Department for
Business, Energy
& Industrial Strategy

# Cost-Optimal Domestic Electrification (CODE)

## Final Report

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# 1. Executive Summary

*Decarbonised electricity offers the promise of very low or even zero-carbon heating for homes – without necessarily carrying out extensive deep retrofit work. This project shows that Great Britain's homes can convert to electric heating at a cost far lower than the accepted wisdom. This can be achieved with no threat to comfort, and greenhouse gas emissions will fall very dramatically as a result.*

## Introduction

The continuing reductions in greenhouse gas emissions from electricity present an opportunity: to make progress towards climate change objectives by converting dwellings from gas or oil to electric heating. Improvements in operating efficiencies of heat pumps make this form of electric heating particularly attractive as a way to reduce emissions from homes.

The UK Government has set a target of installing 600,000 heat pumps a year by 2028.[1] However, there are barriers to installing heat pumps in homes, and historically a major barrier has been the high cost of installing and operating electric heating in dwellings. This research and modelling were commissioned in order to identify cost-optimal ways to install electric heating and energy efficiency measures, and to examine how much flexibility in demand could be provided by homes using electric heating.

The objective of this study was to assess costs based on the perspective of the consumer. It therefore only considers costs that directly impact the consumer: the upfront cost of equipment, energy costs and maintenance costs. The wider energy system is represented by proxy through the energy costs, but it does not take into account future energy system costs in generation or distribution infrastructure. These may be required as a result of homes switching to electric heating. In this study 'Cost optimal' therefore refers to the optimum for the consumer in the present day, and not necessarily what may be cost optimal from a future energy system perspective.

Based on detailed analysis of the British housing stock, we defined 12 house types, which collectively represent 90% of Britain's 28 million dwellings. The house types matched the most common combinations of dwelling (flats, terraces, bungalows, semi-detached houses and detached houses) with the most common forms of construction (cavity or solid walls, and solid or suspended timber floors). The house types also matched the proportions of homes currently installed with combi- and system-boilers (where the latter have hot-water cylinders).

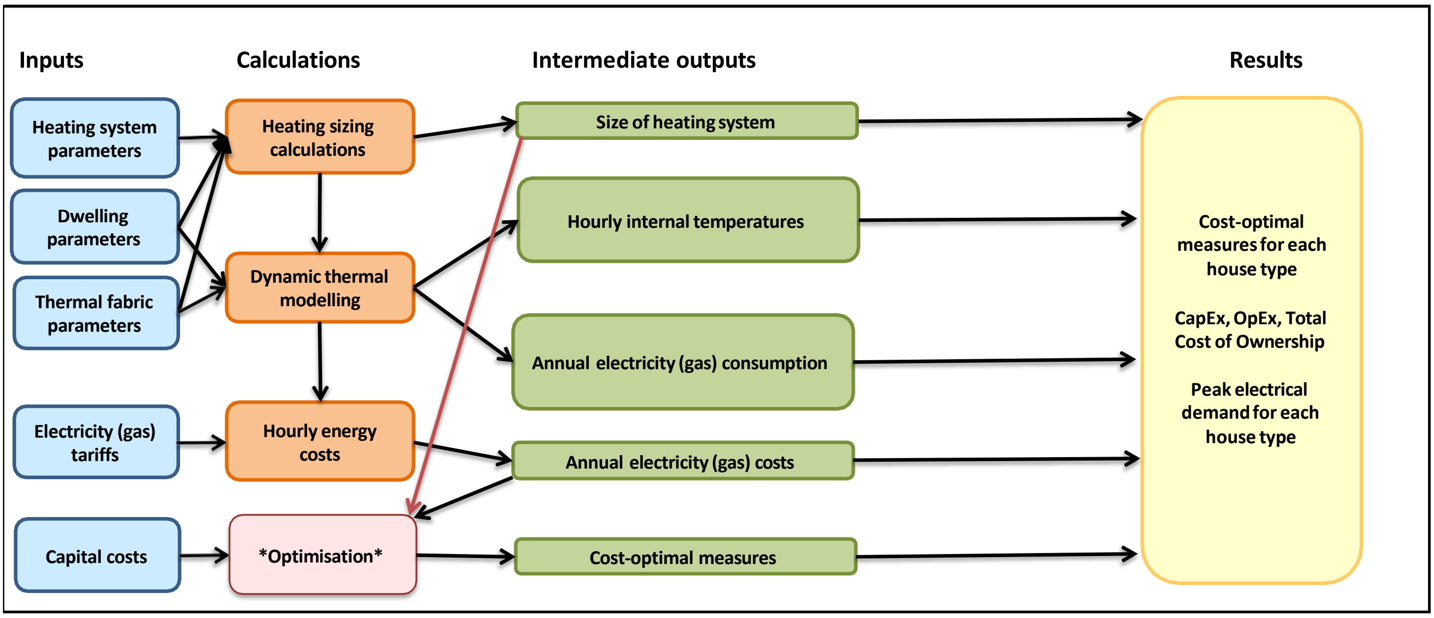
The modelling included capital costs of installing electric heating and other energy-efficiency upgrades, energy costs, maintenance and replacement costs. The structure of the models is shown in Figure 1.1 below. The central scenarios were based on a 15-year time horizon (longer and shorter time horizons were also considered). Future costs and benefits were discounted by 3.5% a year to bring them back to 2020 costs. (Higher and lower discount rates

[1] PM outlines his Ten Point Plan for a Green Industrial Revolution for 250,000 jobs - GOV.UK (www.gov.uk)

were also applied as part of sensitivity testing, see below.) There is considerable uncertainty about how capital costs might change in the future, and much depends how the market for electric heating evolves. For this reason, we assumed simplistically that the costs of electric heating and other upgrade measures do not change over time. Higher and lower capital costs for electric heating were also examined as part of the sensitivity analysis.

Dynamic simulation models including hourly calculations of internal temperature and energy consumption were used in simulations examining costs and comfort for tens of thousands of different combinations of heating systems and energy-efficiency measures. Optimisation selected the lowest cost set of combinations for each house type, including running costs over 15 years. Any combinations that did not achieve thermal comfort settings were rejected, because moving to electric heating must not come at the expense of being comfortable at home, or threaten the health of people living in cold homes.

**Figure 1.1: Structure of the CODE Models**




In all cases, we used the best available evidence about costs, heating regimes, heating system efficiencies, controls and upgrade measures that could be installed alongside new electric heating systems.

The CODE models include electric heating systems currently available in the UK (see Table 1.1), and each of them can be modelled in combination with wall insulation, top-up loft insulation, floor insulation, solar photovoltaic panels (PV), batteries and (where appropriate) a thermal store. All modelling used the best available evidence about costs and product lifetimes, and assumed dwellings provided at least as good thermal comfort as they did before decarbonised heating was installed.

**Table 1.1: Heating technologies included in the CODE models**

| Heating system | Emitters | Notes |
|---|---|---|
| High-temperature air-source heat pump | Radiators | This can make use of existing wet heating systems (radiators). |
| Low-temperature air-source heat pump | Radiators or underfloor heating | This usually requires larger radiators or an underfloor heating system. |
| High-temperature ground-source heat pump | Radiators | This can make use of existing wet heating systems (radiators). It relies on a borehole or slinky coil for the ground couple. |
| Low-temperature ground-source heat pump | Radiators or underfloor heating | This usually requires larger radiators or an underfloor heating system. Again, it relies on a borehole or slinky coil for the ground couple. |
| Air-to-air heat pump | None (warm air provided via internal unit) | No wet heating system needed. Separate system required for domestic hot water. |
| Infra-red radiant panels | Heat provided directly from panel | No wet heating system needed. Separate system required for domestic hot water. Limited evidence of performance or acceptability. |
| Electric storage heaters | Heat provided directly from storage heaters | No wet heating system needed. Separate system required for domestic hot water. |
| Hybrid heat pumps with gas boilers | Radiators | Not included in main analysis and optimisation (see Appendix 1) |

## What did the work reveal about cost-optimal electric heating systems?

- Detailed modelling of energy costs and evidence-based assumptions about capital costs found only small differences in costs over 15 years between low- or high-temperature heat pumps, or air-to-air heat pumps, or storage radiators. Typically the difference was only 10% between the highest and lowest cost.
- Low-temperature air-source heat pumps and air-to-air heat pumps are cost-optimal for most house types when time of use (TOU) electricity tariffs are applied.
- When conventional tariffs (standard flat-rate tariffs and Economy-7 tariffs) are applied, storage radiators displace the air-to-air heat pumps as the cost-optimal system for one of the house types included in the study: the Small flat.

## What did it show about balance of heating technologies to insulation measures?

- The work focused on total costs of ownership over 15 years. For most house types and most electric heating systems, the cost-optimal packages of measures have very limited fabric improvements – most commonly just draught-sealing and top-up loft insulation. (Where appropriate, cavity-wall insulation and loft insulation were assumed to be already installed.) High-cost improvements, like internal or external wall insulation, hardly ever repay the capital costs over 15 years.

## What factors altered the cost-optimal measures?

- Sensitivity testing examining the impact on cost-optimal packages of measures showed that the time-horizon used for total costs or ownership is crucial, and this makes a major difference to the choice of cost-optimal measures. Extending beyond 20 years makes heat pumps less attractive because (unlike other electric heating systems) they are likely to need to be replaced.
- Avoiding very disruptive measures – such as replacing radiators with larger ones – also has a major effect on results, and this makes high-temperature heat pumps more attractive.
- Lower electricity costs would also make a dramatic difference to the cost-optimal measures. Eleven out of 12 house types switch from a heat pump based system (air-air or ASHP) to an electric storage heater with lower power costs. (Higher electricity costs have a less pronounced impact.)
- Applying different discount rates to future electricity and maintenance costs (from the central 3.5% discount rate down to 0% or increased to 7.5%) did not make a major difference to the cost-optimal packages.

## What is the potential for flexibility from electric heating?

- The work indicated that two technologies that could provide flexibility in electricity demand (batteries or thermal stores) were never cost-optimal at current energy costs and capital costs for these systems.
- However, if an 8kWh battery were installed in a dwelling, it could provide approximately 7.5kWh of flexibility a day in cold weather, and this is similar across different house types because the scale of flexibility is governed by the size of the energy store.

- If a 300-litre thermal store were installed in a dwelling, it could provide approximately 2.5kWh (electricity) of flexibility a day, and again this is similar for all house types. However, it varies with the weather – on colder days the DSR potential is greater as the heat pump is less efficient, so it takes more electrical power to heat the thermal store.
- Thermal stores offer better value flexibility than batteries, at current costs. Typically, they cost around £500 per kWh that could be shifted, compared to £700-£800 per kWh for batteries. However, thermal stores cost more to install in dwellings where air-to-air heat pumps are cost-optimal without them – since thermal stores cannot be used with air-to-air heat pumps, so the heating system has to change.

# 2. Stock Analysis – Defining house types

*One of the first tasks in this project was defining house types that are representative of all Great Britain's homes, to use in modelling. There was a balance to strike between a manageable number of house types and ensuring good coverage of all 28 million homes.*

## Method

This chapter explains the approach we developed for classifying the UK housing stock into groups, each represented by a representative house type, or 'archetype'. The archetypes were selected to represent as much as possible of the total stock. However, subsequent analysis using the archetypes was very complex – with large numbers of measures applied to each archetype – and too many archetypes would be impractical. We chose archetypes which represent the range of the most important parameters.

Our approach was informed by previous work addressing related questions, and our review of the literature, see Appendix 2. This section utilised data from the English Housing Survey 2014[2] and was analysed using the Cambridge Housing Model (CHM)[3].

In modelling heating and heating systems, the heat loss parameter (HLP, heat loss per unit total floor area) is key. We used this as a guide, and the factors which drive it (area and type of wall, windows etc). Size was also important because space-constrained homes do not have room for bulky heating systems and/or hot water tanks. In subsequent modelling, we applied a range of heating types and energy efficiency measures to each archetype.

Our method had two phases: classifying according to building form (based on wall to floor and other ratios), and then by construction type (floor, wall, roof and window construction). Both of these are important drivers of heat loss and hence HLP. Construction type also affects thermal mass, which is an important factor driving potential for thermal storage and flexibility in heating demand. In the first phase we manipulated the stock data to give all dwellings the same constructions (solid floor, pitched roof, cavity walls, double-glazed windows) and in the second phase we looked at the dominant construction types in each group.

## Archetype form factors

The approach to defining archetypes was adapted from the approach used in Shoeboxer (Dogam, 2017[4]): dividing the housing stock according to the ratio of wall to floor area (and other similar ratios). Analysis showed this gave the best power of prediction, with greater

2 https://www.gov.uk/government/collections/english-housing-survey#2014-to-2015
3 Cambridge Housing Model and user guide - GOV.UK (www.gov.uk)
4 Timur Dogan, Christoph Reinhart (2017) Shoeboxer: An algorithm for abstracted rapid multi-zone urban building energy model generation and simulation. Energy and Buildings v140, pp140-153,

separation between fabric efficiency than other ways of dividing the stock. We also gave each dwelling a Type which is similar to the types in the Cambridge Housing Model (CHM), except that bungalows were separated out and detached, semi-detached and end terrace are grouped. (See Table 2.1 below.) We grouped the last three because they are actually quite similar in the factors that drive HLP – in particular ratio of external walls and windows to floor. This is explained further below.

Converted flats were not included, because their constructions are similar to other houses and, since they are often rented, treatments are likely to be applied to the whole building, not individual flats. Converted flats account for 4% of the housing stock.

**Table 2.1: Dwelling classifications for defining archetypes**

| Type | Definition |
|---|---|
| Flat-small | Purpose built flat no more than 50 $m^2$ in total floor area |
| Flat-top | Purpose built flat with a roof, more than 50 $m^2$ |
| Flat-mid | Purpose built flat intermediate floor, more than 50 $m^2$ |
| Flat-ground | Purpose built flat on the ground floor, more than 50 $m^2$ |
| Bungalow | Any dwelling other than a flat with a ground floor but no first floor |
| Mid-Terrace | Mid terraced – not a bungalow |
| Other | Semi-detached, detached or end terrace*, not a bungalow. There are several archetypes drawn from this group. |

*These are grouped because from a heat-loss perspective they are very similar, see below. However the archetypes we selected include examples of each.

Small flats with no more than 50 $m^2$ in floor area were separated out because the small size limits the measures that can be applied. The small space precludes appliances or insulation that use up space, and it also reduces future savings from measures that have fixed costs. However, we grouped all the small flats (ground-, mid- and top-floor) together because, if we considered each type of flat separately, the largest of the ‘small’ groups would be less than 2.2% of the stock.

The 50 $m^2$ threshold is consistent with the Nationally Described Space Standard for single-storey dwellings.[5]

[5] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/524531/160519_Nationally_Described_Space_Standard____Final_Web_version.pdf

We described each case in the CHM by class and by parameters for the shape: the ratio of façade to floor area, windows to floor, and so on (see Table 2.2, below). The most important of these was the 'façade ratio' (façade to floor area). We created groups of similar type and within set ratio limits, usually relating to the façade ratio. Each group was ultimately represented by an archetype, chosen to broadly reflect that group.

**Table 2.2: Parameters used to describe dwellings for the purpose of archetype creation**

| Parameter | Calculation |
|---|---|
| Internal floor area | Floor area - excluding any basement or room in roof[6] |
| Façade ratio | (Walls + windows and doors)/Internal floor area |
| Windows ratio | Windows/Internal floor area |
| Perimeter ratio | Exposed floor perimeter/ Internal floor area |

The parameters we chose are those that most accurately predict the overall fabric performance of the dwelling, using the Heat Loss Parameter (heat loss per $m^2$ of floor area, measured in W/K/ $m^2$). The parameters we settled on are shown in Table 2.2.

Using these parameters, we defined nine groups of dwellings, each of which was ultimately represented by an archetype (with characteristics that are representative of that group). The groups are described in Table 2.3 below. In Table 2.3, the three 'Other' groups contain semi-detached, detached and end terrace cases. Between them, these groups cover 82% of the stock (85% ignoring converted flats).

The 'other' classification is divided into three groups according to whether they are average, more or less compact (i.e. with lower or higher ratio of wall to floor). There are examples of end-terrace, detached and semi-detached houses in all groups (as shown in Figure 2.1 below). However, detached houses tend to be more sprawling, while more of the semi-detached houses are compact. We selected examples of all three for the actual archetypes (described in the next section).

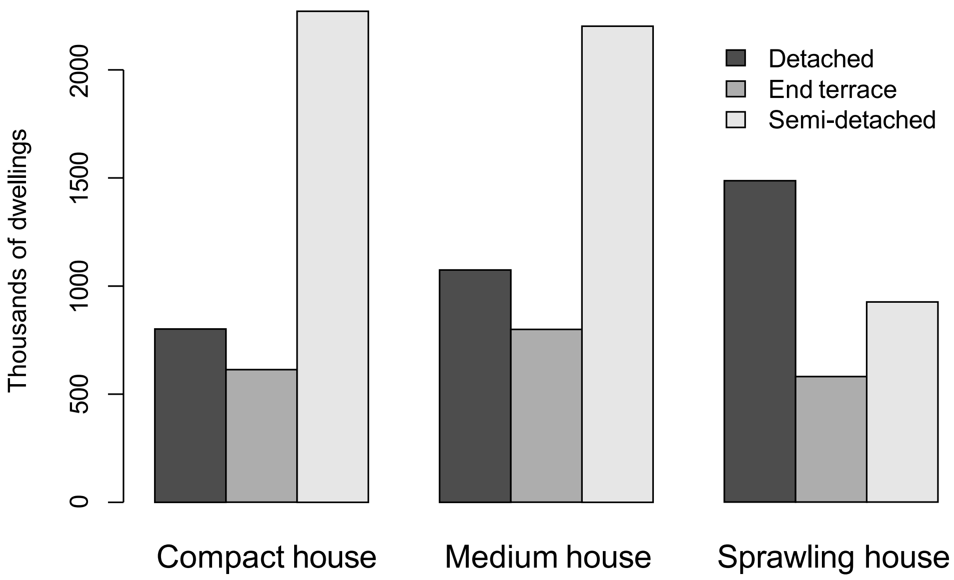
[6] Room in roof is excluded from the internal floor area because it has little effect on the external shape of the building as described by façade ratio etc. However, room in roof is included in the calculation of HLP.

**Table 2.3: Archetypes and coverage**

| Group | % of dwellings | Range for HLP (90% confidence) | Description of dwellings covered (see also Table 2.5) |
|---|---|---|---|
| Mid-Terrace | 14.5 | 2.3 - 3.7 | Mid terraced dwellings |
| Bungalow | 7.1 | 3.1 - 4.0 | Bungalows (includes Terraced, Semi-D and Detached) |
| Flat-small | 5.0 | 2.1 – 3.6 | All kinds of flats but top floor flats are most common in the group |
| Flat-ground | 3.0 | 1.9 – 3.2 | Ground floor flats |
| Flat-mid | 3.0 | 1.7 – 2.8 | Mid floor flats |
| Flat-top | 3.0 | 2.1 – 3.3 | Top floor flats |
| Compact house | 15.9 | 2.7 – 3.5 | Compact (low façade ratio), Detached/Semi-D/End-terrace |
| Medium house | 17.6 | 3.2 – 4.0 | Less compact semi-Ds or detached – approximately half are Detached |
| Sprawling house | 12.9 | 3.5 – 4.6 | Sprawling semi-Ds or detached (high façade ratio and floor area, about half are detached) |
| **Total** | **81.9** | | |

Figure 2.1 below shows the distribution of forms between the Compact-, Medium- and Sprawling-House groups.

**Figure 2.1: Distribution of groups for Detached, End-terrace, and Semi-detached dwellings**




## Archetype constructions

We based this analysis on the stock from the 2014 EHS data. This is a little out of date with respect to insulation, but the rate of UK insulation upgrades is currently very low, and the new build rate is also low, so more recent housing data would be unlikely to make a major difference to the analysis. Based on the proportion of stock with different types of constructions (cavity/solid walls, pitched/flat roofs, solid/suspended floors, etc.), the cases in Table 2.4 below were selected, in agreement with BEIS. This meant three additional archetypes, bringing the total to 12. This increased coverage from 82% to 88% of the stock.

**Table 2.4: Proposed archetype constructions for each archetype form**

| | Roof | Floor | Window | Walls |
|---|---|---|---|---|
| All groups<br><br>(9 archetypes) | Pitched with 100mm insulation | Solid concrete slab with no insulation | 100% double glazed. | Cavity walls with low U-value (<= 0.7 W/ $m^2$K, i.e. filled or built after 1982) |
| ‘Mid-terrace’ and ‘Medium house’ and ‘Sprawling house’<br><br>(3 archetypes) | | Suspended with no insulation | | Solid walls with no insulation |

These cases were chosen because:

- 45% of the stock has between 100mm and 200mm inclusive roof insulation. Only 14% has less than 100mm. However, adding insulation beyond 200mm has relatively little effect.
- 79% of the stock has at least 90% double glazing.
- 49% of the stock has cavity walls and a U-value of 0.7 or less (70% of cavity walls).
- 26% of the stock has solid walls and a U-value of 2.0 or more.

And because, apart from flats that do not have ground floors:

- 54% of the stock has a solid floor and cavity walls.
- 22% has a suspended floor and solid walls, and of these 81% are Mid Terrace, Medium house or Sprawling house.

There is further description of how we defined archetypes in Appendix 3 of this report.

## Heritage buildings

Some measures may not be appropriate for some buildings because of heritage factors. For example, external wall insulation may be rejected on planning grounds for houses in conservation areas. Older buildings are also more likely to have architectural features which the owners wish to preserve, similarly limiting scope for measures such as wall insulation – either internal or external. However, based on stock analysis alone it is difficult to identify which buildings are ‘heritage’. One simple approach would be by age: 20% of dwellings were built up to 1918, including 42% of Mid-terrace dwellings and many converted flats.

In agreement with BEIS, we decided to consider restrictions on heritage buildings as part of the sensitivity analysis, since heritage factors are not technical constraints on fabric upgrades or heating systems. These are not physical barriers (like size, or thermal values), and they may be more flexible over time. The best proxy we have for heritage buildings is building construction date but this is not a good proxy for whether a building is listed or in a conservation area, or if it has important heritage features.

## The archetypes

There are qualitative descriptions of the final archetypes in Table 2.5 below. Readers should note that all dwellings are defined in modelling to face east-west, and flats have external walls with windows facing east and west. The north and south walls of flats are party walls, with the exception of some semi-exposed walls adjoining communal areas. All homes have either filled cavity walls and solid floors, or solid walls and suspended timber floors. The living areas have windows to the front and rear. Mid floors and ceilings are modelled as adiabatic, so there is no heat flow through them. However, the floors and ceilings do have thermal mass. The solid ground floors are concrete and all have carpet.

All of the dwellings with wet heating systems and boilers are assumed to have standard radiator sizes in the base case, with high flow temperatures (60-80°C).

**Table 2.5: Qualitative description of archetype dwellings**

| House type | Description |
|---|---|
| Small flat | This is a small and ‘space-constrained’ 1-bedroom top floor flat, with a flat roof. The façade ratio is high and the living area fraction is also high, mainly because it is small and has only one bedroom. It has electric storage heaters and a small water cylinder with an immersion heater for hot water. |
| Ground floor flat | This 1-bedroom flat has a solid ground floor. Compared to the other flats it has slightly higher ceilings (2.55m compared to 2.50m) and less glazing area (in proportion to the floor area). It has only a small length of semi-exposed wall. It has electric storage radiators for heating and an immersion heater for hot water. |

| House type | Description |
|---|---|
| Mid floor flat | This 2-bed mid-floor flat is average for windows area but has more semi-exposed walls than the others. This flat has a combi boiler for heating and hot water. It has lower infiltration than the previous two flats: 0.8 air changes per hour, compared to 1.28 for the previous two, since it is based on a more recently-built flat. |
| Top floor flat | This 2- bed top floor flat has more windows than the ground and mid floor flats. It has a pitched roof, and a gas combi-boiler with no water cylinder. It has the most air-tight construction of all the flats – 0.64 air changes per hour – and proportionately more glazing. It is based on a flat built from 2000 to 2009. |
| Bungalow | This bungalow has a shallow party wall (so only the front half of one wall is shared with the bungalow next door). This reflects even numbers of detached/semi bungalows across the stock. It is very square in shape. The living areas are on the west side. It has a system boiler and a 110-litre hot water cylinder. |
| Mid terrace-C | This 2-bed mid-terrace with cavity walls is quite narrow, and a 2-storey projecting element makes it quite long from front to back (east to west). External wall area is modest for the floor area. It has a gas combi boiler providing space and water heating. It has above-average infiltration (1.12 air changes per hour). |
| Mid terrace-S | This is a solid wall house with suspended timber floors. It is relatively square in shape, and although it is a little larger than the previous archetype it has an even smaller wall area. It has high ceilings compared to the others. It has no projecting element but it does have a room in the roof. It has a gas combi boiler. |
| Compact (semi-d) | This is a large semi-detached house with 4 bedrooms and cavity walls. It is the largest of all the archetype dwellings, at 132 $m^2$, and the main house is quite square but there is a small single storey projecting element. It has a system boiler with a 210-litre cylinder. |
| Medium (end terrace) | This is a semi-detached house with 3 bedrooms. It has an L-shape plan, with a large square main section and two storey projecting element. It has a gas combi boiler, and a conservatory – the only archetype with a conservatory. It has relatively high infiltration: 1.28 air changes per hour. |

| House type | Description |
| --- | --- |
| Medium (semi-d) | This is a 3-bed end terrace house with solid walls and a suspended timber floor, fairly narrow and with a substantial 2-storey projecting element. It has a gas system boiler, with 140-litre cylinder. It has relatively low infiltration – certainly for a house with suspended timber floors: only 0.8 air changes per hour. |
| Sprawling-C (detached) | This is a relatively square 3-bed detached house with cavity walls. Although it is compact in shape, the façade ratio is high due to its relatively small size (104 $m^2$) and detached form. It has a gas system boiler, with a 140-litre cylinder. It has very good air-tightness, and the lowest infiltration rate of all the house archetypes: just 0.64 air changes per hour. |
| Sprawling-S (detached) | This is a rectangular 4-bed detached house with solid walls, and high ceilings. It has a gas system boiler, with 210-litre cylinder. Although it does not have any projecting elements it has a high façade ratio by virtue of the high ceilings and detached form. |

Table 2.6 below shows representative images of the 12 archetypes. Note that age was not a factor in defining archetypes, and it did not affect modelling. The images are provided to help readers visualise the archetypes and do not reflect buildings that were modelled.

