupant thinks it's important to be environmentally conscious so may be pro-renewable generation. • Sensitive to aesthetics so unlikely to have panels on the roof if he thinks they look 'ugly'.
	District heat network	*Recommended technology based on EPN analysis* • Short distance from house to secondary road therefore assume that connection to heat network would be possible. • The heating network would need to be extended to the rear of the house (internally if the heat interface unit can be installed at the front of the house) and this could be more problematic.	• Likely to be happy to be involved in district heating scheme if it is going to reduce CO_2 emissions of his heating. Heat exchanger unit would have to be hidden as he'd not be happy with it if it looks 'ugly' or 'clunky'.
Heat emission	**High power radiators**	• Living room radiator is boxed in; most of the radiators could be replaced with larger ones in the same location.	• The occupant wouldn't be happy with something that looks 'ugly' or 'clunky', but likely to be accepting if they look inconspicuous.
	Underfloor heating	• Due to suspended timber floor, underfloor heating would be a possible option (except in the kitchen). The floor coverings are quite new but not of high value and therefore would not be a barrier to replacement. • Solid stone floor in the kitchen would make underfloor heating in there impractical.	• Underfloor heating is likely to be a more attractive prospect that larger radiators as it would not be obvious. • Likely to enjoy showing benefits off to friends if he got underfloor heating.

Building fabric	**CWI/SWI**	• House has no cavity walls • The finish of the walls at the rear of the house is in need of improvement and therefore this could be a good opportunity for external wall insulation. • A number of architectural features on the front of the house would make external cladding difficult and at risk of thermal bridging. Internal insulation more suitable for this side of the house.	• Investment case would be weak if occupant decides to move after around 5 years. This could be addressed with a finance model which ties the investment to the house or some external party.
	Floor insulation	• Due to suspended timber floor, underfloor insulation would be a possible option. The floor coverings are quite new but not of specifically high value and therefore would not be a barrier to replacement.	• The occupant has already benefitted from warmer ground floor having laid carpet. If significant benefits are offered by underfloor insulation too, he is likely to be interested.
	Roof insulation	• Current level of insulation is less than building standards recommend and therefore this could be topped up to improve fabric efficiency. • An extension to the current boarding would be required to allow storage to remain in the loft. • It should be a priority to maintain ventilation in cold roof space. • Increased insulation may make storage of items less possible.	• The occupant likes to avoid wasting energy so if additional roof insulation is shown to be beneficial, he is likely to put it in despite the hassle.
	Windows	• Windows are double glazed throughout, however, it appears the quality of the fit is not very high and they are over 15 years old so they are likely to need replacing over the next 20 years.	• Investment case would be weak if occupant decides to move after around 5 years. This could be addressed with a finance model which ties the investment to the house or some external party.
	Ventilation	• Ventilation currently achieved using windows and kitchen door.	• The occupant likes to freshen up the house and avoid stale air. • Uses window opening as a mechanism for cooling down a room quickly, like if it's too warm to go to sleep (so may find mechanical ventilation annoying and restrictive).

Heat storage	**Hot water cylinder**	• The cupboards under/above the stairs are currently used for storage. • Boiler is currently located in a cupboard in the bathroom, which could be a space for a hot water tank if the boiler is removed.	• Limited storage space in house.
Heating control	**Multizone control**	• All radiators are compatible with WRVs except for bathroom radiator.	• Likes the idea of being able to control heating differently in different rooms. • Likes the idea of heating control tracking his location and heating up accordingly.

Table 8-3 House C (1930s semi-detached) technology suitability

Technologies		Building related criteria	Household related criteria
Heat generation	**ASHP**	*One of EPN recommended technologies* • The best location for an ASHP would be on the back wall of the house outside the kitchen, or on the front of the house with a narrower garage door. • There is space in the utility/garage room for the internal unit.	• Technology adopter – enthusiastic about having a 'thing of the future'. • Desire to avoid energy waste may translate to enthusiasm for a highly efficient technology (getting more energy out than you put in). • They are likely to be hands-on about making the heat pump work well for them, i.e. if different control approaches are required.
	GSHP	• The back garden is of ample size to drill vertical boreholes, and the surface covering of a lawn would allow minimal effect on the visual nature of the garden. • No access to the back garden and therefore a GSHP is not a suitable technology. • There is possibility that if a neighbour were to have access for drilling machinery to their back garden, the machinery could be brought in this way with the temporary removal and subsequent replacement of the fence.	• Technology adopter – enthusiastic about having a 'thing of the future'. • Desire to avoid energy waste may translate to enthusiasm for a highly efficient technology (getting more energy out than you put in). • They are likely to be hands-on about making the heat pump work well for them, i.e. if different control approaches are required.
	Hybrid Heat Pump	*One of EPN recommended technologies* • There is sufficient space in the utility room/garage to install the internal unit of the heat pump alongside the existing boiler, or to install a single, combined unit.	• Technology adopter – enthusiastic about having a 'thing of the future'. • Desire to avoid energy waste may translate to enthusiasm for a highly efficient technology (getting more energy out than you put in). • They are likely to be hands-on about making the heat pump work well for them, i.e. if different control approaches are required.