**Table 2.6: Images of archetype dwellings**

| Flats | Image |
|---|---|
| 1. 1970s* One-bed Flat-small<br>42 m$^2$ |  |
| 2. 1950s One-bed Flat-ground<br>67 m$^2$ |  |
| 3. 1990s Two-bed, mid-floor Flat<br>69 m$^2$ |  |
| 4. 2000s Two-bed Flat-top<br>69 m$^2$ |  |

| Houses | Image |
|---|---|
| 5. 1960s* Two-bed Bungalow<br>78 $m^2$ |  |
| 6. Inter-War Two-bed Mid-Terrace-Cavity<br>80 $m^2$ |  |
| 7. Victorian Mid-Terrace-Solid<br>91 $m^2$ |  |

| Houses | Image |
|---|---|
| 8. 1980s Four-bed Compact Semi-D<br>134 m$^2$ |  |
| 9. 1970s Three-bed Semi-D-Cavity<br>103 m$^2$ |  |
| 10. Edwardian Three-bed terrace-Solid<br>113 m$^2$ |  |

| | |
|---|---|
| 11. 2010s Sprawling Three-bed Detached-Cavity<br>104 m$^2$ |  |
| 12. Victorian Sprawling Four-bed Detached house-Solid<br>115 m$^2$ |  |

*Construction ages are listed so readers can visualise properties. In fact, models are blind to age, and only the construction details and areas are important. Consequently, age was not a factor in defining these archetypes, and the percentage of the stock represented by each archetype does not reflect the construction age or styles listed in these tables.

Quantitative details about the archetype dwellings, including floor, wall and window areas, are shown in Table 2.7 below. Note that here the weightings have been refactored to sum to 100%.

### Table 2.7: Quantitative description of archetype dwellings

| Archetype | Weighting | Walls/floor | TFA* (m2) | Bedrooms | Adults | Children | Occupancy | Gross wall area (m2) | Windows area (m2) | Space constrained | Water tank | Baseline heating | Conservatory? |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Small flat (top floor) | 6.1% | Cavity/solid | 42 | 1 | 1 | 0 | Out on weekdays, so unheated | 39.0 | 9.4 | Yes | 110 | Electric storage, immersion DHW | No |
| Ground floor flat | 3.9% | Cavity/solid | 67 | 1 | 2 | 0 | In all day, so heated all day weekdays and weekends | 53.0 | 11.3 | No | 140 | Electric storage, immersion DHW | No |
| Mid floor flat | 3.8% | Cavity/solid | 69 | 2 | 2 | 2 | Out on weekdays | 55.0 | 13.9 | No | None | Gas combi boiler | No |
| Top floor flat | 3.6% | Cavity/solid | 69 | 2 | 2 | 0 | Out on weekdays | 62.0 | 15.3 | No | None | Gas combi boiler | No |
| Bungalow (detached) | 8.6% | Cavity/solid | 78 | 2 | 2 | 0 | In all day | 80.0 | 17.2 | No | 110 | Gas system boiler | No |
| Mid terrace | 8.4% | Cavity/solid | 80 | 2 | 2 | 0 | In all day | 67.0 | 17.6 | No | None | Gas combi boiler | No |
| Mid terrace | 9.2% | Solid/suspended | 91 | 3 | 2 | 1 | Out on weekdays | 56.0 | 15.6 | No | None | Gas combi boiler | No |
| Compact house (semi-d) | 19.3% | Cavity/solid | 132 | 4 | 2 | 2 | Out on weekdays | 138.0 | 30.4 | No | 210 | Gas system boiler | No |
| Medium house, cavity (end terrace) | 17.0% | Cavity/solid | 103 | 3 | 2 | 0 | In all day | 126.0 | 25.7 | No | None | Gas combi boiler | Yes |
| Medium house, solid (semi-d) | 4.4% | Solid/suspended | 113 | 3 | 2 | 0 | In all day | 135.0 | 29.4 | No | 140 | Gas system boiler | No |
| Sprawling house, cavity (detached) | 11.5% | Cavity/solid | 104 | 3 | 2 | 1 | Out on weekdays | 146.0 | 29.1 | No | 140 | Gas system boiler | No |
| Sprawling house, solid (detached) | 4.1% | Solid/suspended | 115 | 4 | 2 | 2 | Out on weekdays | 163.0 | 32.1 | No | 210 | Gas system boiler | No |

Weightings in Table 2.7 refer to the size, shape and structure of the archetypes. However, some additional factors have been added to these archetypes for the analysis, including occupancy. These may not be representative of the total stock when scaled up using the same weighting factors. *TFA = Total Floor Area

# 3. Describing the Models

*This chapter is technical in nature and may only be relevant for modellers or readers who need a very detailed description of the house types or modelling calculations. It describes how fabric upgrades were implemented in the models, heating regimes applied for different household types, and each of the electric heating systems.*

The chapter begins by describing detailed aspects of the modelling house types: wall and floor constructions, and baseline insulation parameters. It goes on to describe each of the insulation and air-tightness measures, and how these measures affect energy use with no change to heating systems. We also explain assumed household sizes in each house type, and how this affects heating regimes and energy-use profiles for lights and appliances.

The chapter explains each of the three baseline heating systems (electric storage heaters, gas-combi boiler and gas-system boiler – with a hot-water cylinder). Then all of the alternative, electric heating systems are described, including simplified schematics of how they were built in EnergyPlus. (EnergyPlus was chosen for CODE among different modelling platforms because it is widely used and tested, and open source.) We provide the nominal COP (coefficient of performance) and the Seasonal COP for each of the heat pumps as implemented in models.

There follows a section describing how batteries interact with solar photovoltaic panels (PV) and electricity tariffs in the models. This is complicated because the charging controls vary depending whether a household has a time-of-use or a traditional tariff, and whether or not they have access to electricity generated by PV panels to charge their battery. This section also shows the financial effect of installing batteries, and (for dwellings with PV installed) how batteries affect their ‘self-consumption’: what proportion of electricity generated by PV they are able to use themselves.

Finally, the chapter describes how thermal comfort is reflected in the CODE models, along with a description of the weather data used in modelling.

## Baseline Constructions and Upgrades

All the archetypes are of two main construction types: cavity walls with solid floors, or solid walls with suspended timber floors. Cavity walls are initially filled, while solid walls are uninsulated. Lofts have 100mm insulation, either between the joists or, if there is a room in roof, between the rafters. The main roof is pitched with gable ends. Where there is a projecting element (which can be single storey or two-storey) this has a flat roof with 50mm insulation. Gables are brick with no insulation unless there is a room in roof. Floors are un-insulated. All windows are double glazed.

The model does not incorporate thermal bridging explicitly, as this would be very computation-intensive. It is modelled as a decrease in performance of insulation (in the baseline construction). It applies to the insulation used in cavity walls, between the joists or rafters in the roof, on the sides and gable ends of a room in roof, and in the flat roof if there is one. The conductivity of the insulation is increased by 15%. It does not apply to solid-wall constructions, where the whole envelope is conductive.

One of the archetypes (the Medium end terrace with cavity walls) has a conservatory. This is constructed of a timber frame with windows. All the windows are double glazed, the same as for the other windows in the building. Building regulations require that conservatories are not heated. However, in practice they very often are. As a compromise, the conservatory in this model is heated but for only a few hours during weekends.

There are a number of options for fabric improvements. Throughout the study we assume that new measures are installed correctly and achieve the design performance standards.

The measures that can be installed are:

- Insulation for each of:
    - walls (either external or internal)
    - roof (top-up insulation)
    - flat roof (top-up insulation)
    - floor – the parameter specifies the additional thickness to apply.
- Triple glazing.
- Draught proofing – which reduces the air-change rate down to the specified level: 0.8 or 0.5 air changes per hour. If it is already below this level then it makes no difference. Hence the impact depends on the starting value.

Figure 3.1 below shows the impact of these upgrades on selected archetypes. The insulation added is 100mm in all cases except floors. For solid floors, 50mm of expanded polystyrene is added. For suspended floors (the same as the solid-wall cases) 120mm of mineral wool insulation is installed between the joists.

Draught-proofing reduces the infiltration to 0.6 air-changes per hour (ACH), which is approximately equivalent to a new dwelling built to current Building Regulations. External wall insulation is allowed even for cavity walls (in addition to the cavity fill) but the impact is relatively small, and it is unlikely this will justify the cost. The additional insulation is not affected by the thermal bridging adjustment, as this is new insulation.

**Figure 3.1: Impact of sequential efficiency measures on baseline archetypes**

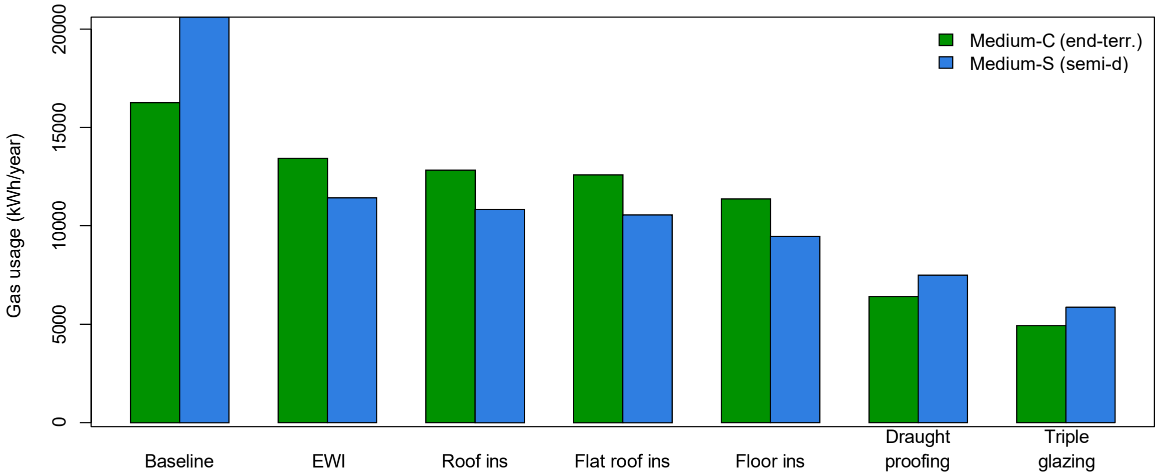



Figure 3.1 demonstrates the cumulative savings that are possible if energy efficiency measures are taken in sequence, with external wall insulation (EWI) first and triple glazing last, for two house archetypes.

Table 3.1 below shows U-values for the baseline constructions, and after the improvements described above.

**Table 3.1: U-values for modelling the effect of different insulation values, before and after the upgrade**

| | Baseline U-value | Improved U-value |
|---|---|---|
| Wall (solid) | 1.76 | 0.25 |
| Wall (cavity – Baseline assumes CWI already fitted, Improved adds 80mm of EPS insulation externally, plus render) | 0.65 | 0.20 |
| Floor (suspended) – to ground | 1.3 | 0.29 |
| Floor (solid) – to ground | 1.2 | 0.39 |
| Loft (pitched roof, top-up loft insulation) | 0.42 | 0.20 |

## Heating zones and occupancy patterns

For the purposes of heating, each dwelling is divided into zones which can have different heating schedules and thermostat settings. Three zones were included for flexibility in later use, however there are only two different heating schedules defined. These have the same timings but different thermostat setting: the living areas are heated to 21°C while the other zones are heated to only 20°C.

The archetypes have different family sizes and some are in all day, others not. This was based on simplified assumptions to broadly reflect the total proportion of households that are considered to have continuous occupation (43%).[7] This dictates the heating requirements, and Archetypes 2, 5, 6, 9 and 10 (see Table 2.7) are taken to be heated all day, while the others have two periods of heating (morning and evening).

Use of hot water, cooking and appliances is mainly derived from SAP (based on floor area and/or occupancy), for the total use. However, for the in-all-day cases there is extra use of appliances during the day. The daily pattern is derived from other models. Figures 3.2 and 3.3 below illustrate the schedules, with cooking combined with appliances use, ranging from 3 to 8 kWh a day, dependent on the house type. The Bungalow has two adults, in all day while Flat-top also has two adults but they are out during the day. For the 'out on weekdays' cases, the schedule for weekends is different for occupancy and for the thermostat settings, but other schedules are the same.

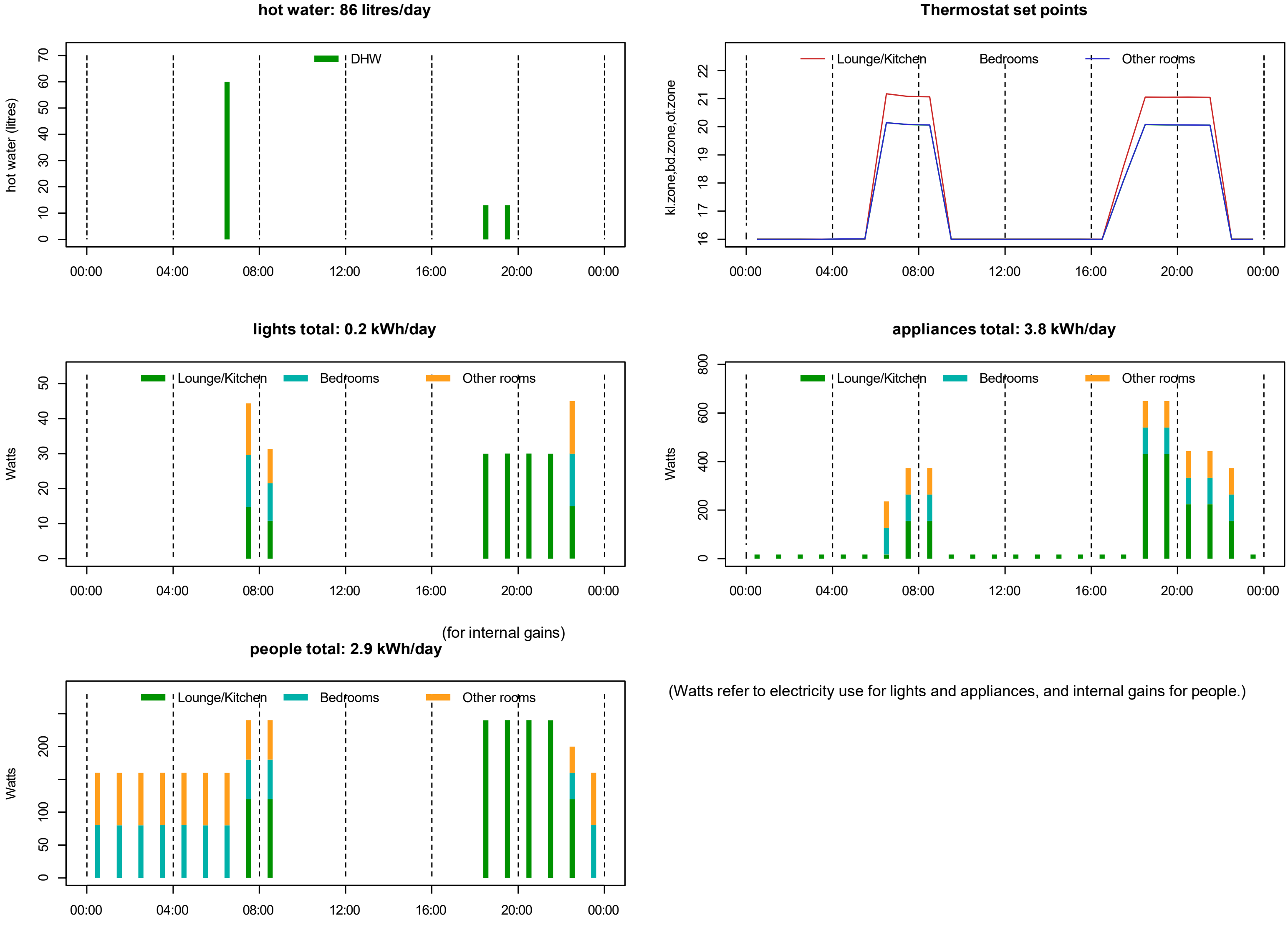
The conservatory in the 'End-terrace house with cavity walls' archetype is heated, but completely independently of the main heating system, using simple electric radiators. This is heated to 20°C but only at the weekends, between 5pm and 11pm, and a door is assumed between the house and conservatory. This means that the conservatory does not benefit from the heat pump.

The heating patterns can be varied by two important parameters. The first is the set-back temperature which is the temperature the thermostat is set to outside of heating hours. In the baseline case this is 12°C – low enough that the heating does not come on at night at all. However, in the charts below it is 16°C, which is suitable for heat pumps. Analysis of the RHPP data[8] has shown that two thirds of heat pumps run continuously, though at reduced load levels. This shows that thermostat settings are decreased slightly overnight. The optimisation of this model used 16°C and 18°C as options for the set-back temperature.

The second parameter is bringing forward the second period of heating so the dwelling is pre-warmed before the peak demand period begins. This only applies to archetypes that are heated in the morning and evening, when using a TOU tariff with a peak time penalty.

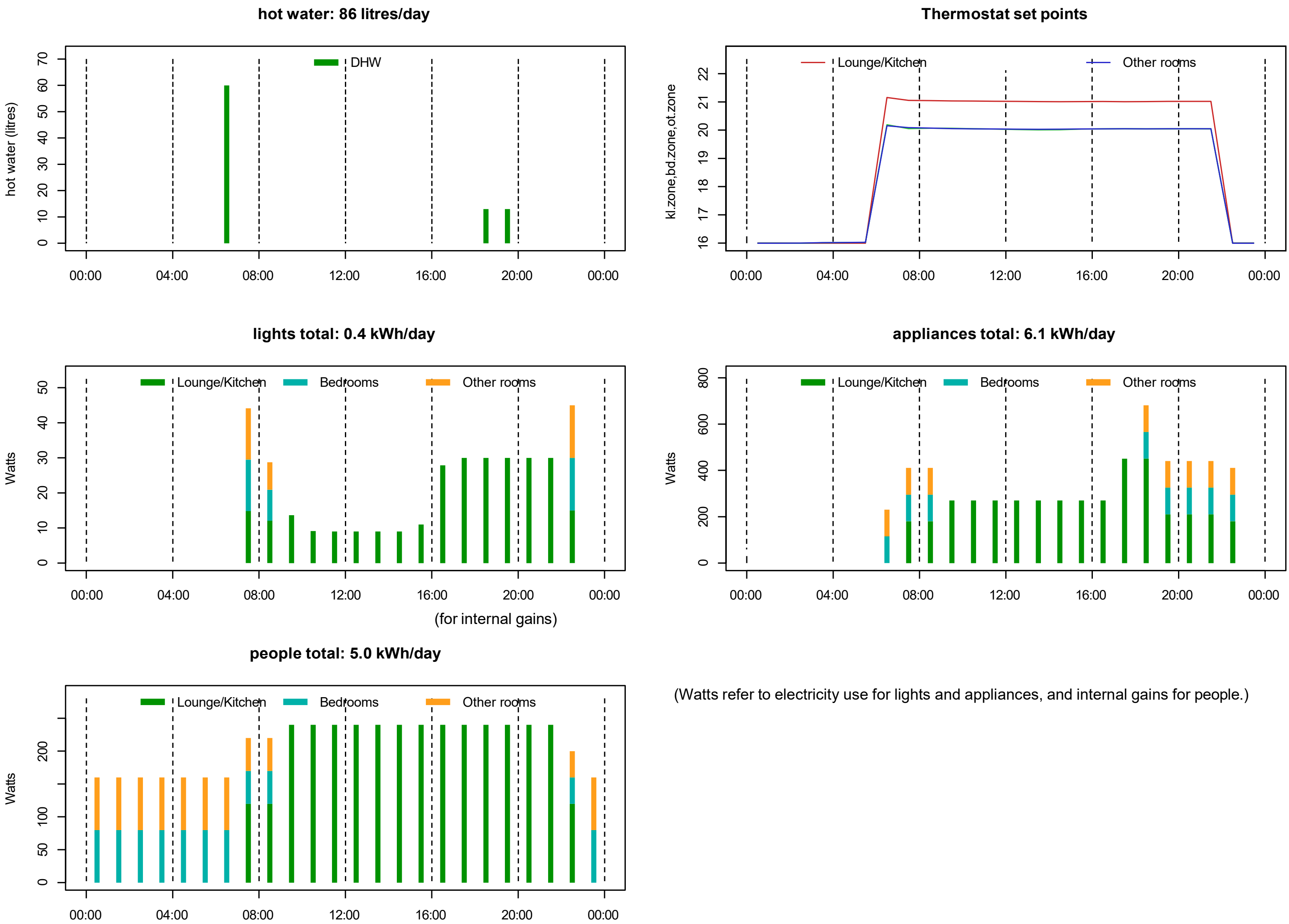
[7] BEIS, Energy Follow Up Survey 2017.
[8] S.D. Watson, K.J. Lomas, R.A.Buswell, How will heat pumps alter national half-hourly heat demands? Empirical modelling based on GB field trials, Energy & Buildings (2021), doi: https:// doi.org/10.1016/j.enbuild.2021.110777

## Figure 3.2: Heating, lighting, appliances schedules for Flat-top (out at weekends)




(Watts refer to electricity use for lights and appliances, and internal gains for people.)

## Figure 3.3: Heating, lighting, appliances schedules for Bungalow (in all day)




(Watts refer to electricity use for lights and appliances, and internal gains for people.)

## Baseline heating types

There are three heating variations in the baseline state for each archetype: either a system boiler, a combi boiler, or storage radiators (with an Economy 7 tariff). The domestic hot water (DHW) cylinder sizes vary between archetypes (110, 140 or 210 litres, so larger dwellings have access to more hot water). In the storage heater case, the cylinder is heated with an immersion heater to the setpoint temperature (65°C) every night. As water is used in the daytime, the cylinder temperature falls and it is topped up as necessary to 50°C. This maximises the benefit of the Economy 7 tariff and also provides pasteurisation for Legionella bacteria. In the system boiler case, the cylinder is heated at all times to the set-point temperature (which is 55°C). For combi boilers, there is no Legionella cycle – since there is no DHW storage.

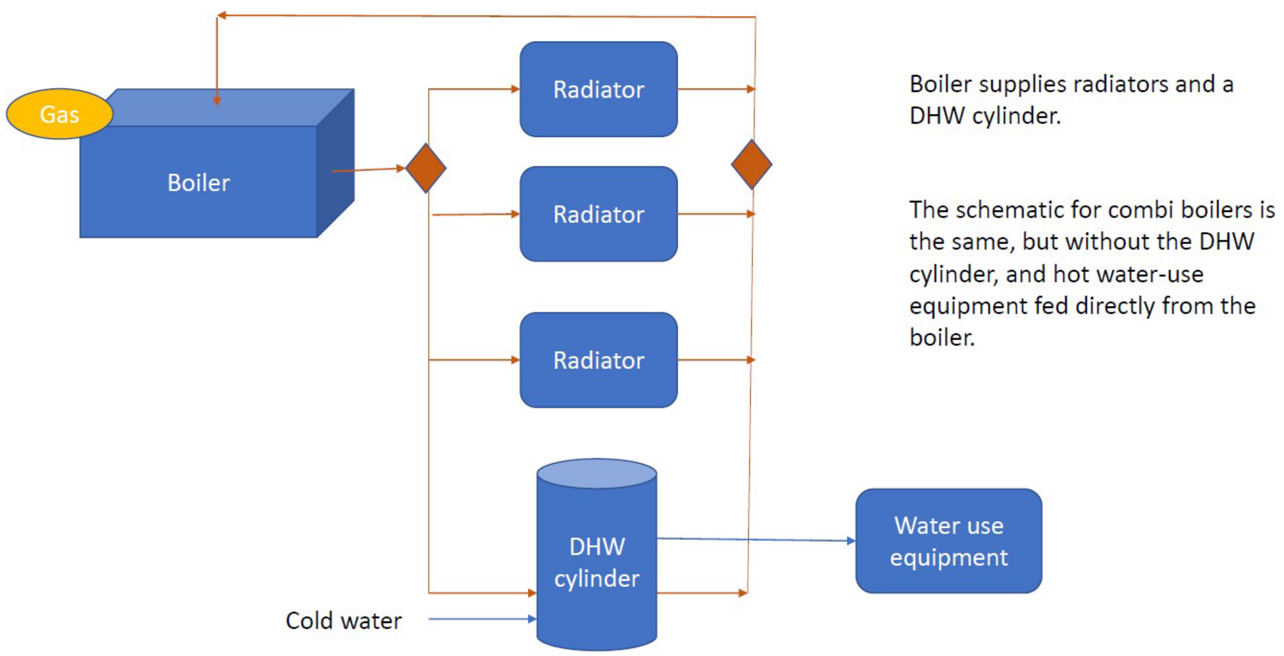
The boilers are modelled for the baseline case only as they are not electric heating. They were used to establish the baseline energy consumption and validate the construction models.

None of the dwellings have electric showers, so all hot water is taken to be generated by the main heating system, via the hot water tank where appropriate.

### Boilers

There are two kinds of boiler: system boiler and combi boiler. The only difference is that with the system boiler hot water is supplied from a DHW cylinder, which in turn is heated from the boiler. In both cases, all DHW is supplied at 50°C at the taps with tempering by cold water as necessary.

**Figure 3.4: System boiler is modelled as a boiler with radiators and a DHW cylinder**



Key features of the model:

**Boiler**

- Boiler capacity is based on heating demand at the design winter temperature (minus three degrees Celsius).
- Efficiency is 85%.
- Water is heated to 70°C for a mean flow temperature in the radiators of 65°C (i.e. losses through the pipework of 5°C, which are retained in the home as internal gains, so contribute to thermal comfort).

**Radiators**

- Flow temperatures: 65°C.
- The baseline size of radiators is based on floor area and construction type. This is 180W/ $m^2$ floor area with the following factors applied (determined for different house types so that comfort is achieved).
- x 1.1 for Mid-terrace with solid walls.
- x 1.5 for other solid wall cases.
- x 0.8 for the Ground-floor flat.
- x 0.5 for the Mid-f floor flat.
- Radiative fraction is 30% (i.e. 70% of heat is convective).

**DHW cylinder (system boiler only)**

- Cylinder size depends on the dwelling/family size: 110,140 or 210 litres.
- Cylinder heat loss 1.8 W/K/ $m^2$ temperature difference, equivalent to 2.5 W/K for the whole tank.

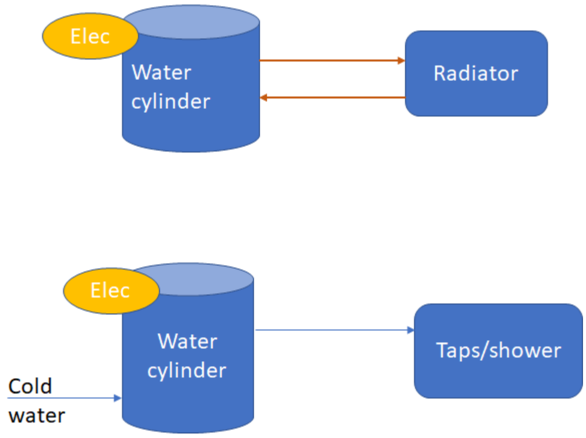
### Storage heaters

EnergyPlus does not have components to model an actual storage heater with a ceramic block with or without a fan system. Instead, each heater is modelled as a water tank, which is heated overnight and provides heat for a standard radiator during the day (see Figure 3.5 below). This achieves the same effect, with the same energy use. The tank is sized to provide enough heat for each day and set storage losses such that if it were not turned on to heating at all it would lose heat over three days.

This model is of a modern dynamic storage radiator system that is highly insulated and thermostatically controlled, with a fan. These are more expensive than products without these features.

The key characteristics of storage radiators are how much heat they can store (kWh), how much they can deliver (kW) and how long they can store the heat for when it is not needed (W/K heat loss). All of these are adequately modelled by the water/radiator system, even though the temperature of the hot water is much less than the temperature of the hot bricks. The cylinder is sized for the kWh required, the radiator is sized for the kW, and the insulation on the cylinder controls the heat loss.

**Figure 3.5: Storage heaters are modelled as a radiator and water cylinder**




The storage is charged overnight, during the heating period:

- November through to March: full charge.
- April through to mid-June: reduced charge (60%).
- Mid-June through to August: no charge.
- September through to October: reduced charge (60%).

Figure 3.6 below shows how the storage temperature varies through each day in the heating season. The overall trends are being driven by external temperatures, with storage-heater temperatures falling faster on colder days. Key features of this model are:

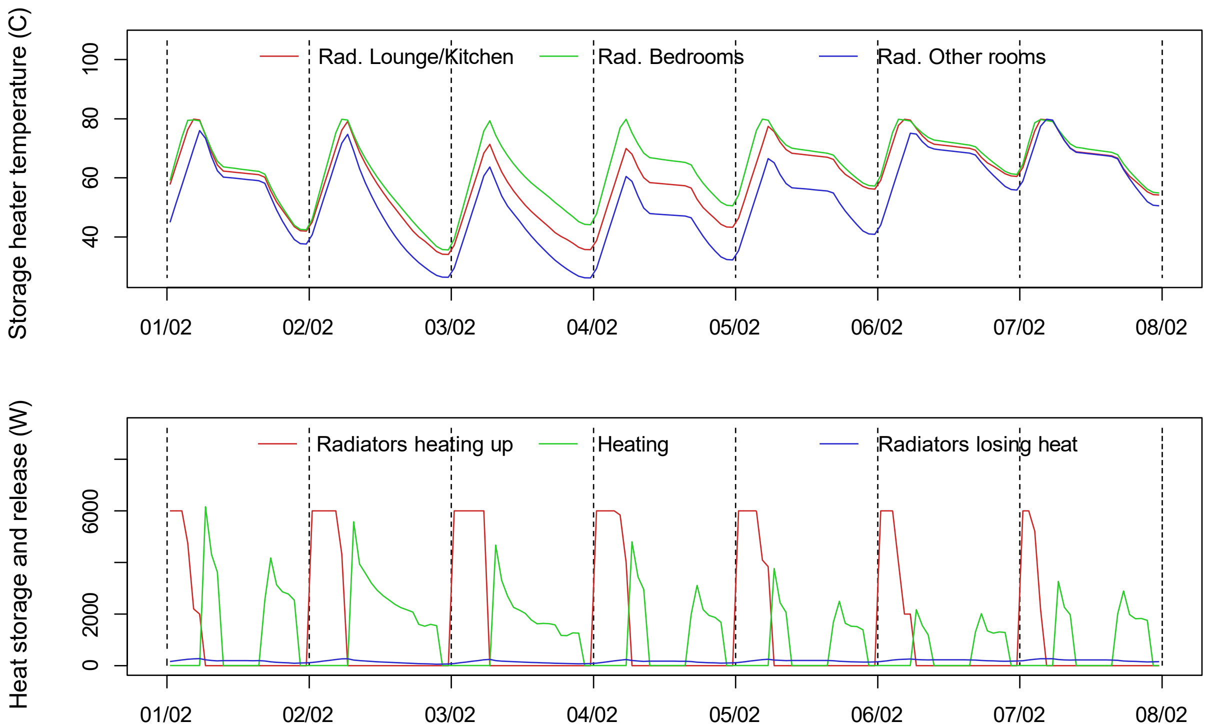
**Heat emitter**

- Heated overnight with Economy 7 tariff.
- Sized as required for the daily demand.
- kW derived from the calculated design day.
- Volume sized to deliver heat for 12 hours (consistent with the Dimplex Quantum model).
- Heat loss designed to lose heat over 3 days if not used: 1.4 W/K.

## DHW

- Cylinder size varies with family size: 110, 140, 210 litres.
- Heat loss 2.5 W/K (where temperature difference is the difference between stored water and indoor temperature) or equivalent. (Heat loss from the DHW cylinder is heat gains for the dwelling).
- Setpoint 65°C to 6am, then 50°C.

**Figure 3.6: Energy storage and temperatures of storage heaters in the Small Flat**



# Alternative heating models

There are six primary alternative heating technologies, in a range of configurations. These can all be combined with one or more fabric upgrades, oversized radiators or underfloor heating, PV, thermal storage and/or battery storage, making hundreds of different permutations in total. There are many different ways of configuring heating technologies in reality, and there may be subtle differences between how they are installed in different dwelling types and/or for different occupants. However, some of this complexity has been simplified in order to build the energy models.

## Air-Source Heat Pump (ASHP)

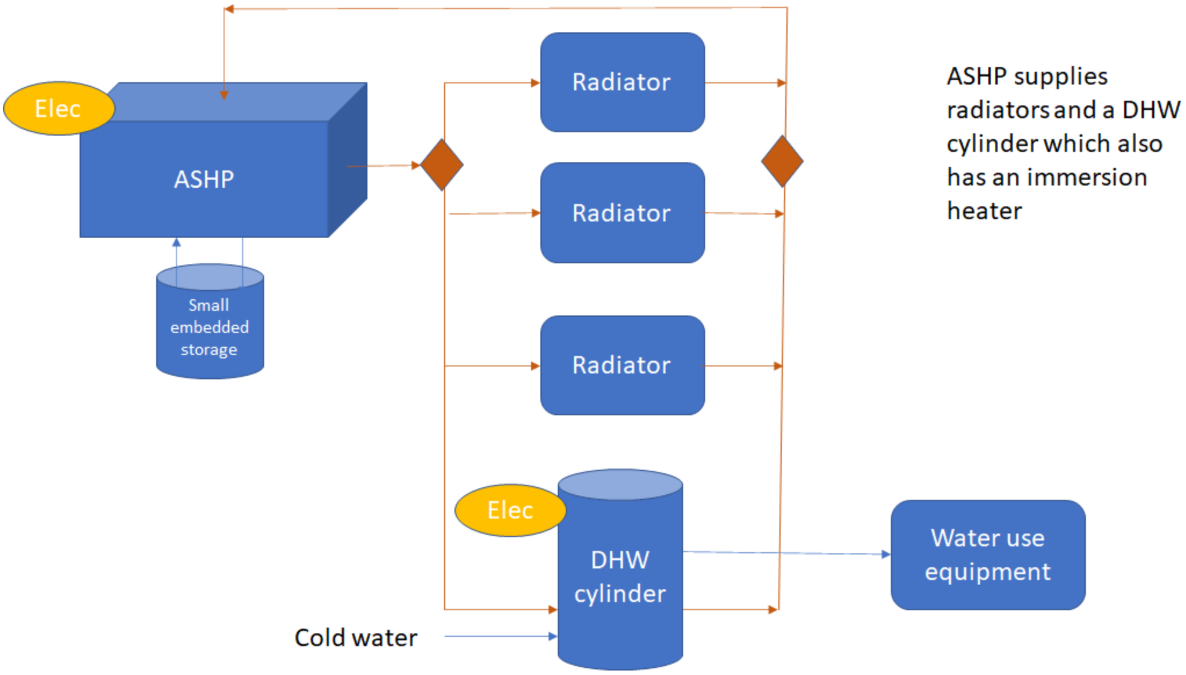
This group has five variants:

- Low-temperature with radiators.
- Low-temperature with underfloor heating.
- Low-temperature with radiators and a thermal store (in addition to hot-water cylinder).
- High temperature with radiators.
- High temperature with radiators and a thermal store.

Typically, one outdoor unit (the evaporator, with a fan), with refrigerant, is linked to the indoor unit (the condenser), which has an integrated heat exchanger to heat water. For space heating, this links to radiators (large radiators may be installed for a new heating system – say double-panel, double-convector/1800W per room). There also needs to be an expansion vessel for the heating water to expand.

As well as different variants using a different heat emitter and flow temperature, they also differ in handling DHW, see Figures 3.7 and 3.9 below. In all cases there is a hot water cylinder, but in the underfloor heating case this is connected to an identical heat pump, running at a higher supply temperature (EnergyPlus does not support supply circuits running at different temperatures). The underfloor heating temperature is not suitable for heating DHW so the model includes a second heat pump – this does not alter energy use compared to a single heat pump providing both. This does not affect the costs for this system – this was a work-around to carry out reliable energy modelling, and the costs are not affected. In all cases, the cylinder has heat from both the ASHP and an immersion heater: heat from the ASHP feeds in at a low temperature in the middle and an immersion heater adds extra heat when necessary. There is a Legionella cycle, heating the whole tank to 60°C for two hours weekly on Sunday, using the immersion heater to raise the tank temperature above what the heat pump can achieve. This schedule ensures that maximum advantage is obtained from the heat pump even though the required hot water temperature is higher than the heat pump can deliver on its own.

**Figure 3.7: Air Source Heat Pump model is defined with domestic hot water provided by both the heat pump and an electric immersion heater in the cylinder. Underfloor heating cases are the same, except the radiators are replaced by underfloor heating circuits.**




Key features of the model:

**Heat pump**

- Heat pump capacity is based on heating demand at the design winter temperature (minus three degrees Celsius[9]). This capacity is adjusted according to the heat pump performance curve for the external temperature – ASHPs normally have less than nominal capacity at low external temperatures. The capacity is then rounded up to the next 2 kW increment. For example, if the heating demand is 8.5 kW and the capacity is 30% below nominal at the winter design temperature, then the minimum capacity is 8.5/0.7 = 12.1 kW. This is rounded up to 14 kW. Costs for the heat pumps are defined as a base cost and a per kW cost, with the latter based on calculated heating demand.
- Nominal COP is 5.0 at 5.5/40°C. (External temperature and supply temperature) Full performance curves are given in the 'ASHP Performance Curves' section below, and Figure 3.16.
- The defrost cycle is 'reverse-cycle', meaning that the heat pump is used temporarily to shift heat from inside the dwelling to heat the external unit and prevent ice building up. This is less than 5% of operating hours. The defrost cycle can trigger when the external temperature falls below 5°C depending on humidity. However, this cycle is not directly modelled; it is allowed for in the performance curve.
- Supply thermostat: The low temperature heat pumps supply at 50°C for radiators, and 40°C for underfloor heating. This equates to flow temperatures of 45°C and 35°C, for radiators and underfloor heating, respectively (again, pipework losses into the dwelling

[9] https://www.gshp.org.uk/pdf/MIS_3005_Heat_Pump_Systems.pdf

of 5°C). The high temperature heat pumps supply at 70°C for a flow temperature of 65°C.

- Weather compensation is incorporated in a simplified manner, by reducing the flow temperatures for space heating by 4°C between March and November inclusive. This saves 1-3% on overall electricity use.
- Embedded storage 50 litres – this represents the volume of the heat pump and the heating loop combined (not a buffer tank) – pipes and heat emitters are not modelled to this level of detail.
- Embedded storage loss rate is 1.5 W/K based on losses from a reasonably insulated, small DHW cylinder.

**Radiators/Under-Floor Heating**

- Flow temperatures: 45°C (low temperature radiators), 35°C (underfloor heating), 65°C high temperature radiators.
- As for boilers, the baseline size of radiators is based on floor area and construction type. This is 180W/ $m^2$ floor area with the following factors applied (determined for different house types by trial and error).
- x 1.1 for Mid-terrace with solid walls.
- x 1.5 for other solid walls cases.
- x 0.8 for the Ground-floor flat.
- x 0.5 for the Mid-f floor flat.
- Radiators can be enlarged by 20%, 50% or 100%, and this is reflected in our CapEx costs. The enlargement factor is for the whole heating system, so if 20% enlargement is needed just two or three radiators would need to be replaced, whereas if 50% is needed most radiators would have to be replaced. The enlargement factor in each case is based on need, driven by the Microgeneration Certification Scheme guidelines on heat emitters. The required radiator size is calculated based on the design heating demand (dependent on insulation, air tightness and glazing measures applied) and the oversize factor recommended by MCS based on the flow temperature. This is compared with the baseline size and the enlargement factor is selected as the smallest that would be satisfactory. If the 100% factor is insufficient then this case is rejected.
- The size of underfloor heating is not constrained, and this is based on the overall heating demand calculation, comprising envelope areas and thermal performance. Since underfloor systems are always new systems, there are no issues of legacy systems that may have been designed to meet different design criteria.
- Radiative fraction is 30% (i.e. 70% of heat is convective).

**DHW cylinder**

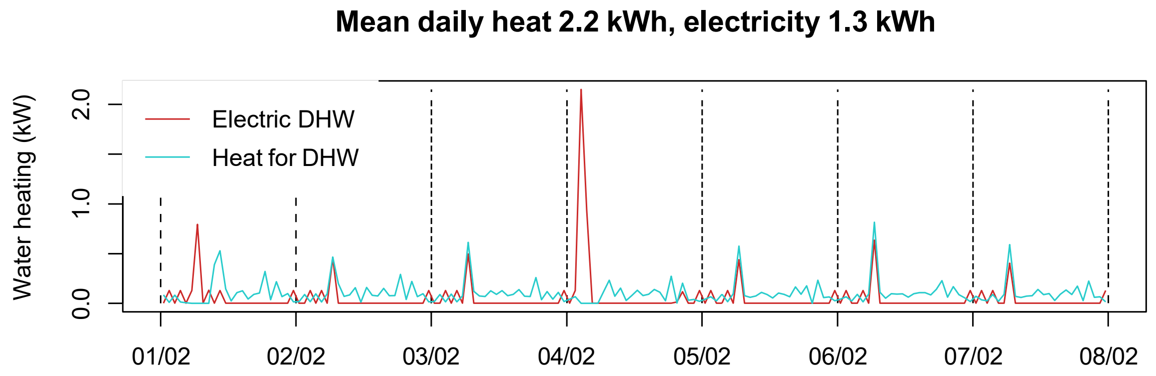
- The DHW cylinder has heat from the heat pump and also an immersion heater for top-up heat and a Legionella cycle (see Figure 3.8 below).

- In the underfloor heating case, the DHW cylinder heat pump is a duplicate of the space heating one, supplying at 50°C instead of 40°C.
- Cylinder size depends on the dwelling/family size: 110,140 or 210 litres (as for the boiler case).
- Cylinder heat loss 1.8 W/K/ m$^2$ temperature difference, equivalent to 2.5 W/K for the whole tank (again, as for the boiler case).
- DHW thermostat is set to 50°C except during the Legionella cycle: 60°C for 2 hours each Sunday morning (a higher standard set point reduces contribution to DHW from the heat pump to only around a third).

**Thermal store (where applicable)**

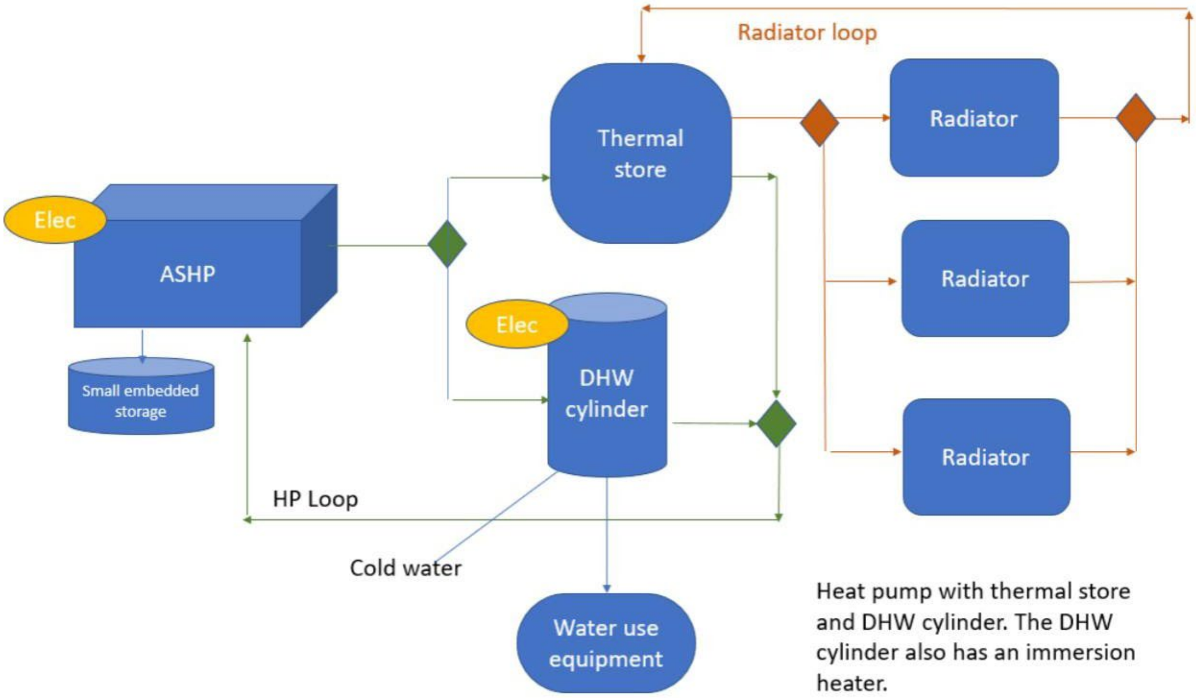
- Thermal store supplies space heating only – the heat pump supplies a cylinder for DHW as before.
- Useful capacity 3 kWh.
- Thermal loss 0.7 W/K/ m$^2$, or 1.0 W/K (more insulation than the DHW cylinder).
- Maintained 5°C above the heating emitter flow temperature, lower in summer for weather compensation as described above.

**Figure 3.8: Split of direct heating provided by the immersion heater ('Electric DHW') vs. the heat pump ('Heat for DHW') during a week. The immersion heater supplies 40% of the heat. The legionella cycle occurs on the 4th Feb. Smaller peaks in the use of the immersion heater are periods of heavy demand from showers. The time resolution is hourly – and the power demand is averaged over each hour.**




There is also a variant of this model with radiators and a thermal store, see Figure 3.9. The thermal store provides heat for the radiators only. The DHW cylinder has heat from the heat pump topped up with an immersion heater as before.

**Figure 3.9: The Air-Source Heat Pump with Thermal Store model has a separate cylinder for hot water, because this is maintained at a different temperature from the thermal store.**




## Ground-Source Heat Pump (GSHP)

This group also has multiple variants:

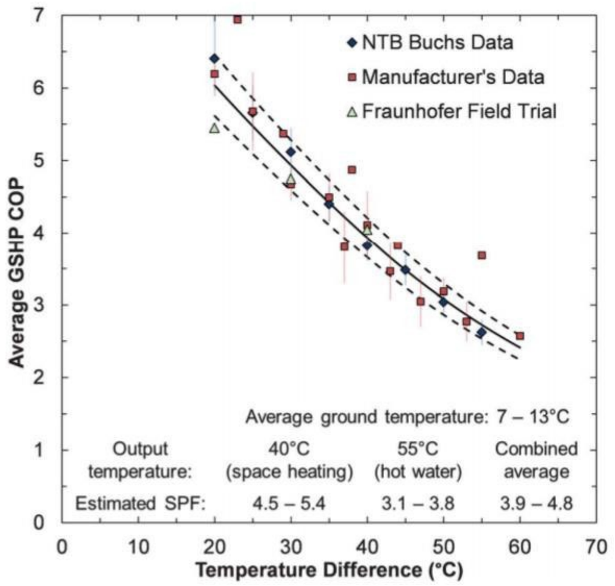
- Low-Temperature GSHP using radiators.
- High-Temperature GSHP using radiators.
- Low-Temperature GSHP using underfloor heating.
- GSHP with thermal store (also a low-temperature version, with a cylinder for DHW).

Typically (using the more common slinky coil, not a bore-hole) a pump runs a glycol solution through the ground loop. This passes through a heat exchanger to pass low-grade thermal energy to a refrigerant circuit that then passes through a heat pump. In other respects, this is similar to an air source heat pump.

The GSHP in CODE is implemented more simply, as a heat source with seasonal performance matching field trials. (EnergyPlus can model a GSHP in detail but this approach is complex with many site-specific features, unsuited to our requirements for a generic heat pump.) Field trial data covering COPs of ground-source heat pumps in the UK, published by Imperial

College and UCL citing data from the Fraunhofer Institute[10], suggested COP values vary between 3.9 and 4.8 depending on the difference in temperature between the ground and the delivered water temperature, see Figure 3.10 below.