	District heat network	• Not an appropriate geographical location for a heat network. • Buried pipework would cross tarmac driveway and would therefore make a visual mark.	• The householders are likely to be enthusiastic about joining a district heating scheme as it is a new technology which would enable them to have low carbon heating.
Heat emission	**High power radiators**	• Radiators in most rooms could be replaced with larger radiators. There would be difficulty in the master bedroom as the size available is restricted by the size of the bay window in which it is located.	• Likely to accept house modifications to ensure they are not wasting energy and their comfort is maximised.
	Underfloor heating	• The original parts of the house have a suspended floor and could therefore be suitable for underfloor heating. • Newly laid floorboards through living room and hallways would need to be raised which could prove expensive to replace.	• The householders are very proud of the oak flooring in the living room and hallway, and unlikely to agree to this being lifted to put underfloor heating in.
Building fabric	**CWI/SWI**	• Walls are solid brick and therefore cavity wall insulation is not applicable. • External wall insulation could not fit on the end wall ground floor. Is likely to be more worthwhile installing internal insulation here. The end wall first floor is exposed but cannot be reached apart from by the flat roof of the extension (utility/garage). There is no external access to the back garden and therefore installation of scaffolding on the back wall for external insulation would be difficult. Fitting external wall insulation to the front façade would be complicated due to traditional style of the house and at risk of thermal bridging. Without also insulating the neighbouring house, external wall insulation would be conspicuous. • There are no major barriers to internal wall insulation, as many of the period features of the house have been modernised. The only inbuilt furniture is in the kitchen and bedroom 1. Before internal wall insulation is introduced, a decision would need to be made as to whether the utility/garage should be either heated/insulated or excluded from the thermal envelope. • There have been ongoing problems of damp with exposed walls in small bedroom and around bay window of master bedroom.	• The household has already made changes to the house to combat the problem of damp in the smallest bedroom, and this suggests they would be open to making additional changes if it would make a demonstrable difference to their energy usage or comfort.

	Floor insulation	• The house has a suspended floor and would therefore be suitable for underfloor insulation. • Newly laid floorboards through living room and hallways would need to be raised which could prove expensive to replace (unless insulation could be installed using non-disruptive technology.	• The householders are very proud of the oak flooring in the living room and hallway, and unlikely to agree to this being lifted to put underfloor insulation in. Only possible if installed using non-disruptive technology.
	Roof insulation	• Existing insulation is 75mm between joists which is less than currently recommended by building regulations. There is potential that if the loft were further insulated, some items being stored would be susceptible to damage due to the roof space being colder.	• The householders have made changes to their home to improve comfort and reduce energy wastage, even if it has resulted in disruption. Therefore it is highly likely that the household would be willing to improve the insulation in the roof if significant benefits are predicted.
	Windows and external doors	• Windows are all uPVC double glazed. • Described by the household as 'quite new, so likely to have been installed since 2010. • There don't seem to be any reasons for replacement to be complicated.	• The householders have made changes to their home to improve comfort and reduce energy wastage, even if it has resulted in disruption. Therefore if window improvements are deemed to offer benefits to energy saving or comfort at a reasonable price, they are likely to be willing to put up with the disruption. • Their sensitivity to wasting energy is linked to not wanting to waste money. Householders are numerically astute and quite rational. Therefore any investment in building fabric upgrades which will offer a saving in their energy bills is likely to be adopted based on its payback period.
	Ventilation		• Currently open all windows for 10 minutes every morning as they like fresh air going through the house. • Have made their own efforts to reduce draughts and therefore they are likely to make required changes to their behaviour to ventilate in an appropriate way (for example to work with mechanical ventilation) if the house is made air tight.