**Figure 3.10: Field trial data showing COPs of ground-source heat pumps at different output and ground temperatures**




Key features are as for the air source heat pumps above except:

**Heat Pump**

This is modelled as a heat source with an overall SCOP (Seasonal Coefficient of Performance) based on the difference in temperature between ground temperature and supply hot water temperature. The SCOP varies linearly from 6.0 with a 20°C difference, to 2.0 with a 60°C difference. The ground temperature used is derived from the weather file. This varies from 13.8°C in September to 5.2°C in April.

Supply thermostat: 50°C for radiators 40°C for underfloor heating, as for the LT ASHP. This equates to flow temperatures of 45°C and 35°C, for radiators and underfloor heating, respectively.

Weather compensation is incorporated in a simplified manner, by reducing the flow temperatures for space heating by 4°C between March and November, inclusive.

**Radiators** (as ASHP above).

**DHW Cylinder** (as ASHP above).

**Embedded storage** and **thermal store** (both as ASHP above).

[10] Staffell et al. (2012) A review of domestic heat pumps. Energy & Environmental Science 5(11):9291-9306 https://www.researchgate.net/publication/255759857_A_review_of_domestic_heat_pumps/link/0c96052a39c98d9227000000/download

## Air to Air (A2A) heat pump

This is similar to air conditioning and widely used in commercial environments such as hotels, although the CODE model only provides heating, not cooling. There is an external evaporator (with fan) connected to an internal compressor (heat pump), with only refrigerant passing between them. Historically "split systems" had one external unit connected to each internal compressor and this is how it is in CODE, but now it is possible to link a single external unit to, say, five internal compressors. It would not provide DHW heating, so a separate system is needed for hot water. In most cases this is just a cylinder with an immersion heater. For the two flats that originally had a combi boiler, there is an instantaneous water heater, because this takes less space and the flats are small.

Key features:

**Heat Pump**

This runs like the air-source heat pump, with refrigerant passing from a single external unit to internal units in rooms (through-the-wall units). There is a large fan in the external unit, with a compressor (a 'package terminal heat pump') in the internal unit, and pumps to circulate refrigerant. Fan coils in the internal units draw air across the refrigerant to provide heating to rooms. There is a supplementary resistance heater in the internal units, but this only used for very cold weather: it accounts for just 3.2% of heating energy, and it runs 87% of the time when the external temperature is 0°C or below.

- One per zone.
- Nominal COP is 5.0 at 8.3/21.1°C.
- Capacity as required for the zone.
- Defrost cycle is reverse-cycle, using heat from the dwelling to prevent ice building up. This cycle operates when it is below 5°C outside, based on demand, and it depends on both internal temperature and humidity. This is included in the modelling.

**DHW cylinder**

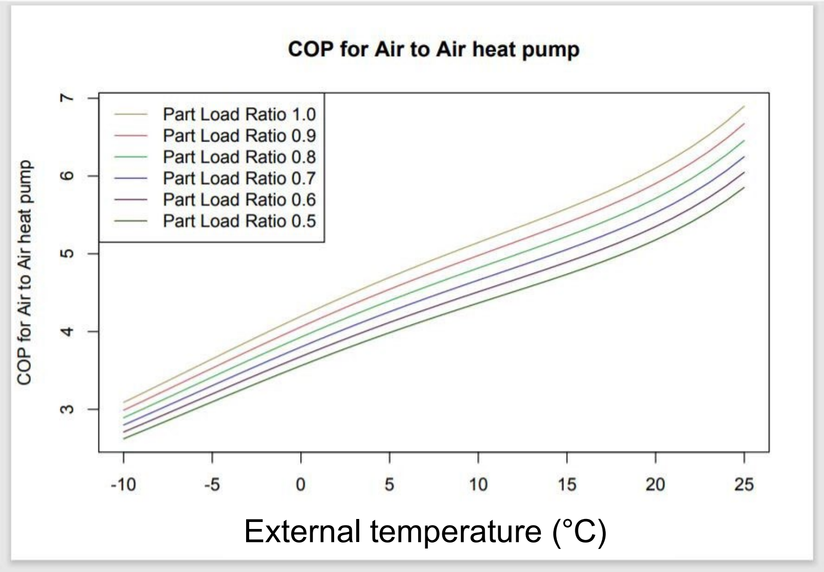
- Cylinder size varies with family size: 110, 140, 210 litres.
- 2 kW heating capacity.
- Heat loss 2.5 W/K.
- Set point 55°C with a Legionella cycle to 60°C each Sunday morning for 2 hours.

**Instantaneous water heater (only for archetypes less than 70m$^2$ that do not already have a DHW cylinder)**

- The water heater has 10 kW heating capacity.

As you would expect, COPs for air-to-air heat pumps vary with the external temperature, and at part load. Figure 3.11 below shows the COP performance curves, using a nominal COP for the air-to-air heat pumps of 5.0.

**Figure 3.11: Relationship between external temperature and COP for the air-to-air heat pump with different loads**




These COPs have been compared against seven detailed tests of different air to air heat pumps in Finland (all seven using R32 refrigerant).[11] They all have different COP curves, but there are consistent patterns between them:

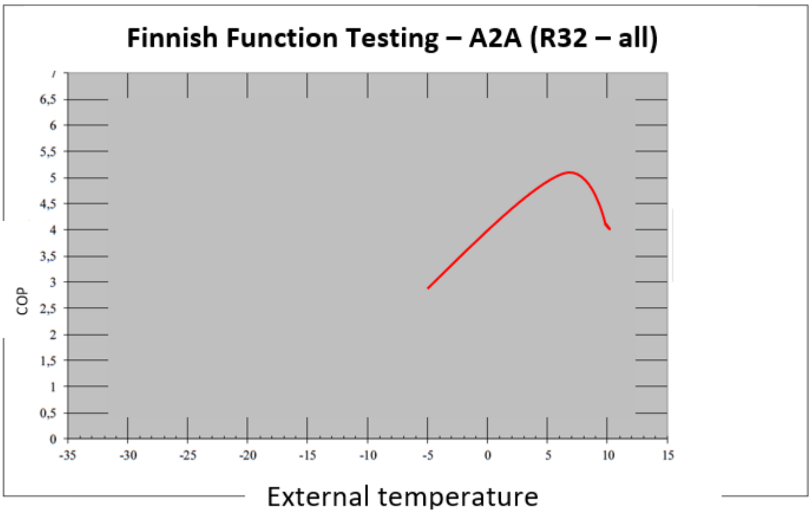
- All of these A2A HPs achieve peak COP at 5-8°C external temp.
- At the common UK 'coldest day' temperature of -5°C they have measured COPs from 2.5 to 3.2, with most from 2.5 to 2.8.
- At the common 'mild winter day' temp in the UK of 10°C, they have measured COPs from 3.2 to 6.0, with the median 4.0.

These are broadly consistent with the COP curves.

The 'line of best fit' through all the Finnish tests – for typical UK temperatures - looks like Figure 3.12 below. Note that for air-to-air heat pumps, air generally heats up faster than the fabric of the building, as air has a lower heat capacity, and it cools faster too. Other things being equal, running costs for an air-to-air system would be higher than an equivalent air-or ground-source heat pump with low temperature radiators or underfloor heating.

[11] See https://www.scanoffice.fi/vttn-testiraportit-ilmalampopumppuvertailu/ [in Finnish].

**Figure 3.12: Summary results from Finnish testing of air-to-air heat pumps (all tests combined)**




The decline in COP above 8°C is consistent with our COPs at part load, in Figure 3.10.

## Radiant heaters

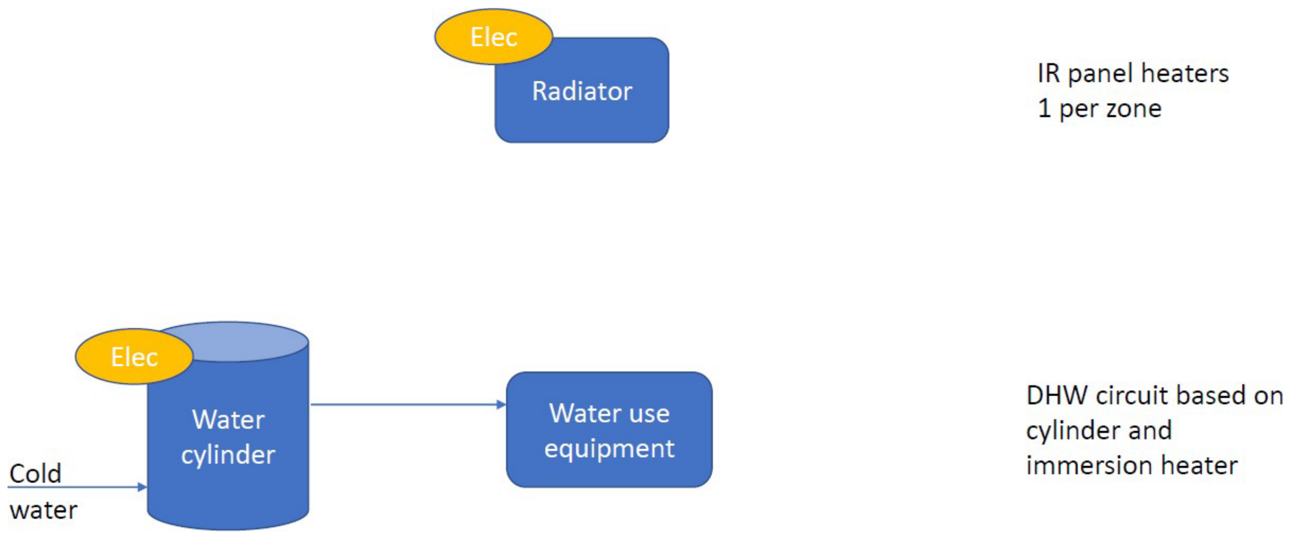
This is a direct electric heating system, using electric infra-red panels[12], see Figure 3.13. The key differences in the model between the wet radiators and these are that they are powered by electricity and most of the heat emitted is radiant rather than convective – 70% radiant instead of 30% radiant. They are thermostatically controlled.

High temperature radiant heaters provide directional heat and their position is very important – if furniture is placed in front of the heater people may become uncomfortable. In this model the heaters are lower temperature, with a substantial proportion of convected heat as well as radiant so the position is less critical. In any case, the thermostat control is based on operative temperature which also utilised an average radiative temperature in each zone.

DHW is provided separately using a cylinder and immersion heater or an instant water heater, as with reversible air to air heat pumps.

[12] For more information about infra-red panel heaters, see Element Energy (2019) Evidence gathering for electric heating options in off gas grid homes: Final Report. London: BEIS. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/831079/Electric_heating_options_in_off-gas_grid_homes.pdf

**Figure 3.13: Radiant panel heaters are modelled as resistance heaters, with a separate system for domestic hot water**




Key features:

**Radiators**

- Directly powered by electricity.
- Capacity is based on floor area (150 W/ $m^2$ for all archetypes, as for the wet radiators).
- Radiative fraction is 70% (there is some uncertainty about this fraction, and so far there is no reliable evidence about the split of radiative and convective heat transfer from radiant panel heaters).

**DHW cylinder**

- Cylinder size varies with family size: 110, 140, 210 litres.
- Heat loss 2.5 W/K.
- Set-point 55°C with a Legionella cycle to 60°C for 2 hours each Sunday morning.
- Instantaneous water heater (for flats only).
- The water heater has 10 kW heating capacity.

Figures 3.14 and 3.15 below compare internal temperature for the small flat installed with radiant heaters, and then a high temperature heat pump. The CODE models use operative temperature for the thermostat[13], a combination of air temperature and radiant temperature.

[13] The performance of radiant panel heaters is very sensitive to the location of thermostats. In the CODE models we assume all heating systems have a single thermostat controlling the heating in each zone. In reality, for radiant panel heaters, controls would be more elaborate.

Radiant temperature reflects the temperature of fabric and furniture. People sense both air and radiant temperature on our skin. Wet radiator heating systems heat the air more than the fabric of the building, whereas radiant heating does the reverse. Air generally heats up faster than the fabric of the building, as air has a lower heat capacity, and it cools faster too. However, with the radiant heating system the air temperature and radiant temperature are more similar.

**Figure 3.14: Mean radiant temperature and air temperature for the small flat with radiant heating**

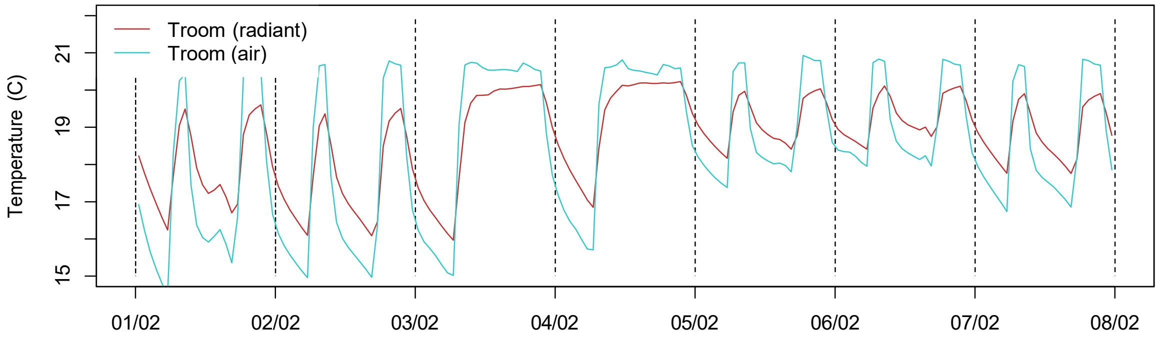
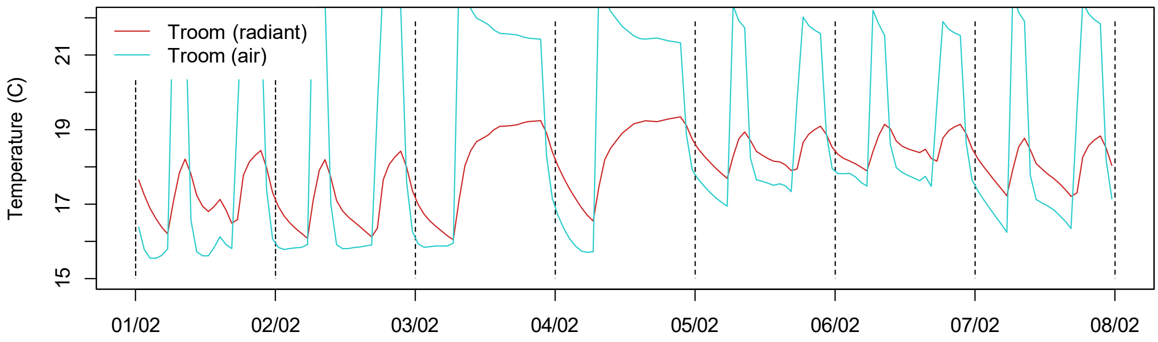



**Figure 3.15: Mean radiant temperature and air temperature for the small flat with a high temperature heat pump**




Radiant heating is rarely used in a domestic context and there is little empirical data to compare these charts with (or evidence of people's acceptance of radiant heating). Plots are included here so that they can be compared in future, when more data is available about radiant panel heaters. The key parameter is the fraction of heating which is radiant. The IES modelling system[14] recommends 0.7 for vertical and ceiling panel heaters. High temperature radiant systems have a higher fraction still (0.9) but they are not suitable for indoor domestic use.

[14] Integrated Environmental Solutions | IES (iesve.com)

## ASHP performance curves

For air source heat pumps (air to water), performance is strongly affected by external air temperature, and by the water supply temperature required (this is somewhat higher than the flow temperature). These conditions affect both the efficiency (COP = coefficient of performance) and the heating capacity. Reduced load also affects the COP. Our models for high- and low-temperature heat pumps incorporate these effects using performance curves giving COP and heating capacity, relative to the nominal value, as a function of external temperature and hot water supply temperature.

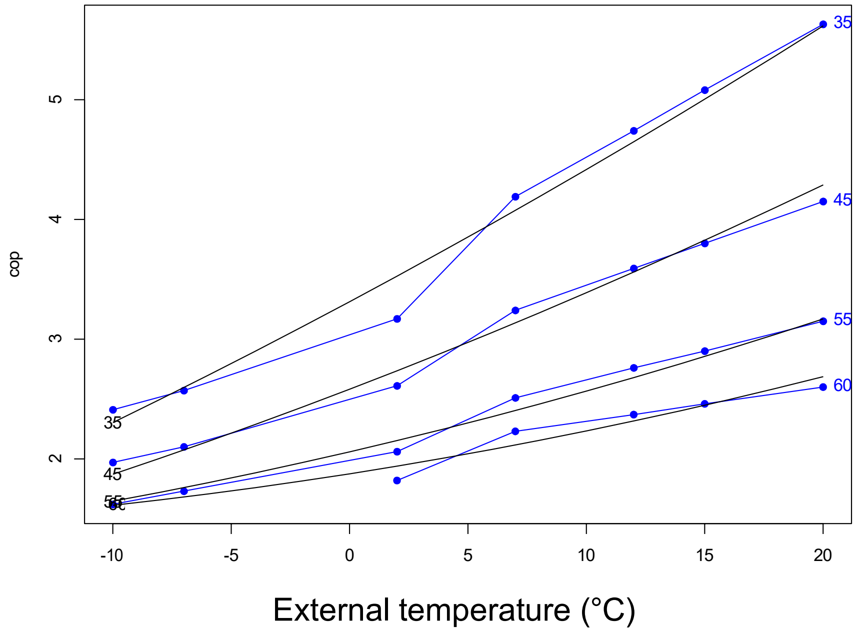
These performance curves take into account the impact of defrost cycles, required to avoid the external unit icing up in cold and humid weather. The most common defrost mechanism used in air-source heat pumps is to run the heat pump in reverse for a short period, to warm up the external unit. The impact of this is taken into account in the performance curves. For example, an experimental study on defrost cycles (Chen and Guo, 2008)[15] found a 70% reduction in performance at -8°C relative to 5°C, almost identical to the corresponding factor in the performance curve we are using.

Readers should note that the performance curves do not incorporate any improvement in heat pump performance over time, as new models are released and learning effects improve installation.

We analysed performance data from Panasonic[16] and Mitsubishi[17] ASHP systems to determine how COP varies, see Figure 3.16. They were similar, after normalising for nominal COP. We used the Mitsubishi data to derive performance curves in the form required by the EnergyPlus model. These charts show the Mitsubishi Ecodan performance curve and our approximation.

[15] Yi-guang Chen and Xian-min Guo (2008) Dynamic defrosting characteristics of air source heat pump and effects of outdoor air parameters on defrost cycle performance. Applied Thermal Engineering 29, 2701-2707.
[16] Panasonic [undated] Decouvrez les Pompes a Chaleur Air-Eau Aquarea [in French]. Paris: Panasonic.
[17] Mitsubishi Electric (2019) Air to water heat pump systems data book. London: Mitsubishi. Ecodan ATW Databook 2019 - Document Library - Mitsubishi Electric

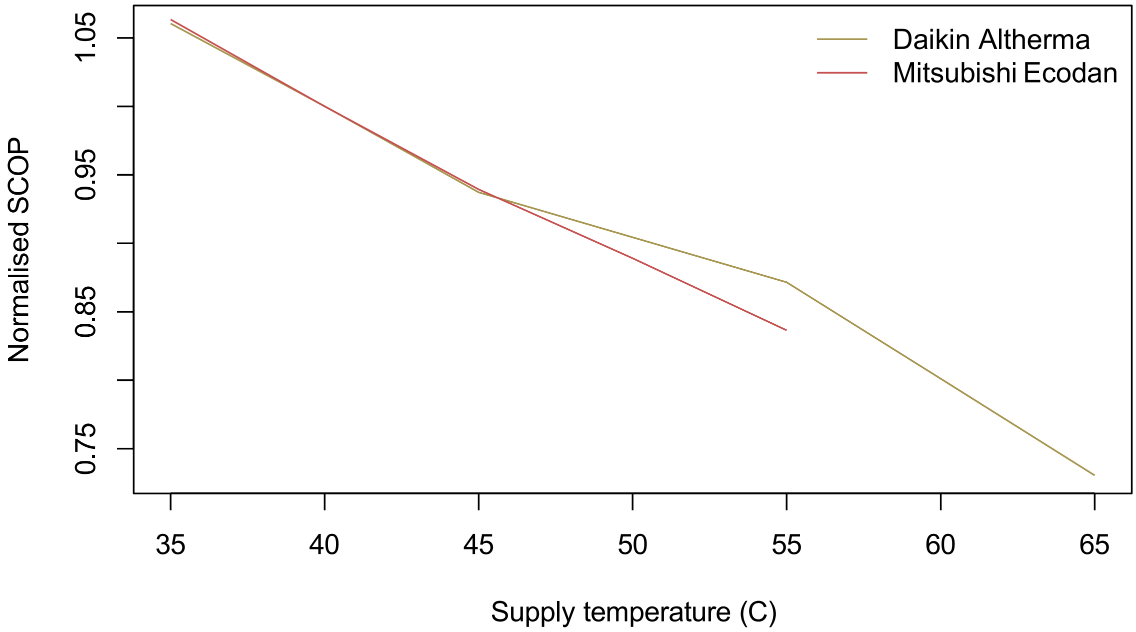
**Figure 3.16: Performance data from 11kW Mitsubishi Ecodan air-source heat pump (blue), compared to CODE modelled COPs (black). Figures on the left and right are flow temperatures.**




There was no significant difference between the COP performance of high temperature and low temperature products – the COP of the high temperature heat pumps at high temperatures was consistent with what would be expected extrapolating the curves to those conditions. The Daikin Altherma HT is another common example with medium performance[18]. There was no available COP data for this but SCOP data was obtained from the MCS database. (SCOP is the seasonal average COP.) Figure 3.17 below compares SCOP Daikin Altherma with the Mitsubishi Ecodan, using data from that database. (Daikin Altherma is high temperature, Mitsubishi Ecodan is low temperature.) The Daikin curve runs close to where the Ecodan curve would be if it was extrapolated to higher flow temperatures, although it is lower by perhaps 0.03 at 55°C. Accordingly CODE uses the same COP curves for low- and high-temperature heat pumps.

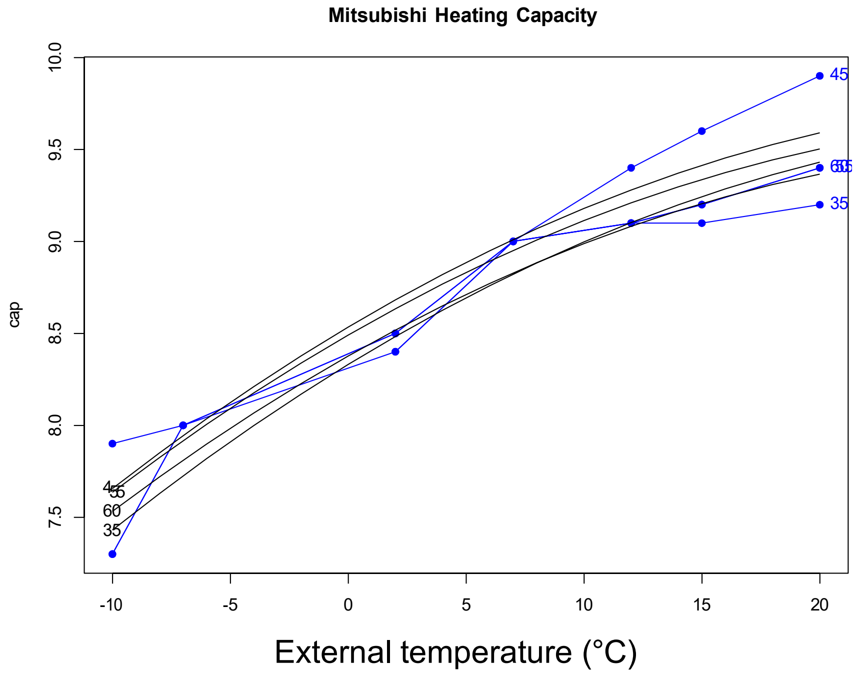
[18] The Heating Hub: Focus on High Temperature Heat Pumps https://www.theheatinghub.co.uk/articles/high-temperature-heat-pumps

**Figure 3.17: Performance data from high- and low-temperature air-source heat pumps shows the SCOPs are very similar up to 55°C**




Heating capacity also varies with external temperature and flow temperature – the capacity is reduced relative to the rated capacity at lower external temperatures. This affects the size of heat pump required as it needs to supply the required heat at under design conditions allowing for this reduction in capacity. Again, Mitsubishi ASHP data was used as the basis for the CODE ASHP model. This shows more variation than the Panasonic products, where the heating capacity was hardly affected. Figure 3.18 below shows the Mitsubishi data and the modelled approximation of it. Each corresponds to a different supply temperature. The modelled capacities are compared to the Mitsubishi Ecodan manufacturer’s data in the figure.