Heat storage	**Hot water cylinder**	• There is currently space in the utility/garage for a tank or large thermal storage capacity. There is also an under-stairs cupboard, but this is full of stored items including shelves which reduce the full height space.	• As there is space available for a typical hot water tank which would not severely compromise the existing storage space, the household is unlikely to block the installation of appropriate thermal storage.
Heating control	**Multizone control**	• All radiators have compatible valves for the attachment of wireless radiator valves.	• Technology adopter – enthusiastic about having a 'thing of the future'. • Currently hold frustrations about their existing heating control not being able to provide a consistent temperature throughout the house.

Table 8-4 House D (1970s mid-terrace) technology suitability

Technologies		Building related criteria	Household related criteria
Heat generation	**ASHP**	*One of EPN recommended technologies* • There is not space for an external unit on the front – the windowsill is at a height of 0.52m and therefore not sufficient space for it to be installed under here. • At the back, there is space for installation of the external unit either against the kitchen wall or against the low wall leading to the higher portion of the garden. The location of drains and waste water pipes prevent the kitchen wall being an easy location for the external unit. • The boiler is located in the adjacent corner of the kitchen and therefore this location is beneficial for feeding into the existing wet radiator system. There is potential for the internal unit to be located where the existing boiler is (perhaps requiring extension of the current boiler cupboard). Alternatively, the internal unit could be located outside.	• Provided the end result is cosy heat and is controllable, and someone else will deal with the hassle, the household would have no barriers to adoption. • Desire not to waste energy may be a trigger to adopting a more efficient heating system, but they are unlikely to do so of their own initiative.
	GSHP	• There is likely to be sufficient space in the back-garden for vertical boreholes, and there is sufficient access via an alleyway at the back of the terrace. Much of the back garden is grass and therefore would not have long term damage from the boreholes, however there is paving for the rear 2.8 m and if the boreholes need to be this far back, the damage would be visible long term unless new paving was laid. • There is a large grass area forming a common green around which the terraces are built. Another option would be for a communal ground source heat pump project to be undertaken which could feed many houses in this area and reduce the price per house compared to individual installations. For this option, the hot water would feed in to the front of the house and would require a new routing of the wet radiator network water piping.	• Provided the end result is cosy heat and is controllable, and someone else will deal with the hassle, they would have no barriers to adoption. • Desire not to waste energy may be a trigger to adopting a more efficient heating system, but they are unlikely to do so of their own initiative.

	Hybrid Heat Pump	• Due to limited space in the kitchen, there is not sufficient space to install an internal heat pump unit and hydrobox alongside the existing boiler in the kitchen. There is space in a downstairs cupboard to house the additional equipment required.	• Provided the end result is cosy heat and is controllable, and someone else will deal with the hassle, they would have no barriers to adoption. • Desire not to waste energy may be a trigger to adopting a more efficient heating system, but they are unlikely to do so of their own initiative.
	Solar thermal	• Back of house faces south west and therefore this would be the preferred side for solar thermal or PV. The roof has nailed on tiles in a fair condition. The surface area available is approximately 25 m^2.	• Provided the end result delivers hot water when they want it, and someone else will deal with the hassle, they would have no barriers to adoption. • Desire not to waste energy may be a trigger to adopting a more efficient heating system, but they are unlikely to do so of their own initiative.
	District heat network	• Not an appropriate geographical location for a heat network. • The house is far from the nearest secondary road, but close to the tertiary road of the estate. The most suitable space for the heat exchanger may be beside the front door in place of the electricity meter which is currently located there, if the heat network were to run to the front of the house. • If the network ran to the rear of the house, the heat exchanger would best be located in place of the current boiler, provided the wall attachment can be made sufficient to withstand the weight.	• Provided the end result delivers cosy heat and is controllable, and someone else will deal with the hassle, they would have no barriers to adoption. • Desire not to waste energy may be a trigger to adopting a more efficient heating system, but they are unlikely to do so of their own initiative.
Heat emission	**High power radiators**	• Most radiators could be replaced with larger ones in the same location.	• Due to bad experience with warm air ducted heating, they may be cautious of having radiators which deliver a lower temperature unless they can be guaranteed that they will still be sufficiently cosy in the living room.