**Figure 3.18: The reduction in capacity of heat pumps as a function of external temperatures and flow temperatures**




Our review of part-load performance found no degradation in COP down to at least 30% loading (actual load/rated capacity under the same conditions). This has changed dramatically now heat pump models modulate more efficiently. In fact, manufacturer data[19] shows the COP can be up to 20% higher at 30% of nominal load. This does not mean that the overall system COP is the same at low load values, as there are more electrical loads than the heat pump itself. In particular, circulating pumps run some of the time when the heat pump is off.

[19] Mitsubishi Electric (2019) Air to water heat pump systems data book. London: Mitsubishi. Ecodan ATW Databook 2019 - Document Library - Mitsubishi Electric

## Heat pump annual efficiencies achieved

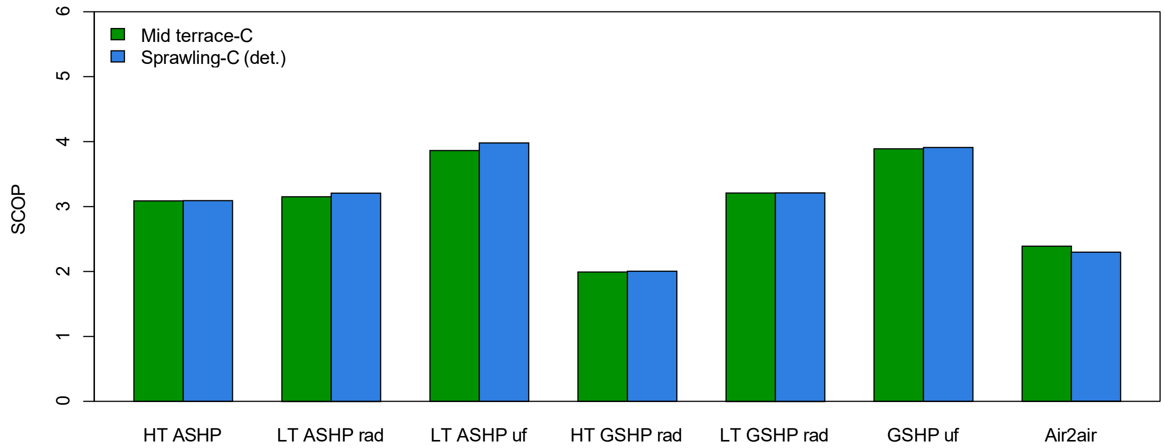
Figure 3.19 and Table 3.2 below show the modelled seasonal efficiencies (SCOPs) for solutions involving heat pumps. This varies between archetypes because of differences in heat demand, in particular the relative demands for hot water and space heating affect the achieved SCOP, as hot water is needed throughout the year. Results from two archetypes are shown, the Mid-terrace house with cavity walls is occupied by two people, who heat the house all day. The sprawling house, also with cavity walls, has more people and they heat only for a short period in the morning and then in the evening (from 5.30pm to 10.30pm in the default case), however the house itself is considerably larger. The dwellings have all been given some draught proofing.

Figure 3.19 shows the overall efficiency including circulating pumps and fans and supply of hot water (i.e. the 'H4' boundary as defined by SEPEMO ('System Boundaries for System Performance Factor Calculation'), including auxiliary electric heating to top up the DHW cylinder, and is widely used[20]). Table 3.2 shows additional information. The two high-temperature options use the existing radiators, with flow temperature of 65°C. For the air-to-air case all DHW heat is supplied by immersion heater and in the low temperature ASHP and GSHP cases DHW is topped up by immersion heater - this affects the overall SCOP considerably. In the case of wet underfloor heating the DHW loop runs at a higher temperature than the underfloor heating loop and this also reduces the SCOP compared to what would be expected from the flow temperature. By and large, however, the SCOP achieved is as would be expected: best for underfloor heating, then low temperature radiators, then high temperature radiators. Also the ground source heat pumps do better than the air source, except at high temperatures.

Note that high-temperature GSHP has similar performance to high-temperature ASHP, even though ground temperatures vary less than air temperatures, because the GSHP has not been optimised for such high delivery temperatures. ('uf' in the figure denotes underfloor heating.) This is a limitation in modelling. However, even with an optimised system the high-temperature GSHP would not be among the cost-optimal solutions over 15 years, because of high installation costs.

[20] OFGEM (2015) Easy guide to heat pumps. London: Ofgem. https://www.ofgem.gov.uk/sites/default/files/docs/2015/02/es888_rhi_easyguide_to_heat_pumps.pdf

### Figure 3.19: Overall annual heating efficiency, including supply of DHW




### Table 3.2: Nominal COP and modelled seasonal COP for different heat pumps in the CODE models

| Heating type | Nominal conditions | Nominal COP at rated conditions | SCOP (including DHW supply)**** |
|---|---|---|---|
| HT ASHP radiator | 5.5/40°C* | 5.0 | 3.0-3.1 |
| LT ASHP radiator | 5.5/40°C* | 5.0 | 3.1-3.2 |
| LT ASHP underfloor | 5.5/40°C* | 5.0 | 3.6-4.0 |
| HT GSHP radiator | 30°C** | 6.0 | 1.9-2.0 |
| LT GSHP radiator | 30°C** | 6.0 | 3.1-3.2 |
| GSHP underfloor | 30°C** | 6.0 | 3.7-4.0 |
| Air-to-air | 8.3°C*** | 5.0 | 2.2-2.4 (3.4 - 3.5 excluding DHW) |

*External temperature and heat supply temperature.

**Difference in temperature between ground and supply.

***External temperature.

**** CODE uses weather data for Finningley, near Sheffield.

## Battery and solar PV models

Modelling battery use and how this interacts with any PV system and tariffs is complex, especially when a battery is used with a variable tariff. This section of the report summarises the options and modelling decisions.

All the house types with roofs have a pitched roof facing East and West. When solar PV is enabled, PV panels are incorporated into the models by placing them equally on each side of the roof[21], adding up to a total of approximately 4 kWpeak. (In the case of the Mid-terrace with solid walls, the attic gets in the way and the total is slightly less.) Heat losses from the inverter warm up the Kitchen/living area zone.

The parameter 'batterykWh' controls the size of the battery if present. Zero means there is no battery. There are costs for two sizes of battery: 4 kWh and 6 kWh. This is the useful kWh – this is usually less than the nominal battery size because batteries can be damaged if they are discharged fully. The maximum charge or discharge rate is 4 kW for a 4 kWh battery, or 5 kW for an 8 kWh battery. The lifetime of the battery is 10 years (so there is a cost for replacing batteries after 10 years). This is based on typical use, and one charge-discharge cycle a day. The round-trip charging efficiency is 90% and the inverter efficiency is 90%.

The modelling allows for either PV, or a battery, or both, or none. Having a battery allows demand shifting to reduce energy bills when a variable tariff is used. This is achieved by avoiding drawing from the grid at peak times and by charging when it is cheap. However, the modelled time of use (TOU) tariff does not have a cheap rate overnight, unlike Economy 7, for example. The TOU tariff is based on wholesale prices and at time of writing, these are not particularly low overnight.

The modelling has simple control policies for how to use a battery depending on the situation, as described in Table 3.3 below.

**Table 3.3: Battery-control strategies for different combinations of PV and tariff**

| PV | Tariff | |
|---|---|---|
| No | Conventional | Battery is pointless. No use of battery. |
| Yes | Conventional | Default behaviour: surplus PV goes into battery and this is used whenever there is a need |
| No | TOU | Charge overnight (up to 5.30am) and use from 4pm |
| Yes | TOU | See below |

[21] In reality PV is more likely to be installed on the south-facing roof, where output is higher. This is a limitation of the model, and PV facing south would be somewhat more attractive, with higher annual output per kWp installed.

The cases with a variable tariff are complex. They are described in more detail below.

Figures 3.20 and 3.21 below show the overall impact on self-consumption and on peak power demand in the Mid-terrace case with cavity walls, which is typical. ‘Self-consumption’ is the proportion of total PV generation that is used in the dwelling rather than exported.

**Figure 3.20: Proportion of self-consumption for Mid-terrace house with cavity walls and different battery systems**

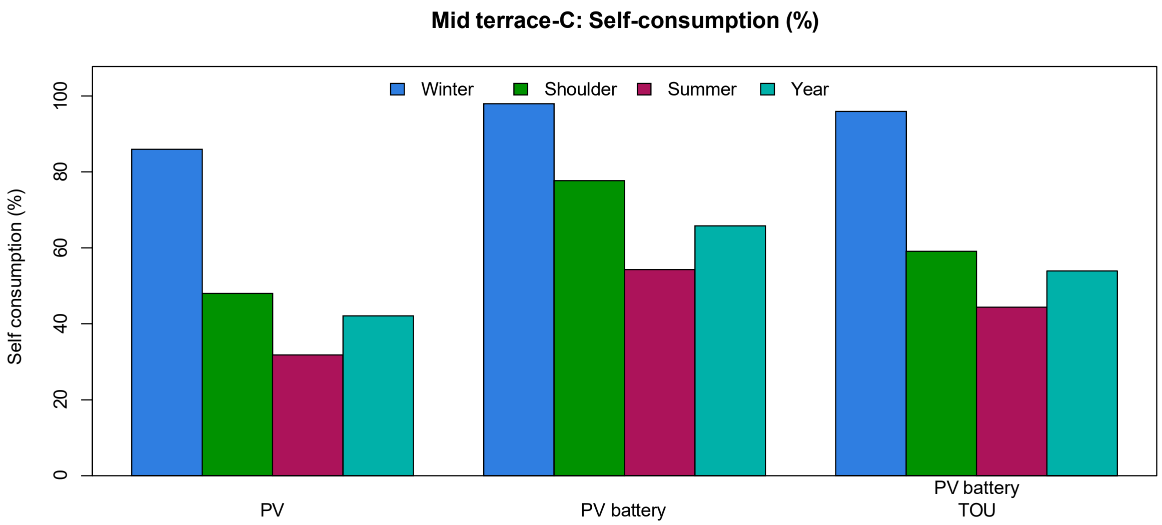
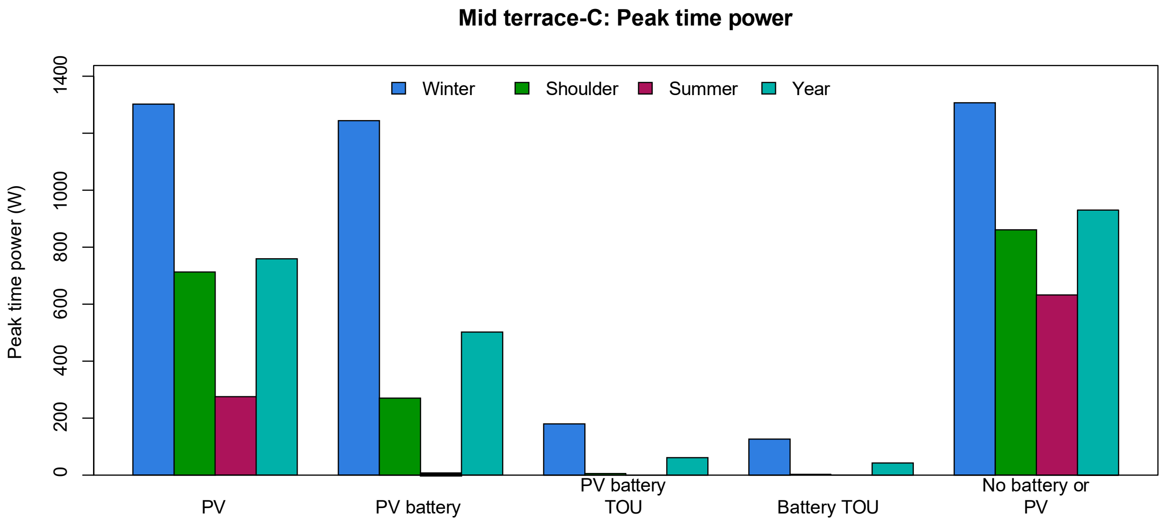



**Figure 3.21: Peak power draw for Mid-terrace house with cavity walls and different battery systems, in different seasons**




Self-consumption is always very high in winter. Using a battery further enhances self-consumption, especially in the shoulder seasons, when there is significant solar generation. In the summer, self-consumption is less than in the shoulder season because there is more power available than is needed.

Under the TOU tariff, when battery power is saved until peak times, the battery is very effective at reducing peak time power consumption (see also Flexibility chapter, below).

## Battery and PV with a TOU tariff

When there is a battery and PV with a TOU tariff there is a trade-off between storing cheap electricity overnight and hoping for free electricity during the day. There is also a trade-off between using stored electricity during the day or saving it for peak time.

The models have rules for how much to charge the battery overnight, and when to use it during the day. For the overnight charges:

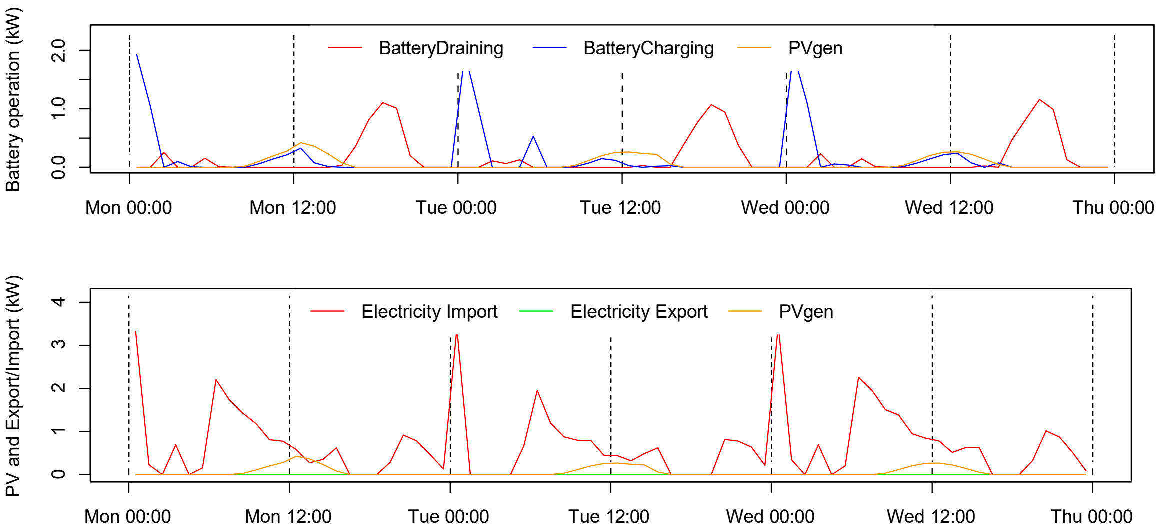
- 80% of maximum charge in Jan, Feb, Nov, Dec
- 50% in Mar, Apr, Sep, Oct; and
- 0% in May, Jun, Jul, Aug.

The other rules for when to use the battery are as follows:

- Between 5.30 am and 4pm, the battery can charge up from surplus solar PV.
- Between 5.30 am and 3pm, it can also discharge - provided that it is 90% full.
- After 4pm, the battery is allowed to discharge as required and can also charge up from surplus PV.

This regime is illustrated at different times of year in Figures 3.22 to 3.24 below. In Figure 3.22 (January) the battery charges fully overnight, allowing some use in the morning when it is nearly full, and main use at peak time and during the evening. In Figure 3.23 (March) there is less use of the battery at peak time as there is still some solar power available. In Figure 3.24 (July) there is no overnight charging, and the battery is mainly used after the evening peak, because before the peak there is little demand and during the peak there is sunshine and hence PV electricity available.

## Figure 3.22: Battery and PV with TOU tariff in January




## Figure 3.23: Battery and PV with TOU tariff in March

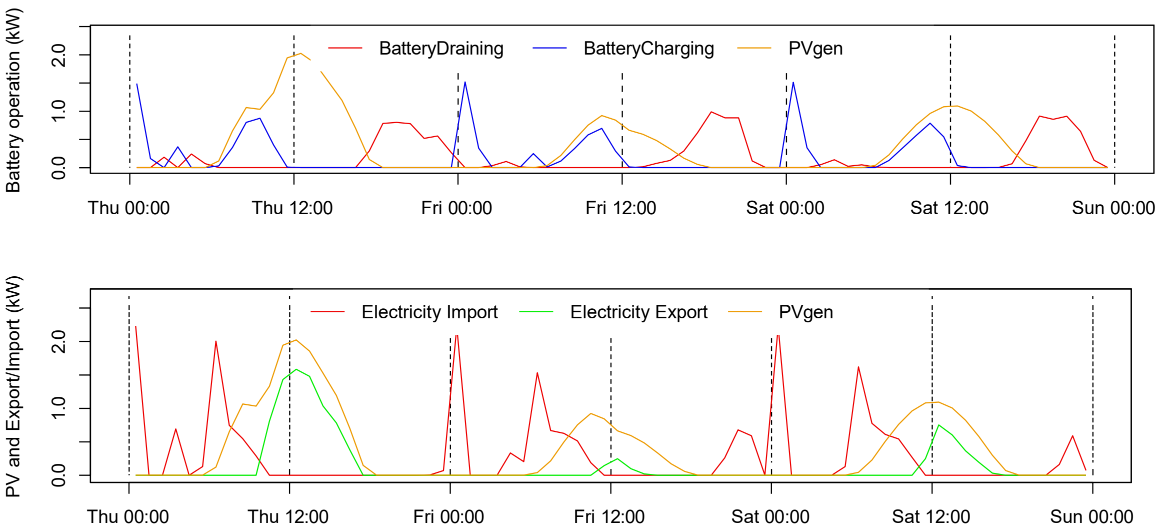
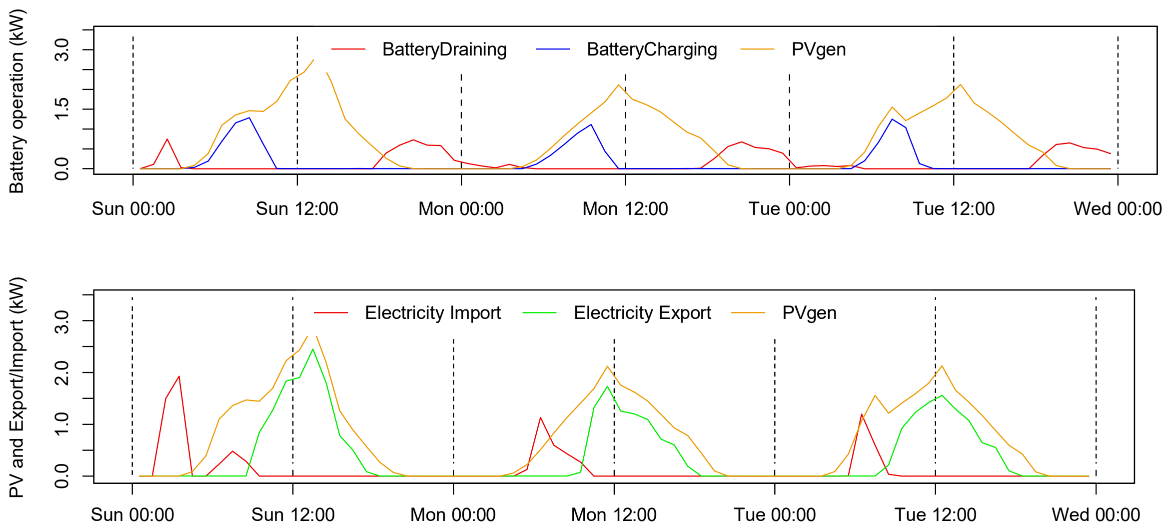


**Figure 3.24: Battery and PV with TOU tariff in July**

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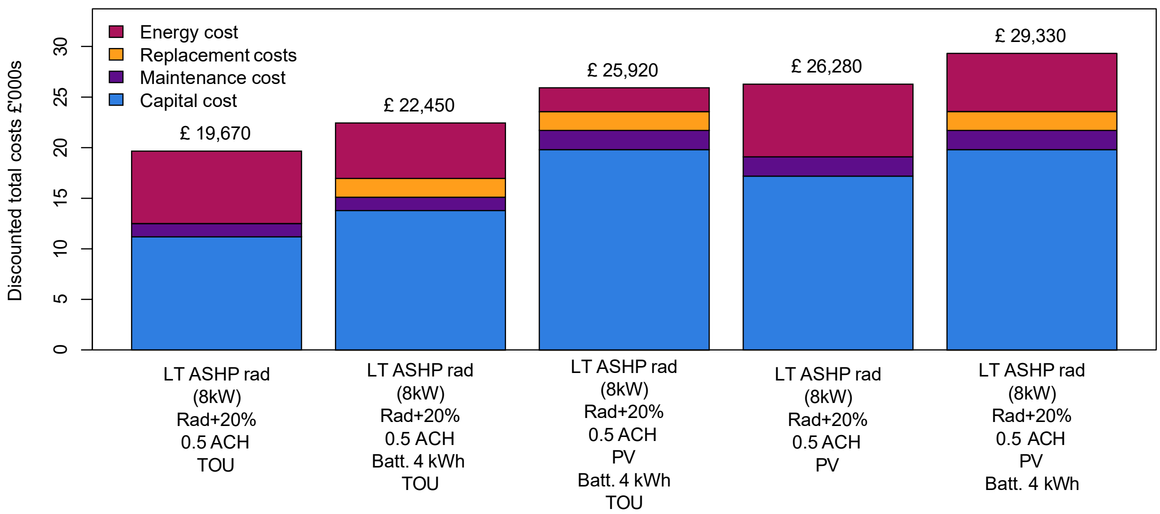
## Effect of battery and PV on total costs

Although the use of the battery reduces energy costs by reducing peak time power consumption, this is not enough to override the extra costs involved. In particular, the 10-year lifetime of the battery means replacement costs are incurred during the 15-year accounting period. Costs are discussed in more detail in later chapters, but Figure 3.25 below indicates the effect of these measures on costs in the standard scenario (allowing either time-of-use or conventional tariffs) with a 3.5% discount rate. In the battery-only case, energy savings are roughly balanced by the replacement costs, and capital costs are also increased. Adding solar panels reduces energy costs still further, but the increased capital cost (CapEx) is almost as much as the total cost in the base case. In the figure, the base case is the cost optimal package for this archetype, with a low temperature heat pump and draught proofing to 0.5 ACH (air changes per hour).

**Figure 3.25: Impact of a 4 kWh battery on costs for Mid terrace-C**



# Tariffs

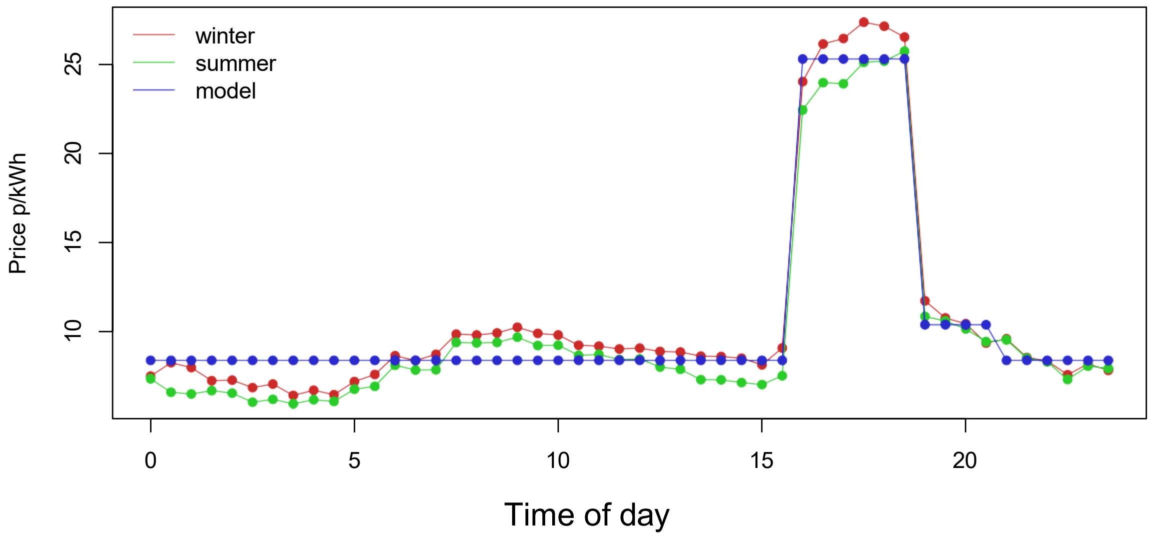
The models use three different tariffs for energy use:

- Conventional fixed rate tariff (all heating types except storage radiators) 19.4p/kWh.
- Economy 7 (for storage radiators) 22.8p/kWh daytime, 9.8p/kWh overnight.
- TOU (Time of Use) variable tariff 25.3p/kWh peak time 4-7pm, 8.4 – 10.4p/kWh at other times.

For the Economy 7 and the TOU tariffs, there are different prices at different times of the day. The Economy 7 tariff is markedly cheaper overnight (midnight to 6am), while the TOU tariff is markedly more expensive at peak time. The TOU tariff uses typical values derived from the Octopus Agile tariff prices in 2019[22], which is in turn based on wholesale prices. These vary hour by hour, dependent on a range of factors, of which weather (and hence demand and renewable energy availability) is only one. There was no clear seasonal trend but very clear trends through the day. These are approximated by different levels, see Figure 3.26 below.