	Underfloor heating	• The house has a solid ground floor, and the downstairs ceiling is already quite low (2.24 m, lower than the upstairs floor to ceiling height of 2.32) therefore for underfloor heating to be installed would require digging down into the solid floor. • There are a mix of floor coverings - exposed floorboards, tiles, laminate flooring and carpet – none of which appear to be valuable and would not be an issue to replace.	• Due to bad experience with warm air ducted heating, they may be cautious of having radiators which deliver a lower temperature unless they can be guaranteed that they will still be sufficiently cosy in the living room. • High amount of disruption during installation is likely to put household off wanting underfloor heating.
Building fabric	**CWI/SWI**	• Cavity wall – the walls have a brick and block construction and there is no evidence that the cavity has been filled. Filling the cavity may be more challenging due to the hanging tiles design of the first floor front and back façade. The cavity may not be suitable for insulation if it is too narrow for sufficient benefit, if the construction is such that damp problems may occur, or if the cavity has been poorly filled previously. • External wall - If the cavity is not suitable to be insulated, there is theoretically space at the front and back of the house for external wall insulation. Services would need to be moved including the gas meter and rainwater pipes to the front and security light, tap, draining and satellite dish to the rear. There is a low hedge and gables supporting the front window which can be assumed to be weight bearing and would present thermal bridging risk. Eaves overhang is approximately 150mm. • Internal wall – As the house is mid-terrace, there would only be two walls to insulate, and windows and doors take up much of the façade. Internal insulation in the kitchen would be difficult due to large window and door and fitted furniture. Internal wall insulation in the first floor would require moving the radiators, as well as the bath, sink and toilet in the bathroom.	• Provided the end result delivers cosy heat and is controllable, and someone else will deal with the hassle, they would have no barriers to adoption. • Desire not to waste energy may be a trigger to adopting insulation, but they are unlikely to do so of their own initiative.
	Floor insulation	• The solid floor and low height of the ceiling in the ground floor would mean that underfloor heating would be disruptive and would require digging down into the concrete floor of the house.	• Desire not to waste energy may be a trigger to adopting insulation, but they are unlikely to do so of their own initiative. • High amount of disruption during installation is likely to put household off wanting underfloor insulation.

	Roof insulation	• Existing insulation is 75mm thick and is therefore less than current building regulations and benefit may be achieved by increasing this. • To raise the insulation above the height of the joists would mean that additional supports would be required to enable items to be stored. • Increasing insulation may cause damage to some stored items as they are paper or fabric which may be susceptible to damage from being cold or damp.	• Large number of items stored in the loft (especially belonging to their grown up children) – would be a large hassle to remove it all to put in extra insulation.
	Windows	• All windows are uPVC double glazed and appear to be more than 15 years old. In some rooms the trims are poorly installed and therefore not airtight. The windows in most rooms look as though they require redecorating.	• Provided the end result delivers cosy heat and is controllable, and someone else will deal with the hassle, they would have no barriers to adoption. • Desire not to waste energy may be a trigger to adopting insulation, but they are unlikely to do so of their own initiative.
	Ventilation		
Heat storage	**Hot water cylinder**	• There is a no hot water tank currently, but there are two cupboards which could house one; both are currently used for storage. • There is an additional voided space between the living room and kitchen which is left over from the previous hot air heating system. This is not available for storage currently and is blocked up, but if this could be opened up, a space could be available for thermal storage without losing space. • The two bedrooms which are often vacant could provide the opportunity to build a hot water storage cupboard, but it would make the room quite small and this would be at the opposite side of the house to the heating system.	• Giving up current storage space would not be an option.
Heating control	**Multizone control**	• All radiator valves are compatible with WRVs.	• Occupants currently think it's a waste heating the whole house when they are only using a few rooms, so multizone control would be an attractive proposition.