Octopus Agile may change over time and future wholesale-based tariffs may differ significantly from this pattern. However, Agile is most popular example of a dynamic tariff we have at this time.

**Figure 3.26: Mean prices from the Agile tariff, used as our reference model for the TOU tariff, compared with the actual prices used**




[22] Agile Octopus | Octopus Energy

The actual rates for the TOU tariff in the model are:

8.4 p/kWh (midnight-4pm)
25.3p/kWh (4pm-7pm)
10.4p/kWh (7pm-9pm)
8.4p/kWh (9pm-midnight)

There are variations to heating operation when the TOU tariff is active:

- options for earlier start times for the twice a day heating cases may be selected – reducing energy use during the evening peak
- for the thermal store cases, heating of the thermal store during peak times is disabled (unless the temperature drops below a threshold)
- for the hybrid cases, the boiler is used instead of the heat pump during peak times, 4-7pm.

These points are included in the optimisation, with different runs for earlier start times.

## Thermal comfort

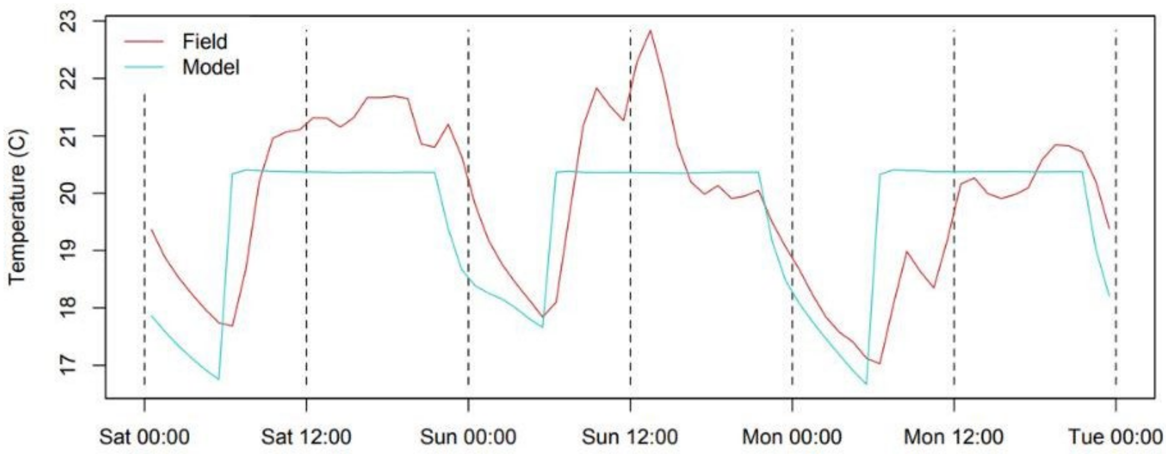
All the EnergyPlus models have thermostatic control of heating, based on the operative temperature, calculated as the mean of the air temperature and radiant temperature. Air temperature is commonly used in modelling, but operative temperature is a better measure of comfort levels. Also, thermostats and other measuring devices are in practice significantly affected by wall temperature, which is one of the main drivers of radiant temperature. The radiant temperature comes from surfaces such as walls, floor and furniture – according to their temperature. It changes much more slowly than the air temperature.

For validation, CODE model temperature profiles were compared with profiles from an alternative energy model and with field data. The alternative modelling system used was IES. Equivalent modelling showed similar (not identical) patterns of radiant and operative room temperature.

The field data comparison used data from similar homes that had detailed monitoring, taken from another CAR project. Figure 3.27 below shows a temperature profile from the field compared to one from an EnergyPlus model. The temperature profiles depend on the external temperature, the thermal envelope efficiency (insulation and infiltration), heating regimes and also thermal mass effects. In the field they also depend on ‘micro’ changes occupants might make, such as window opening, changing thermostatic radiator valves, using hot water (which can divert water from the space heating circuit), cooking and a host of other factors. This means that field data is more erratic, while modelled data is smoother, with fewer spikes and troughs. Figure 3.27 below compares real and modelled temperatures over three days in winter, with field data chosen so the dwelling matched archetype characteristics as closely as possible.

The plots are certainly not identical, but the patterns are similar. Readers should note that the warming up and cooling gradients are similar when heating is on and off (albeit with steeper warm-up times for the modelled temperatures), and also that whereas the real home temperature is almost never stable, the dynamic simulation indicates roughly stable temperatures when the heating is on. The mean temperatures are almost the same, and gas or electricity use are unaffected by the differences, so they do not affect the cost-effectiveness evaluations.

**Figure 3.27: Typical temperature profile from a real 'field' home with a combi boiler (an 80m² semi-detached house with un-insulated cavity walls), measured by temperature sensors fixed to a wall, alongside the closest archetype dwelling**



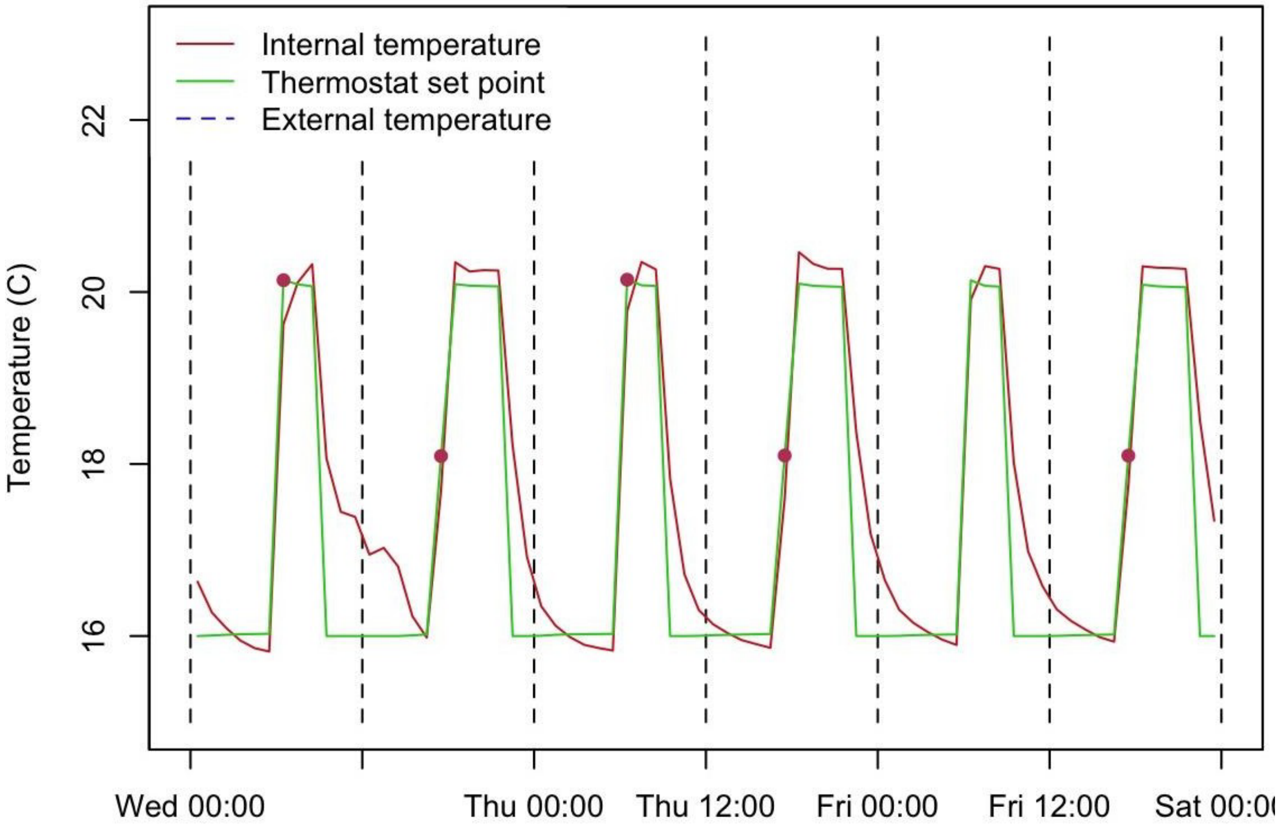

The thermostat setting is 21°C in the living/kitchen area and 20°C in all other rooms. This is different from SAP, where other rooms are heated to only around 18°C (with the actual temperature depending on the heating system and insulation). However, data from the Energy Follow-Up Survey 2018 (EFUS)[23] shows that most homes have only a one-degree difference between different parts of the house (partly because people leave internal doors open). All of the heating systems are sized to provide adequate heating down to an external temperature of -3°C. However, response times are also important so post processing includes checks that the thermostat setpoints are achieved adequately. The checks applied are:

- Count the number of hours in the year (unmet hours) when the mean operative temperature is more than 0.25°C below the setpoint in any heating zone.
- The number of unmet hours in the year must be no more than 200.

In practice, the first hour when the heating comes on is usually marginally unmet (because it takes time for rooms to come up to temperature) and if there are two periods of heating in the day this often happens both times, hence the limit of 200. Figure 3.28 below shows a typical plot in cold weather (mean temperature 3°C), with red points indicating where heating settings are not achieved.

[23] BRE (Forthcoming) Energy Follow Up Survey 2018. Watford: BRE.

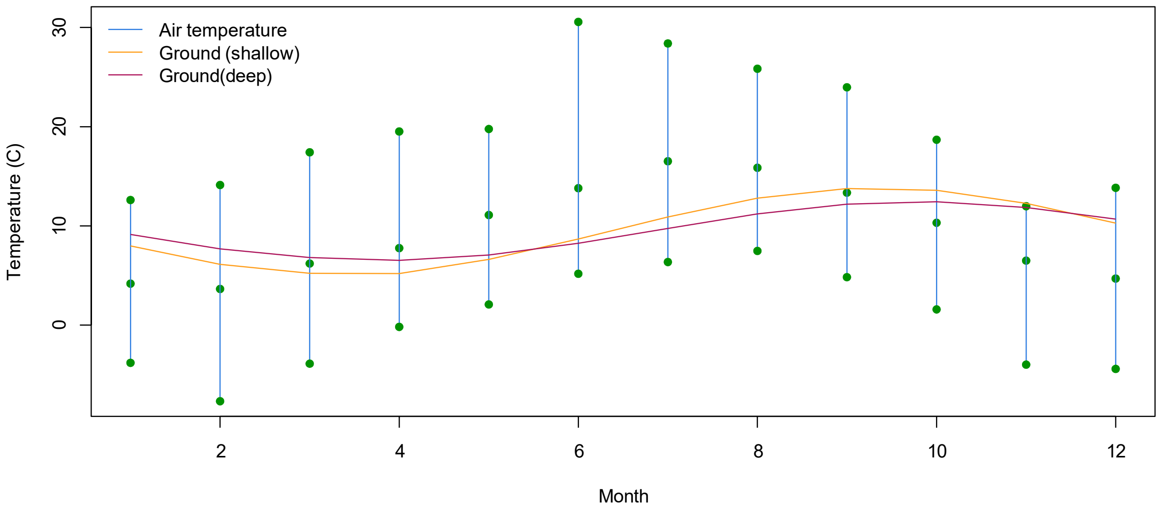
**Figure 3.28: Unmet hours for a typical winter day: red dots show times when the heating system does not achieve within 0.25°C of the setpoint**



# Weather data

The weather used in the model is from Finningley (near Sheffield). This is taken to be average across the whole of Great Britain, following precedents in other work – notably the early versions of SAP, the Standard Assessment Procedure, used for energy assessments in Building Control.[24] Comparing annual means, the CODE weather mean is 9.5°C, while the UK long-term average is 9.9°C.[25] Figure 3.29 below shows the temperature variation through the year. Ground temperatures are also included. The shallow ground temperature relates to heat loss through floors and the deeper temperatures are used in the ground source heat pump models. The deeper ground has a similar mean temperature but varies less.

**Figure 3.29: Temperature data through the year used in modelling, monthly external temperature ranges, and ground temperatures.**




24 [SAP - Standard Assessment Procedure | BRE Group](#).
25 Energy Trends Table 7.1 https://www.gov.uk/government/statistics/energy-trends-section-7-weather.

# 4. Costs

*Capital costs and operating costs in CODE are based on the best available evidence, using UK Government sources where possible. All sources are documented and referenced in the Assumptions Log for the CODE models.*

## Building a picture of costs for domestic electrification

The CODE models are necessarily complex, and they include capital costs for a wide range of different house types and technologies. The house types were drawn from analysis of housing archetypes, while the technologies were selected in discussion with BEIS, and informed by a detailed review of the literature about providing electric heating in homes.

The house types included in models are shown in Table 4.1 below.

**Table 4.1: House types included in CODE**

| House type | Description |
|---|---|
| Small flat | This is a small and 'space-constrained' 1-bedroom top floor flat, with a flat roof. The façade ratio is high and the living area fraction is also high, mainly because it is small and has only one bedroom. It has electric storage heaters and a small water cylinder with an immersion heater for hot water. |
| Ground floor flat | This 1-bedroom flat has a solid ground floor. Compared to the other flats it has slightly higher ceilings (2.55m compared to 2.50m) and less glazing area (in proportion to the floor area). It has only a small length of semi-exposed wall. It has electric storage radiators for heating and an immersion heater for hot water. |
| Mid floor flat | This 2-bed mid-floor flat is average for windows area but has more semi-exposed walls than the others. This flat has a combi boiler for heating and hot water. It has lower infiltration than the previous two flats: 0.8 air changes per hour, compared to 1.28 for the previous two, since it is based on a more recently-built flat. |

| House type | Description |
|---|---|
| Top floor flat | This 2- bed top floor flat has more windows than the ground and mid floor flats. It has a pitched roof, and a gas combi-boiler with no water cylinder. It has the most air-tight construction of all the flats - 0.64 air changes per hour – and proportionately more glazing. It is based on a flat built from 2000 to 2009. |
| Bungalow | This bungalow has a shallow party wall (so only the front half of one wall is shared with the bungalow next door). This reflects even numbers of detached/semi bungalows across the stock. It is very square in shape. The living areas are on the west side. It has a system boiler and a 110-litre hot water cylinder. |
| Mid terrace-C | This 2-bed mid-terrace with cavity walls is quite narrow, and a 2-storey projecting element makes it quite long from front to back (east to west). External wall area is modest for the floor area. It has a gas combi boiler providing space and water heating. It has above-average infiltration (1.12 air changes per hour). |
| Mid terrace-S | This is a solid wall house with suspended timber floors. It is relatively square in shape, and although it is a little larger than the previous archetype it has an even smaller wall area. It has high ceilings compared to the others. It has no projecting element but it does have a room in the roof. It has a gas combi boiler. |
| Compact (semi-d) | This is a large semi-detached house with 4 bedrooms and cavity walls. It is the largest of all the archetype dwellings, at 132 $m^2$, and the main house is quite square but there is a small single storey projecting element. It has a system boiler with a 210-litre cylinder. |
| Medium (end terrace) | This is a semi-detached house with 3 bedrooms. It has an L-shape plan, with a large square main section and two storey projecting element. It has a gas combi boiler, and a conservatory – the only archetype with a conservatory. It has relatively high infiltration: 1.28 air changes per hour. |

| House type | Description |
|---|---|
| Medium (semi-d) | This is a 3-bed end terrace house with solid walls and a suspended timber floor, fairly narrow and with a substantial 2-storey projecting element. It has a gas system boiler, with 140-litre cylinder. It has relatively low infiltration – certainly for a house with suspended timber floors: only 0.8 air changes per hour. |
| Sprawling-C (detached) | This is a relatively square 3-bed detached house with cavity walls. Although it is compact in shape, the façade ratio is high due to its relatively small size (104 m2) and detached form. It has a gas system boiler, with a 140-litre cylinder. It has very good air-tightness, and the lowest infiltration rate of all the house archetypes: just 0.64 air changes per hour. |
| Sprawling-S (detached) | This is a rectangular 4-bed detached house with solid walls, and high ceilings. It has a gas system boiler, with 210-litre cylinder. Although it does not have any projecting elements it has a high façade ratio by virtue of the high ceilings and detached form. It is modelled with four occupants, which affects hot water and appliance use. |

Each of these dwelling types has different costs attached to fabric upgrades (insulation and airtightness), and improvements to heating systems. The differences come from different floor areas/configurations (e.g. the ratios of floor to wall and floor to window areas), and from different starting points (e.g. what thickness of wall insulation, if any, they have before any upgrades take place; and what heating system they have).

Some of the upgrades only apply to specific dwelling types, so flat-roof insulation only applies to dwellings with flat roofs, top-up loft insulation does not apply to flats, and floor insulation only applies to dwellings with suspended timber floors.

All homes are taken to have some loft insulation in the base case, and dwellings with cavity walls are taken to already have cavity-wall insulation.

Most of the fabric upgrades in CODE have costs separated into fixed and variable costs, with variable costs related to floor, wall, roof and window area, see Table 4.2 below. The variable components of internal and external wall insulation are both scaled based on net wall area (wall minus doors and windows). Draught-stripping and floor insulation have fixed costs only, because evidence cites a flat cost per dwelling, while triple glazing and flat-roof insulation have only variable costs, because this is how the evidence presents these upgrade costs. All costs include labour costs but exclude VAT.

**Table 4.2: Fabric upgrades included in CODE**

| Measure | Fixed cost | Variable cost |
|---|---|---|
| External wall insulation | £4,490 | £40/ $m^2$ (net wall area)[26] |
| Internal wall insulation | £1,800 | £90/ $m^2$ (net wall area)[27] |
| Top-up loft insulation | £175 | £6/ $m^2$ (roof area)[23] |
| Floor insulation | £3,835[23] | - [but costs adjusted -20% to +40% based on floor area] |
| Draught-stripping to achieve 0.8 ac/h | £200[28] | - |
| Draught-stripping to achieve 0.5 ac/h | £400 | - |
| Triple glazing | - | £320/ $m^2$ (window area)[29] |
| Flat roof insulation | - | £80/ $m^2$ (roof area)[30] |

The heating systems are all sized according to both the house type under consideration, and the fabric improvement measures that have taken place. This works by the CODE models performing a ‘coldest day’ calculation of the space heating load when the external temperature is -3°C. For example, a small flat with improved wall insulation might need 5 kW of heating to achieve comfort on the coldest day of the year, while a large, detached house with solid walls and no improvements to insulation might need 20kW of heating on the coldest day. The same detached house might need only 12kW of heating on the coldest day if it first has all fabric upgrades applied (external wall insulation, triple-glazed windows, top-up loft insulation, floor insulation and draught-stripping).

[26] J Palmer et al. (2017) WHAT DOES IT COST TO RETROFIT HOMES? Updating the Cost Assumptions for BEIS’s Energy Efficiency Modelling. London: BEIS.
[27] D Glew et al. (2020) Thin Internal Wall Insulation (TIWI): Measuring Energy Performance Improvements in Dwellings Using Thin Internal Wall Insulation. Leeds: Leeds Beckett University (p19).
[28] EST website, for professional work to exclude drafts (https://energysavingtrust.org.uk/home-insulation/draught-proofing).
[29] J Palmer et al. (2018) How much would it cost to raise standards? Initial Costs for the Energy Aspects of SHAP’s Healthy Housing New Build Standard. Birmingham: SHAP.
[30] https://www.insulation-info.co.uk/roof-insulation#flatroof

**Table 4.3: Heating system upgrades included in CODE**

| Measure | Fixed cost | Variable cost |
|---|---|---|
| Air-to-air heat pump | £910 per room | £175/kW[31] |
| High-temperature air-source heat pump | £2,390 | £880/kW[32] |
| Low-temperature air-source heat pump | £1,870 | £690/kW[33] |
| Ground-source heat pump | £8,370 | £1,030/kW[34] |
| Hybrid heat pump with existing boiler | £1,870 | £690/kW[35] |
| Radiant panel heaters | £680 per room | £350/kW[36] |
| Storage heaters | £310 per room plus £195 for the WiFi controller | £430/kW[37] |

According to the heating system under scrutiny, costs vary according to floor area. All costs are adjusted from the year evidence was collected to 2020, using the Retail Price Index.

The costs of a ground-source heat pump can be lower with a shared ground-couple (borehole or slinky coil). However, this option is site specific and not always possible, so this is excluded here.

[31] BEIS Assumption.
[32] https://www.gov.uk/government/publications/evidence-gathering-high-temperature-heat-pumps-hybrid-heat-pumps-and-gas-driven-heat-pumps.
[33] Delta-EE (2020) Cost of Domestic Heating Measures Final Cost Database. BEIS: London. https://www.gov.uk/government/publications/cost-of-installing-heating-measures-in-domestic-properties?
[34] Delta-EE (2020) Cost of Domestic Heating Measures Final Cost Database. BEIS: London.
[35] Carbon Trust/Rawlings Support Services (2016) Evidence Gathering – Low Carbon Heating Technologies Domestic High Temperature, Hybrid and Gas Driven Heat Pumps: Summary Report. London: BEIS.
[36] BEIS Assumption.
[37] https://www.alertelectrical.com/dimplex-quantum-1250w-high-heat-retention-storage-heater-with-iq-controls-qm125rf.html?

**Table 4.4: Ancillary heating upgrades included in CODE**

| Measure | Fixed cost |
|---|---|
| Hot-water cylinder (for houses where this is not already present, including a buffer tank) | £2,190[38] |
| Wet heating system (for houses or flats where this is not already present) | £4,380 (house) £2,190 (flat) [35] |
| Larger radiators (where radiators are already present) | £270 per radiator[35] |
| Thermal store | £1,760[39] |
| Underfloor heating | £5,480 (flat) to £12,600 (detached house)[35] |
| Instantaneous electric water heaters (for flats which do not have a hot water cylinder already). | £350[40] |

There are 7,200 different combinations of fabric upgrade measures, heating systems and costs covering all house types in the model.

## Energy prices

Turning to running costs, energy costs, maintenance costs of heating systems, and replacement costs are all included in the models. The energy prices are most significant (although all come into the optimisation work). Energy prices come from BEIS's Retail Fuel Prices, Tables 4-6, using the 'Central Domestic' figures for 2020, and the prices used in CODE are listed in Table 4.5 below.

Most of the energy prices are self-explanatory. The time-of-use tariffs have already been described in 'Tariffs', above. The electricity export price comes into play for homes with photovoltaics systems that allow households to generate their own power, and sell any excess generation they cannot consume themselves back into the grid. Export prices are invariably lower than prices for using electricity from the grid.

[38] Delta-EE (2020) Cost of Domestic Heating Measures Final Cost Database. BEIS: London. https://www.gov.uk/government/publications/cost-of-installing-heating-measures-in-domestic-properties?
[39] Committee on Climate Change (2019) Net Zero Technical Report. London: CCC.
[40] https://www.plumbnation.co.uk/water-heaters/instantaneous-water-heaters/

**Table 4.5: Energy prices in CODE models**

| Energy | Price per kWh |
|---|---|
| **Electricity (standard)** | 19.4p |
| **Electricity (Economy 7)** | 22.8p (peak)<br>9.6p (off-peak) |
| **Time-of-Use Electricity (based on Octopus Agile Tariff)** | 8.4p (midnight-4pm)<br>25.3p (4pm-7pm)<br>10.4p (7pm-9pm)<br>8.4p (9pm-midnight) |
| **Electricity exported to the grid** | 5.5p |
| **Gas** | 4.8 |

Readers should note that energy tariffs are very likely to change over time, and this snapshot only aims to capture present energy costs. As the UK moves forward to Net Zero, electricity generation and supply will change, and this is likely to affect energy prices.

Readers should also note that the CODE models include feedback to heating operation when the TOU tariff is active:

- earlier start times for the twice a day heating cases may be selected – reducing energy use during the evening peak
- for the thermal store cases, turning off heating the thermal store during peak time (unless the temperature drops below a threshold)

## Discounting

BEIS asked us to focus CODE modelling on a 15-year time horizon, so we take into account all costs linked to energy use in the 12 archetype dwellings falling in the next 15 years. Capital costs to fund fabric upgrades and/or heating systems fall in Year 1 and these are straightforward, but for energy costs incurred in the future, maintenance costs and/or replacement costs, we apply discount rate of 3.5% (the Social Discount Rate used in the Treasury's Green Book), as directed by BEIS. The Green Book advocates a 3% discount rate beyond 30 years, but this is not relevant here. In our sensitivity analysis we also explored the impact of not having any discounting, and a high rate of 7.5%. These would put less, and greater emphasis, respectively, on up-front costs.

# 5. Optimisation

*Finding the optimal costs for electric heating in homes was a central task in this project. Total costs were assessed for every combination of fabric upgrade and electric heating system, and mathematical optimisation selected the lowest-cost package of measures for each house type.*

## Optimising total costs over 15 years

The total costs of electric heating include not only up-front capital costs (CapEx), but also energy costs, maintenance costs and replacement costs (collectively known as OpEx). Higher initial costs may be justified by lower running costs, and the accepted wisdom is that it is better to invest in insulation and air-tightness prior to installing a heat pump, because this allows the heat pump to work more efficiently, which reduces running costs and $CO_2$ emissions.

There is a balance to strike between insulation, air-tightness and the choice of heating system, and this balance changes depending on the thermal performance of a dwelling to begin with. It also changes according to which tariff is selected, whether the dwelling needs to be heated continuously or intermittently, and (sometimes) depending how many occupants there are (which affects hot-water use). The optimisation set out to explore optimum total costs, initially over a 15-year time horizon, and subsequently over longer and shorter periods (25 years and five years), to see how the balance of measures might change depending how far into the future those investing consider. The optimisation includes estimated service lives and replacement costs for components that are likely to be replaced, using assumptions about service lives that are consistent with assumptions made by the Committee on Climate Change[41], which suggests that heat pumps are likely to last 15 to 20 years.

Most people put more value on costs or benefits affecting them now than on costs or benefits that fall in the future. This is known as the 'time value of money', and the accepted method of reflecting this (e.g. in the Treasury's Green Book[42]) is to discount future costs and benefits. In this project future costs are discounted at 3.5% a year, the rate used in the Green Book for investments of up to 30 years. (Alternative discount rates were also examined as part of sensitivity analysis, see 'Sensitivity Analysis' section, p110.)

In this project iterative optimisation using a genetic algorithm was applied to combinations of dwelling archetype, insulation and airtightness measures, electric heating system and tariff. There are between 12,000 and 101,000 different combinations of fabric upgrade measures, heating systems tariffs and configuration options for each archetype in the model. Genetic algorithms work by first selecting a random combination of measures and tariff, then making small changes to the measures and monitoring whether the changes result in higher or lower total costs. Subsequent iterations learn from this, so each successive iteration gets closer to

[41] Committee on Climate Change (2019) Net Zero Technical Report. London: CCC.
[42] https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent

the optimum combination of parameters, and the process continues until the outcome cannot be improved.

Genetic algorithms are not guaranteed to produce the optimal result, so a local optimisation step was also added, carrying out an exhaustive search in small areas of the search space around the best solution for each combination of archetype and heating system. For tariffs, the options were a conventional electricity tariff where the price per kWh is either constant, or (for the storage radiator cases) Economy 7 (with cheaper night-time electricity); or a Time-of-Use tariff (in this case modelled on Octopus Energy's Agile tariff, with prices more reflective of the wholesale cost of electricity).

This part of the report is divided into five parts:

1. The optimum selection for all house types (the single best combination of measures for all archetypes).
2. The optimum for one house type (showing the best combination of measures for each of the heating systems – illustrating the full range of measures for one archetype).
3. The costs, energy use and carbon emissions for all house types and all heating systems, presented as matrices.
4. Annual energy use and daily achieved temperature profiles for one house type.
5. The 'optimisation frontier' for one house type (plotting costs and emissions of many combinations of measures, with the optimums shown).

## Optimum selection for all house types

Capital costs, maintenance costs and energy costs for the most cost-effective combinations of measures are shown in Figure 5.1 below. Looking across all 12 archetypes, there is an even split between low-temperature air-source heat pumps (LT ASHPs, with heat pumps supplying the existing system of radiators and a hot-water cylinder) and reversible air-to-air heat pumps (Air2air, without radiators, and with a separate system for providing hot water). Six of the 12 house types select LT ASHPs as the lowest-cost combination, and six select air-to-air heat pumps.

All six of the LT ASHPs need slightly larger radiators (in order to improve the seasonal coefficient of performance, and response times). One of these systems – the Mid-terrace house with solid walls – also requires a higher set-back temperature (18°C rather than the usual 16°C) in order to achieve comfort when heating is needed. The set-back temperature is the thermostat setting outside the usual heating times.

Air-to-air heat pumps came out as the lowest-cost combination of measures for all four flats, and the two large houses with solid walls (the Medium semi-detached house with solid walls, and the Sprawling detached house with solid walls). Air-to-air heat pumps do not need radiators, so this option reduces installation costs by eliminating the need to replace radiators with larger ones (although costs of disposing of the old radiators are included). Air-to-air heat pumps also have lower 'variable costs' than other heating systems, so they are relatively economical for larger systems with higher heat output. (A large (12 kW) air-to-air system might cost £6,500, compared to £10,200 for a large LT ASHP system.)

All four of the flats selected a high setback temperature as part of their optimised package. This increases annual electricity use, but it means they come up to temperature more quickly, and allows them to pass the thermal comfort test. The thermal comfort test is described earlier in ‘Thermal Comfort’.

The two flats that had electric storage heaters in the base case select air-to-air heat pumps in the optimised scenario. The original storage heaters (with poor control and no fan) would have failed the thermal comfort test, and this partly explains why the flats could not simply continue using the existing storage heaters. These two cases both have improved air tightness, but additional roof insulation was not justified for the small flat, which has a roof.

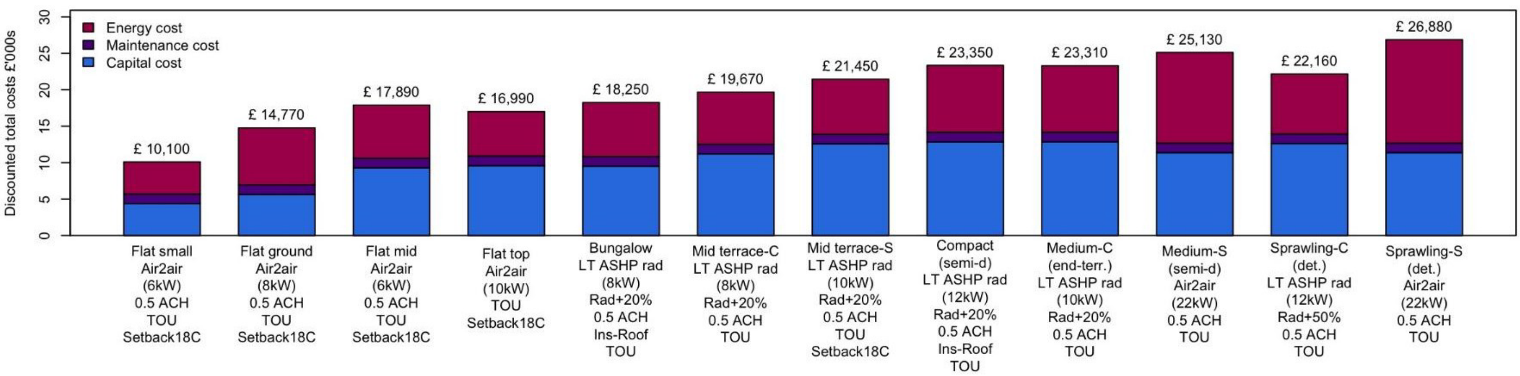
For domestic hot water, all the LT ASHP cases have a cylinder which is partly heated by the heat pump, with top up from immersion. The air-to-air heat pump cases have a cylinder and immersion heater unless they are 70 m$^2$ or less, in which case they have instantaneous water heaters. For larger properties that did not have hot-water cylinders in the base case (i.e. those with combi boilers) this means they will have to find space to install new hot-water cylinders.

Readers should note that the heating systems are sized for each house type based on the fabric measures specified, so more insulation and/or better airtightness means that smaller heating systems are needed. Smaller heating systems flow through and reduce the capital cost of that package. There is also a check in each case that comfort requirements are met.

In all cases, any costs of stripping out and disposing of the existing heating system, pipework and/or radiators are included in the optimisation as appropriate.

Hybrid heating systems (using a heat pump in tandem with the existing gas boiler) are omitted here because they still burn gas – with concomitant carbon emissions – as well as using electricity. However, we return to hybrid systems in Appendix 1.

**Figure 5.1: Optimum measures for all house types, any tariff**



**Key**

ASHP – Air-Source Heat Pump
Air2Aair – Air-to-Air Heat Pump
GSHP – Ground-Source Heat Pump
Heating start = 15:00 – Evening start time for heating brought forward in order to achieve comfort (here, to 15:00, compared to 17:30 normally)
HT – High Temperature (flow rate of 55°C)
LT – Low Temperature (flow rate of 45°C for radiators, 35°C for underfloor heating)
ACH – Infiltration rate (in air-changes per hour, which is a measure of air-tightness, and lower is better for energy efficiency)
Radiant – Radiant panel heaters
Radiators +20% – if oversized radiators are needed to achieve comfort, this shows how much larger they need to be than standard radiators
Ins-Roof = 100 – top up loft insulation 100mm thick
Setbacktemp = 16 – if a higher temperature is needed outside normal periods of heating, in order to achieve comfort, this shows the higher set-back temperature (default is 16°C for heat-pump systems; 12°C for other heating systems)
Storagerad (8kW) – Electric storage heaters (in this case, with 8kW total output)
TOU – time of use tariff based on wholesale prices (not the baseline Economy 7)
Ts – thermal store
Uf – underfloor heating

All of the optimised choices above come out with the 'high' airtightness measure – resulting in 0.5 air-changes per hour. This is not surprising, since airtightness is a cheap measure (£400). However, this is contentious. Many commentators[43,44] would say that this level of airtightness is undesirable and causes humidity and condensation unless there is mechanical ventilation. This is an unintended consequence[45] of energy efficiency measures. The counter-argument is that these potential problems can and should be managed with better ventilation practices (e.g. avoiding drying clothes indoors, putting lids on pots while cooking, opening windows when more ventilation is needed, etc.) which are not necessarily costly or mechanical.

Not one of the optimised combinations has any of the more expensive fabric measures: internal or external wall insulation, or floor insulation. This indicates that none of these are justified for purely financial reasons for the boundary of this model. This situation may change if the scope of the costs included the whole energy system (electricity generation, transmission and distribution), as happens in BEIS and UCL's UK TIMES model[46].

Figure 5.1 (which we call a 'standard' run of the models) shows the optimum selections when the time-of-use tariff is allowed. This has very attractive electricity prices outside of the evening peak (see below). The time-of-use tariff is selected for all 12 optimised cases, because it offers households lower energy costs than conventional flat-rate or Economy 7-type dual rate tariffs.

[43] F R Stephen et al. (1997) Ventilation and house air tightness: Effect on indoor temperature and humidity in Southampton, UK. Building Services Engineering Research and Technology 18 (3) pp 141-147.
[44] J Fernandez-Aguera et al. (2019) Thermal comfort and indoor air quality in low-income housing in Spain: The influence of airtightness and occupant behaviour. Energy and Buildings 199 (15) pp 102-114.
[45] M Davies, T Oreszczyn (2012) The unintended consequences of decarbonising the built environment: A UK case study. Energy and Buildings v.46 pp80-85.
[46] See UK TIMES | UCL ENERGY INSTITUTE MODELS - UCL – University College London.

However, the TOU tariff may not be available to all households (note that the Agile tariff is currently offered only by Octopus energy), so Figure 4.2 below shows an equivalent chart where the TOU tariff is excluded from the optimisation search space. This shows that the change in tariffs causes a re-ranking of the most cost-effective heating systems, and new combinations of heating systems and fabric upgrades. Now that the optimisation algorithm can only select a flat electricity tariff or a dual rate tariff (for storage heaters), LT ASHP heating systems become the most economical proposition for all eight of the 'house' archetypes. The Small flat now has modern and more controllable electric storage heaters rather than the air-to-air heat pump selected before, while the Ground-floor, Mid-floor and Top-floor flats stay with air-to-air heat pumps. For the Small flat, lower heat demand combined with the benefit of an overnight electricity rate mean it is more economical to select storage heaters.

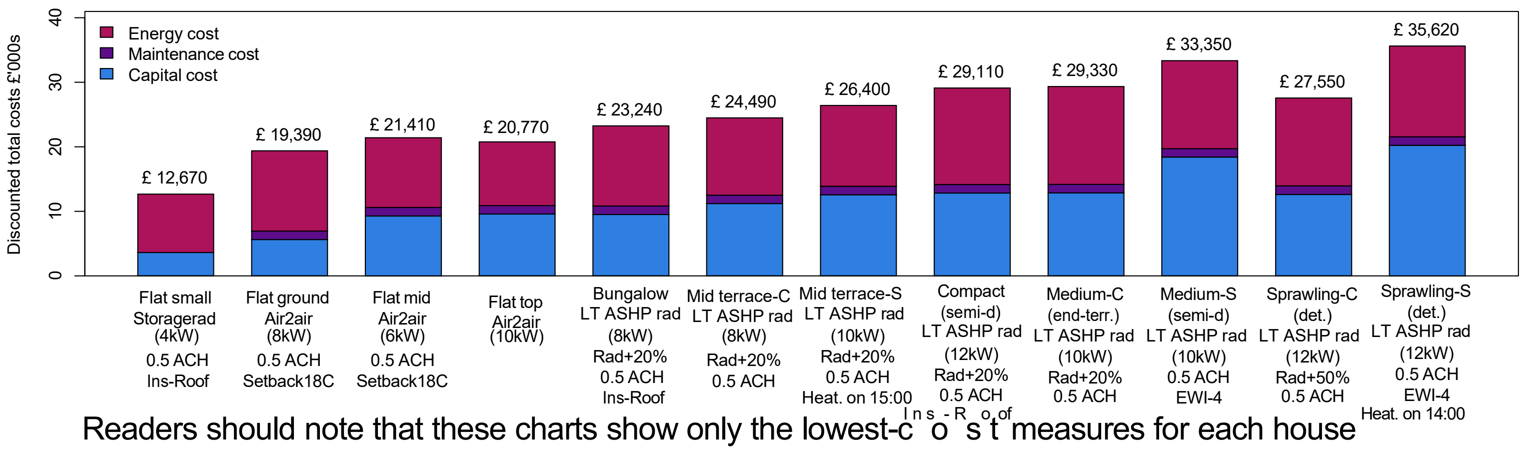
With conventional tariffs (Economy 7 for storage heaters) and electric heating, external wall insulation now becomes financially viable for two of the three house types with solid walls ('Medium S' and 'Sprawling S'). (EWI is several times more expensive than replacing radiators, which are needed for the other large house types, but not for the solid-wall houses with EWI. 'EWI-4' means all four walls are insulated, with 100mm of expanded polystyrene.)

However, apart from these two house types now adopting external wall insulation, there is little change to fabric measures as a result of using conventional tariffs (for example, it makes no difference to floor insulation, which is never selected).

Two house types select earlier afternoon start times for heating: Mid-terrace-S, and the Sprawling-S detached house with solid walls. In both cases, this is needed to achieve comfort conditions in the evening.

In all of these cases, energy costs are higher without the (economical) time-of-use tariff. There are no maintenance costs for the Small flat because new storage heaters are very unlikely to need any maintenance within the next 15 years.

Figure 5.2: Optimum measures for all house types, conventional tariffs only




Readers should note that these charts show only the lowest-cost measures for each house type over 15 years (with discounting), and in fact for most house types the cost of the first, second, third and fourth most economical can be very similar, see next two sections. This is important, and it means there is often little to choose between some sets of measures when selecting purely on cost grounds.

## Optimum selection for a single house type

In addition to finding the single optimum combination of measures and electricity tariff for each archetype, we also used optimisation to find the most cost-effective combination of measures and tariff for each of the heating systems, for each house type. This basically answers the question: "For this house type, what is the most cost-effective way to install X", where 'X' is an air-source heat pump, an air-to-air heat pump, or any of the 12 heating systems.

Tables showing total costs, energy use and carbon emissions for all house types and all heating systems are provided in the next section, but here we focus on two specific house types to illustrate the approach. First we use the 'Sprawling-C' case, a three-bedroom house type that is one of the most common house types in the country. This has insulated cavity walls, a solid concrete floor, a system boiler with a 140 l hot-water cylinder, and double glazing in the base case. The floor area is 104 $m^2$. The three occupants are out in the daytime, so there is conventional two-period heating, and there is no conservatory.

Figure 5.3 below shows the lowest cost packages of measures, with the same split of CapEx, maintenance costs and energy costs over 15 years we saw before.

For this house type the most cost-effective package has a low-temperature air-source heat pump and radiators 50% larger than the existing ones, with 'high' air-tightness measures resulting in a low air-change rate, and using the TOU tariff. No other measures are selected for this package. However, the next-best combination of measures has only slightly higher costs (just £640 more over 15 years). The second-best combination uses an air-to-air heat pump with a TOU tariff and a high setback temperature to achieve comfort conditions. No fabric upgrades are selected whatsoever through the optimisation. Note that this house type was air-tight to start with – 0.64 air-changes per hour – which means there is limited benefit from the air-tightness measures. This house was also relatively well insulated, based on a house built since 2010.

The next four packages of measures have total costs only slightly higher, and all within £770 of each other: a high-temperature air-source heat pump with and without a thermal store, a low-temperature ASHP with thermal store (where savings in energy costs from the thermal store shifting energy demand outside the 4-7pm peak period do not quite repay the increased capital costs), and electric storage heaters. For the electric storage heater case, higher energy costs mean that top-up roof insulation is now justified on cost grounds. Although storage heaters have much lower installation costs than the heat pumps, increased energy costs more than offset this benefit.

There is a large jump in costs to the next-best package of heating system and measures: £4,860 more over 15 years for radiant panel heaters. This is similar to the electric storage heaters in that installation costs are low, but energy costs are much higher – three or four times higher than the heat pump systems.

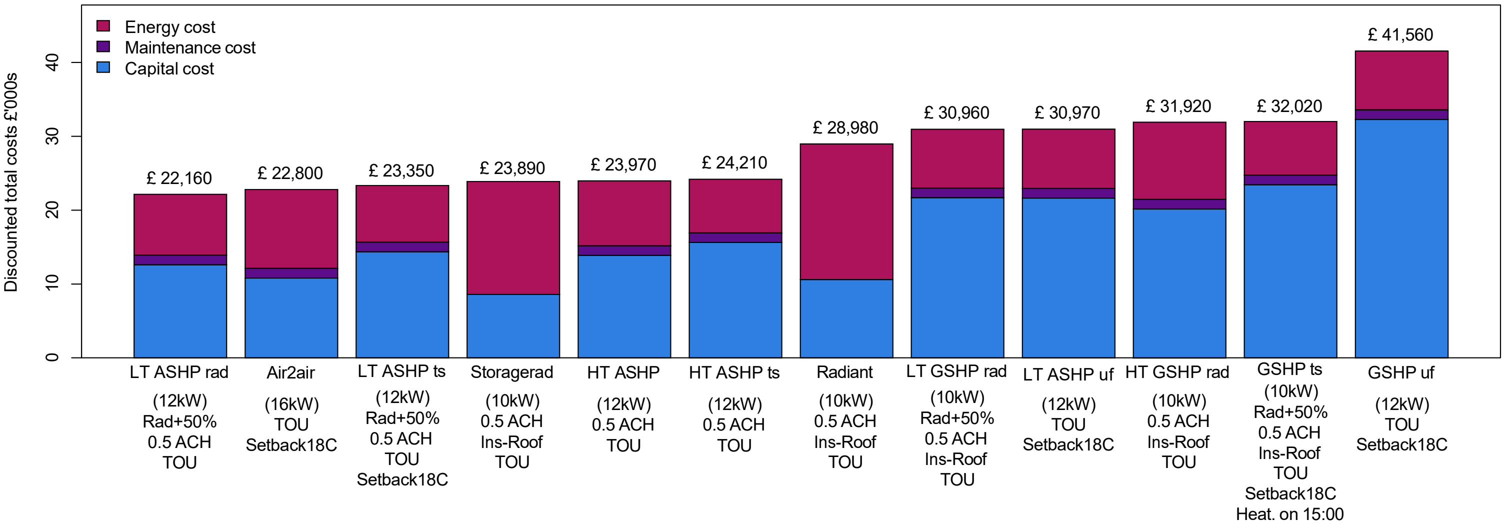
The next four packages of heating systems and measures witness another large increase in costs, and all have broadly similar costs. The four include three ground-source heat pump systems (high and low temperature, and with a thermal store), and an air-source heat pump with underfloor heating. For the latter, the small improvement in the coefficient of performance from the underfloor heating is offset partly by the slower response time (which forces a higher setback temperature to achieve comfort). This means that energy costs are almost the same as the same heat pump serving oversized radiators, but with much higher capital costs.

The last package of measures has a GSHP with underfloor heating. Although this brings some energy savings by improving the seasonal coefficient of performance of the heat pump, once again there is a penalty from slower response time, and these savings still fall short of repaying the much higher CapEx of underfloor heating within 15 years.

Readers should note that not all of the heating systems are sized the same for this house: the heating demand was calculated based on the fabric measures, so more insulation and better airtightness means that smaller heating systems are needed. The cost calculation process also includes a check that comfort requirements have been met, with a large cost penalty in case it has not, so that these cases are never selected.

Notice also that storage heaters and radiant panel heaters have no maintenance costs (because no servicing or maintenance should be needed in the first 15 years of installation). Nevertheless, increased energy bills (because they both provide direct heating without the benefit of the coefficient of performance multiplier that applies to heat pumps) outweigh the savings in maintenance costs.

**Figure 5.3: Optimum measures for a typical three-bedroom house**

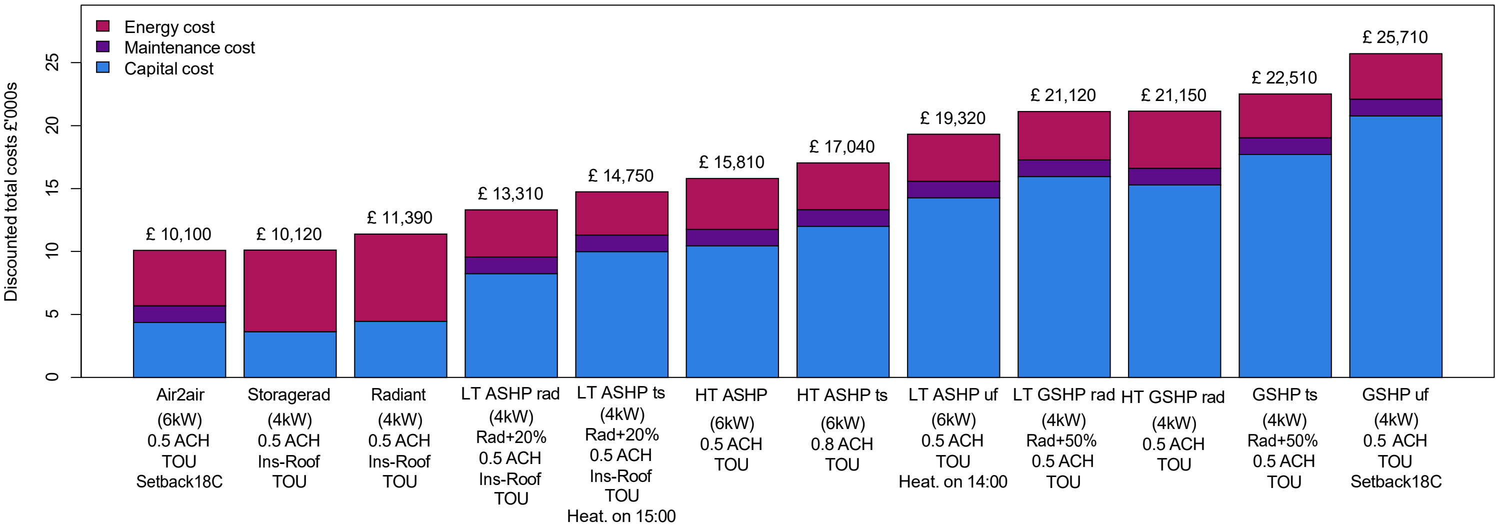



The second example of a single house type focuses on the Small flat, see Figure 5.4 below. This is a top-floor flat with insulated cavity walls and a solid floor. The floor area is only 42 $m^2$, and there is a single occupant. The base case heating system for this flat is electric storage heaters, with an immersion heater for domestic hot water.

The cost optimal combination of measures in this case uses air-to-air heat pumps, but the next-best combination – costing only £20 more over 15 years – uses new, controllable storage heaters. Radiant panel heaters are not much more expensive over 15 years, although energy costs (and energy use) for this option and storage heaters is higher. These two direct electric heating systems both benefit from negligible maintenance costs over 15 years – neither should need to be replaced within 15 years.

All of the other combinations of measures (all of the air-source and ground-source heat pumps) have the same maintenance costs, and broadly similar energy costs over 15 years. However, installation costs (CapEx) rise for successive packages moving from left to right across the chart, with ground-source heat pumps and underfloor heating costing more than other options. This trend is consistent across most of the house types, see next section.

**Figure 5.4: Optimum measures for a small flat**




## Matrices of total cost, energy use and emissions

This section of the report provides information about the overall effect of all of the modelled heating systems on all house types. Figure 5.5 below shows the Net Present Value[47] of the optimised combinations over 15 years, including maintenance and energy costs. As before, future costs are discounted at 3.5% a year. The bottom row in grey shows baseline costs – just electricity and gas bills – for each unimproved house type. (Abbreviations in the figure are explained in the key on p70 above.)