Table 8-5 House E (1980s detached) technology suitability

Technologies		Building related criteria	Household related criteria
Heat generation	**ASHP**	• External unit in back garden close to rear wall, internal unit in utility room on back wall. Allow extra capacity to meet future extension above the single-storey extension.	• Concerned for what others might think, so may not like an ugly box stuck on their back wall. • The householders are careful with money, so likely to be tempted by a technology if it would save them money in the long term. • Occupants use warm radiators as an indication of heating working properly, so if heating system changes to heating being on at different times for example, they would need some other indication of the heating system working to feel in control. • The household is only likely to be happy having heating on when house is empty (i.e. higher standby temperature which is an option for running heat pumps) if they have clear information that this is cheaper.
	GSHP	*EPN recommended technology* • Insufficient width of access route for drilling machine to rear of property as width of path between house and concrete pillars of fence is 0.83 m. • Garden lawn is accessed via 3 steps up from lower wooded deck, and grass lawn (7.5 m x 12.8 m) is marginally large enough for vertical boreholes, but more space may be required for sufficient heating power for large house. • Insufficient space for mini drilling machine, and difficult access to rear. • GSHP not suitable at front as no space for drilling.	
	Hybrid Heat Pump	• There is space for external unit in back garden close to rear wall with a hydrobox next to the existing boiler in utility room. The distance and obstructions between the two (kitchen) will make the installation complicated, with possible loss of performance from pressure and heat losses.	
	Biomass Boiler	• In principle there is space for a biomass store in the garden. • There is currently no chimney.	• The householders are likely to be sufficiently proactive to feed the biomass boiler if they deem the additional effort to be worth it in terms of improved comfort or saving money.

	Solar thermal	• Total roof area 60m^2 (43 main house+17 single storey extension). No chimney. East-west facing roofs.	• The householders are unlikely to want to adopt if they think it will spoil the aesthetics of the house as they appear to be sensitive to what other people think.
	District heat network	• Not identified as an appropriate geographical location for a heat network.	
Heat emission	**High power radiators**	• Existing radiators mostly high spec or large (relative to room size).	• The householders are unlikely to be happy for house to look aesthetically strange as they appear to be sensitive to what other people think, so larger radiators may not be acceptable if they look out of place. • If larger radiators looked ok and provided better comfort then they are likely to be accepting.
	Underfloor heating	• The ground floor is solid. • The hall, kitchen and bathrooms have tiled floors, the extensions have low-cost but recent laminate flooring, and the rest of the house has carpets in good condition.	• The householders don't dry their laundry on radiators, so replacing radiators with underfloor heating wouldn't be a problem in this regard. • The householders use warm radiators as an indication of heating working properly, so if heating system changes to heating being on at different times for example, they would need some other indication of the heating system working to feel in control.

Building fabric	**CWI/SWI**	• Walls all insulated cavity walls.	
	Floor insulation	• The ground floor is solid. The hall, kitchen and bathrooms have tiled floors, the extensions have low-cost but recent laminate flooring.	• Occupants consider house improvements worth it for the benefits, so are likely to be willing to put up with disruption if it will improve their comfort and save them money on their energy bill
	Roof insulation	• Insulation in the pitched roof above the single-storey extension is 100 mm - access may be limited (low head room). • There is 100mm of insulation in the main loft, with boards above. • insulation in the extension (above the new master bedroom) has been installed poorly, with some of it still in the rolls, so fixing this could be an easy option.	• Occupants consider house improvements worth it for the benefits, so are likely to be willing to put up with disruption if it will improve their comfort and save them money on their energy bill. • They don't have very much stored in the loft currently, so adding additional insulation wouldn't be too much disruption.
	Windows	• Glazing is uPVC double glazing throughout, • Upstairs windows were replaced in about 2012. • Downstairs windows are older than 2002 (assumed to be the original windows from 1982).	• Already thinks that downstairs windows need replacing, so likely to be willing to adopt if shown that it would be a benefit to their comfort.
	Ventilation	• Existing ventilation is limited to trickle vents on the kitchen back door and an extract fan in one of the bathrooms. Nevertheless, there are no existing damp or condensation problems (except in the conservatory).	• In the habit of opening upstairs windows every evening to aerate the house. Also open windows in bathroom to let condensation out (despite also having an extractor fan).
Heat storage	**Hot water cylinder**	• There is currently space in the utility room for a tank or large thermal storage capacity.	• As the addition of a typical hot water tank would not severely compromise storage space, the household is unlikely to block the installation of appropriate thermal storage.

Heating control	**Multizone control**	• The main room thermostat is located in the single-storey extension, suggesting that it was moved or added when the extension was built. • All radiator valves are compatible with WRVs.	• The householders currently hold frustration about their current heating control not being able to control the heating in different rooms. • The householders reported that sometimes they forget to change the programmed heating settings to reflect changes in their routines and feel frustrated at wasting energy – something with which they feel an improved interface would help.

Annex 1. Thermal Storage Landscape Review

a. Thermal Storage Landscape Review Report

Annex 1 Domestic
Heat Storage Lands

b. Thermal Storage Landscape Data Matrix

TechnologyMatrix_2
0171305_v04.8.xlsx

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