The figure shows how heating systems relate to each house type, but as well as the heating systems other fabric measures accompanying the heating systems vary from case to case, based on the optimisation, as with 'Optimum selection for all house types', above.

These running costs go from £8,610 to £20,140. Blue cells in the matrix show the total costs of each new, electric heating system applied to these house types. These costs include energy, capital costs of installing the new system and accompanying insulation and airtightness measures, and maintenance costs. The cells are colour-coded so that lower total costs appear lighter, and the 'best' financial proposition is marked with a black box. Looking across all house types, total cost of ownership for the electric heating systems runs from £10,100 over 15 years (for air-to-air HPs in a small flat) up to £49,100 for a GSHP and underfloor heating in the sprawling house with solid walls.

Indeed, the GSHP with underfloor heating emerges as the highest-cost option in every case. It is more difficult to generalise across the more economical heating systems, but air-to-air heat pumps are most attractive for the flats. Low-temperature air-source heat pumps with radiators have lowest costs for all of the houses apart from Medium-S (semi-d) and Sprawling-S (detached), which both have solid walls. For these two houses, air-to-air heat pumps again come out most economical, as we saw above.

What is revealing in this chart is how close some of the different packages of measures are on total cost of ownership – at least for some house types. For example, for the Bungalow or Sprawling-C (detached), low-temperature air-source heat pumps, high-temperature ASHPs,

[47] The total of all future costs and benefits, discounted back to today's money.

air-to-air heat pumps, and the hybrid heating systems are all within £1800 of each other over 15 years.

Note that hybrid systems are considered separately here because they do not completely switch to electric heating. However, Figure 5.5 shows that total costs are very competitive, and in some cases total cost of ownership is lower than the cost-optimal all-electric package of measures. Hybrid combi-boilers have lowest costs for flats and houses that already have combi-boilers. For house types that previously had system boilers, they are only slightly more expensive than the lowest-cost option. (The hybrid systems do not apply to the first two flats because they did not have boilers in the base case, and they can only link to hot-water cylinders for homes with system boilers in the base case.)

**Figure 5.5: Net Present Value of all heating systems in all house types over 15 years, in £2020**

| | Flat small | Flat ground | Flat mid | Flat top | Bungalow | Mid terrace-C | Mid terrace-S | Compact (semi-d) | Medium-C (end-terr.) | Medium-S (semi-d) | Sprawling-C (det.) | Sprawling-S (det.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GSHP ts | £22,510 | £27,250 | £27,740 | £26,890 | £28,730 | £30,400 | £33,000 | £34,680 | £34,320 | £37,780 | £32,020 | £39,560 |
| HT ASHP ts | £17,040 | £19,590 | £19,130 | £20,400 | £20,680 | £22,740 | £23,900 | £27,080 | £27,790 | £30,730 | £24,210 | £33,240 |
| LT ASHP ts | £14,750 | £18,540 | £19,160 | £19,570 | £19,370 | £20,870 | £23,380 | £24,670 | £24,380 | £28,390 | £23,350 | £31,110 |
| Hybrid system | NA | NA | NA | NA | £18,400 | NA | NA | £23,380 | NA | £27,330 | £22,170 | £28,460 |
| Hybrid combi | NA | NA | £15,710 | £16,090 | NA | £17,410 | £19,130 | NA | £21,040 | NA | NA | NA |
| GSHP uf | £25,710 | £30,120 | £30,270 | £30,140 | £35,720 | £37,490 | £39,840 | £44,520 | £42,600 | £46,130 | £41,560 | £49,100 |
| LT GSHP rad | £21,120 | £25,650 | £26,360 | £27,460 | £27,330 | £29,080 | £29,570 | £33,750 | £33,130 | £36,990 | £30,960 | £38,630 |
| HT GSHP rad | £21,150 | £26,060 | £25,880 | £26,180 | £28,280 | £29,610 | £30,830 | £35,630 | £34,440 | £40,020 | £31,920 | £40,980 |
| LT ASHP uf | £19,320 | £21,590 | £21,880 | £22,530 | £26,530 | £28,340 | £30,090 | £34,800 | £32,730 | £36,410 | £30,970 | £39,330 |
| LT ASHP rad | £13,310 | £17,190 | £17,930 | £18,370 | £18,250 | £19,670 | £21,450 | £23,350 | £23,310 | £27,270 | £22,160 | £28,350 |
| HT ASHP | £15,810 | £18,600 | £18,260 | £19,630 | £19,770 | £21,290 | £23,450 | £27,080 | £27,080 | £30,530 | £23,970 | £33,290 |
| Air2air | £10,100 | £14,770 | £17,890 | £16,990 | £19,000 | £21,430 | £21,940 | £24,500 | £24,250 | £25,130 | £22,800 | £26,880 |
| Radiant | £11,390 | £17,580 | £19,330 | £19,860 | £23,700 | £24,620 | £26,610 | £31,480 | £30,130 | £33,930 | £28,980 | £36,240 |
| Storagerad | £10,120 | £15,320 | £17,980 | £17,870 | £20,130 | £21,350 | £22,800 | £26,440 | £26,080 | £30,680 | £23,890 | £32,120 |
| Baseline | £8,610 | £14,220 | £9,340 | £9,240 | £13,830 | £12,570 | £12,540 | £15,210 | £16,770 | £18,680 | £13,020 | £20,140 |

## Annual energy use

Figure 5.6 below shows the total annual energy use for all of the housing archetypes, with the same heating systems and measures as in the cost matrix above. For the base case and hybrid systems, figures in brackets are gas consumption. All other figures are electricity use, and this includes lights and appliances as well as heating and auxiliary loads. Again, cells are colour-coded so that lighter colours show lower consumption.

For the base cases, electricity use varies from 1,480 kWh a year for the top-floor flat, up to 12,180 kWh a year for the ground-floor flat with electric storage heaters. Gas use varies from

6,460 kWh a year up to 24,120 kWh a year for the Sprawling-S house with uninsulated solid walls. These modelled figures are consistent with Ofgem's Typical Domestic Consumption Values[48] for 2020: the 'medium' figures are 2,900 kWh for electricity and 12,000 for gas.

For the new electric heating systems and accompanying fabric improvements to come out of optimisation, electricity use ranges from 2,750 kWh a year for the small flat with GSHP and underfloor heating up to 14,310 kWh a year for the Compact semi-detached house (which is the largest house type, at 132 $m^2$) using storage radiators.

In terms of energy use alone, storage heaters and radiant panel heaters come out worst for most house types. Again, this is because they do not benefit from the coefficient of performance multiplier that applies to heat pumps. Also, in the case of storage heaters, some electricity is wasted by charging the heaters when no heat is needed in dwellings.

GSHP with underfloor heating comes out top in most cases, just beaten by the high-temperature air-source heat pump for the mid-floor flat, where improved response times brings a small saving compared to the GSHP packages. The GSHP with a thermal store ("ts") has lowest annual energy use for the Mid-terrace house with solid wall, and for the Sprawling detached house with cavity walls. In both cases, energy use is only a little lower than the GSHP with underfloor heating. They win out here not because of the thermal store per se, but because having this and being able to shift power use outside the peak period changes the other measures that are installed alongside the heat pump and thermal store.

While the hybrid heating systems result in low electricity consumption, this is outweighed by the increase in gas use – from two-thirds as much gas as electricity, rising in the case of the Sprawling-C case up to more gas than electricity, in kWh a year.

48 https://www.ofgem.gov.uk/gas/retail-market/monitoring-data-and-statistics/typical-domestic-consumption-values

**Figure 5.6: Annual electricity (gas) consumption for all heating systems and house types (MWh)**

| | Flat small | Flat ground | Flat mid | Flat top | Bungalow | Mid terrace-C | Mid terrace-S | Compact (semi-d) | Medium-C (end-terr.) | Medium-S (semi-d) | Sprawling-C (det.) | Sprawling-S (det.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GSHP ts | 2.85 | 4.72 | 4.43 | 3.79 | 5.26 | 5.42 | 4.37 | 6.58 | 6.39 | 7.86 | 5.62 | 5.78 |
| HT ASHP ts | 3.17 | 4.77 | 4.58 | 4.34 | 5.50 | 5.56 | 5.41 | 6.89 | 6.85 | 8.55 | 6.06 | 9.48 |
| LT ASHP ts | 2.81 | 4.67 | 4.55 | 4.26 | 5.24 | 5.06 | 5.92 | 6.56 | 6.43 | 8.11 | 5.99 | 5.97 |
| Hybrid system | NA | NA | NA | NA | 3.96(3.16) | NA | NA | 4.65(4.82) | NA | 6.68(4.03) | 4.39(4.62) | 6.97(5.94) |
| Hybrid combi | NA | NA | 2.97(3.54) | 2.69(2.84) | NA | 3.80(2.58) | 3.68(3.94) | NA | 5.03(3.18) | NA | NA | NA |
| GSHP uf | 2.75 | 4.25 | 4.29 | 3.70 | 5.01 | 4.70 | 4.90 | 6.26 | 6.06 | 7.45 | 5.71 | 5.61 |
| LT GSHP rad | 2.90 | 4.63 | 4.49 | 4.01 | 5.23 | 5.45 | 5.20 | 6.66 | 6.48 | 8.00 | 5.70 | 5.98 |
| HT GSHP rad | 3.19 | 5.29 | 4.59 | 4.53 | 6.48 | 6.07 | 6.30 | 8.64 | 8.17 | 11.18 | 7.30 | 7.42 |
| LT ASHP uf | 2.84 | 4.30 | 4.44 | 4.12 | 5.06 | 4.77 | 5.04 | 6.06 | 6.10 | 7.63 | 5.80 | 8.81 |
| LT ASHP rad | 2.86 | 4.72 | 4.59 | 4.14 | 5.37 | 5.18 | 5.45 | 6.46 | 6.56 | 8.14 | 5.89 | 8.77 |
| HT ASHP | 3.00 | 4.80 | 4.25 | 4.36 | 5.49 | 5.26 | 5.47 | 7.01 | 6.87 | 8.61 | 6.14 | 6.20 |
| Air2air | 3.35 | 5.38 | 4.67 | 4.29 | 6.15 | 5.91 | 6.45 | 8.28 | 7.44 | 8.94 | 7.42 | 10.06 |
| Radiant | 5.01 | 8.63 | 6.57 | 6.90 | 10.87 | 9.43 | 10.64 | 13.95 | 12.97 | 11.06 | 12.51 | 12.25 |
| Storagerad | 5.63 | 8.91 | 7.77 | 8.06 | 11.08 | 9.78 | 11.14 | 14.31 | 13.23 | 11.52 | 13.01 | 12.14 |
| Baseline | 7.78 | 12.18 | 2.00(6.46) | 1.48(7.61) | 2.36(13.15) | 2.38(10.89) | 1.98(12.14) | 2.64(15.14) | 3.09(16.26) | 2.74(20.61) | 2.09(12.68) | 2.49(24.12) |

## Greenhouse gas emissions

When homes switch to efficient electric heating they are likely to be compatible with the Government's Net Zero targets. Decarbonised electricity is a key plank in the UK's move to Net Zero. The emissions factor for electricity is falling every year due to increased generation from renewables, and it also changes through the day and through the year, depending on the generation mix and where in the UK power is consumed. However, it is outside the scope of this project to incorporate variable emissions factors.

Figure 5.7 below applies current, fixed emissions factors to gas and electricity use generated in the CODE models (184 $gCO_2e/kWh$ for gas and 233 $gCO_2e/kWh$ for electricity[49]). There are some clear links between the patterns in Figure 5.7 and Figure 5.6 above: storage heaters and radiant panel heaters bring highest emissions, while GSHPs with underfloor heating bring lowest overall emissions in most cases. Again, the high-temperature air-source heat pump (HT ASHP) comes out very well for the mid-floor flat, and the low-temperature ASHP with underfloor heating comes out best for the Compact semi-detached house. The HT ASHP benefits when there is relatively low demand for space heating, because it can heat water to the 60°C needed for a weekly Legionella cycle – without relying on a less efficient immersion heater.

49 https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020

**Figure 5.7: Annual greenhouse gas emissions (Tonnes, $CO_2e$)**

| | Flat small | Flat ground | Flat mid | Flat top | Bungalow | Mid terrace-C | Mid terrace-S | Compact (semi-d) | Medium-C (end-terr.) | Medium-S (semi-d) | Sprawling-C (det.) | Sprawling-S (det.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GSHP ts | 0.66 | 1.10 | 1.03 | 0.88 | 1.23 | 1.26 | $\boxed{1.02}$ | 1.53 | 1.49 | 1.83 | $\boxed{1.31}$ | 1.35 |
| HT ASHP ts | 0.74 | 1.11 | 1.07 | 1.01 | 1.28 | 1.30 | 1.26 | 1.61 | 1.60 | 1.99 | 1.41 | 2.21 |
| LT ASHP ts | 0.66 | 1.09 | 1.06 | 0.99 | 1.22 | 1.18 | 1.38 | 1.53 | 1.50 | 1.89 | 1.40 | 1.39 |
| Hybrid system | NA | NA | NA | NA | 1.50 | NA | NA | 1.97 | NA | 2.30 | 1.87 | 2.72 |
| Hybrid combi | NA | NA | 1.34 | 1.15 | NA | 1.36 | 1.58 | NA | 1.76 | NA | NA | NA |
| GSHP uf | $\boxed{0.64}$ | $\boxed{0.99}$ | 1.00 | $\boxed{0.86}$ | $\boxed{1.17}$ | $\boxed{1.09}$ | 1.14 | 1.46 | $\boxed{1.41}$ | $\boxed{1.74}$ | 1.33 | $\boxed{1.31}$ |
| LT GSHP rad | 0.67 | 1.08 | 1.05 | 0.93 | 1.22 | 1.27 | 1.21 | 1.55 | 1.51 | 1.86 | 1.33 | 1.39 |
| HT GSHP rad | 0.74 | 1.23 | 1.07 | 1.06 | 1.51 | 1.41 | 1.47 | 2.01 | 1.90 | 2.61 | 1.70 | 1.73 |
| LT ASHP uf | 0.66 | 1.00 | 1.03 | 0.96 | 1.18 | 1.11 | 1.17 | $\boxed{1.41}$ | 1.42 | 1.78 | 1.35 | 2.05 |
| LT ASHP rad | 0.67 | 1.10 | 1.07 | 0.96 | 1.25 | 1.21 | 1.27 | 1.51 | 1.53 | 1.90 | 1.37 | 2.04 |
| HT ASHP | 0.70 | 1.12 | $\boxed{0.99}$ | 1.02 | 1.28 | 1.23 | 1.27 | 1.63 | 1.60 | 2.01 | 1.43 | 1.44 |
| Air2air | 0.78 | 1.25 | 1.09 | 1.00 | 1.43 | 1.38 | 1.50 | 1.93 | 1.73 | 2.08 | 1.73 | 2.34 |
| Radiant | 1.17 | 2.01 | 1.53 | 1.61 | 2.53 | 2.20 | 2.48 | 3.25 | 3.02 | 2.58 | 2.91 | 2.85 |
| Storagerad | 1.31 | 2.08 | 1.81 | 1.88 | 2.58 | 2.28 | 2.60 | 3.33 | 3.08 | 2.68 | 3.03 | 2.83 |
| Baseline | 1.81 | 2.84 | 1.66 | 1.74 | 2.97 | 2.56 | 2.69 | 3.40 | 3.71 | 4.43 | 2.82 | 5.02 |

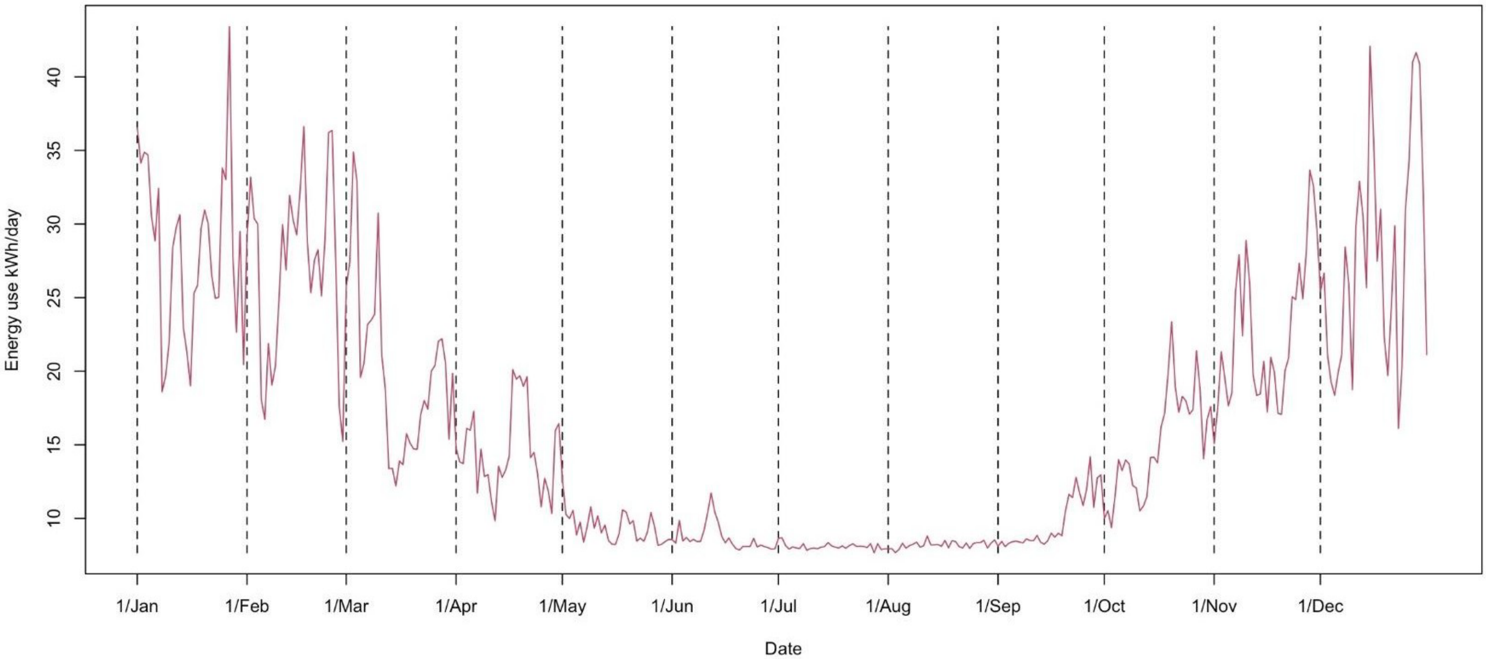
### Hybrid systems

Hybrid systems cannot match the carbon savings from entirely electric heat pump systems, even with current emission factors for electricity – and hybrids will benefit less than other forms of electric heating from continued reductions in greenhouse gas emissions from electricity. However, with current emissions factors they still offer significant benefits over storage radiators and radiant panels – apart from the two large solid-wall houses (Medium-S and Sprawling-S). Lower energy costs mean that fewer fabric measures are justified on cost grounds, resulting in higher emissions.

## Annual demand profiles

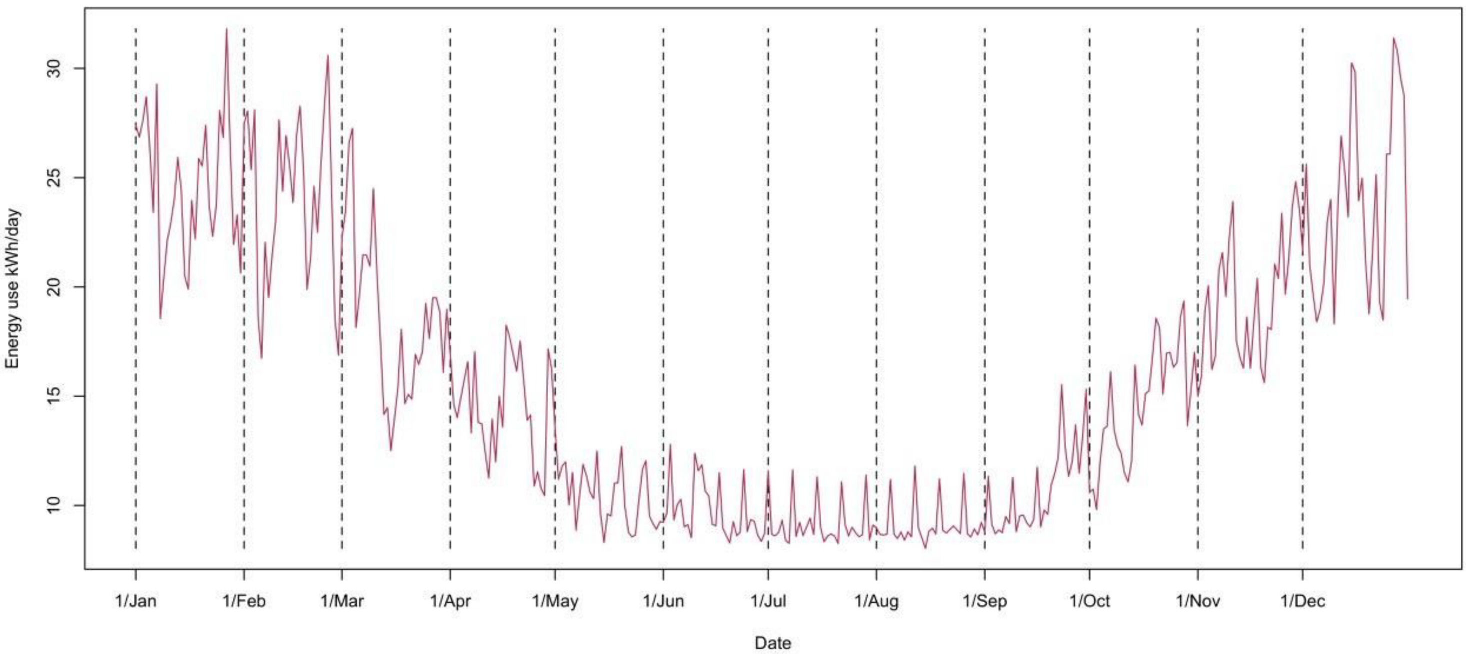
The CODE models generate annual electricity-use profiles for all combinations of house type and optimised heating system. To illustrate the outputs, Figure 5.8 below shows the daily demand for electricity of the sprawling house with cavity walls (the same single house examined above, with the most cost-effective basket of measures, including a high-temperature air-source heat pump), plotted over a year. This chart is for the house on a TOU tariff – conventional tariffs may well lead to different optimal packages of measures, and so different demand profiles. The electricity use for water heating, lights and appliances during the summer is around 8kWh a day, rising to 44 kWh a day on very cold days in January and December.

**Figure 5.8: 12-month profile of electricity use – typical three-bedroom semi-detached house with high-temperature air-source heat pump**




As a contrast, Figure 5.9 below shows the same house with the heating system resulting in lowest annual electricity use: the GSHP with underfloor heating. This has a similar electricity consumption in summer but peak consumption of only 32kWh a day on the coldest days in winter. The mean winter electricity use falls from about 25kWh a day in winter with the high-temperature ASHP down to 22 kWh a day with the ground-source heat pump, and an even larger reduction in ‘shoulder’ months of March and October. Summer consumption is peakier in Figure 5.9 because, while the high-temperature heat pump runs hot enough to generate domestic hot water directly, the (low-temperature) ground-source heat pump does not, so an immersion heater must be used for heating water above 40°C.

**Figure 5.9: 12-month profile of electricity use – typical three-bedroom semi-detached house with ground-source heat pump and underfloor heating**



Despite the marked differences in electricity consumption between these two heating systems, both offer similar thermal comfort, see Figures 5.10 and 5.11 below. Both figures show the coldest day of the year – the day when the average temperature was lowest. The top graph in each figure shows the achieved temperature (blue) compared to the temperature outside. Pink bars show the peak electricity demand periods from 4-7pm. The house reaches 21°C when occupants want it in the morning and evening (i.e. two periods of heating), and at weekends.

The most significant difference between the charts is the clear effect of the 18°C set-back temperature that is selected for the ground-source heat pump with underfloor heating in Figure 5.10. This means that the internal temperature is much more stable, and higher, than for the high-temperature air-source heat pump example.

The high-resolution electricity use charts emphasise the point above about electrical demand being higher for the high-temperature ASHP: just over 4kW on the coldest days, against just over 3kW for the ground-source heat pump with underfloor heating. If large numbers of homes used this heating system in preference to high-temperature ASHP this would mean considerably less pressure on the electricity supply system. Readers should note that periods of high heating demand in the charts usually coincide with high electrical demand for other uses, and the peak power draw in these cases occurs towards the end of the 4-7pm national peaks.

**Figure 5.10: Coldest day achieved temperatures – typical three-bedroom semi-detached house with ground-source heat pump and underfloor heating**

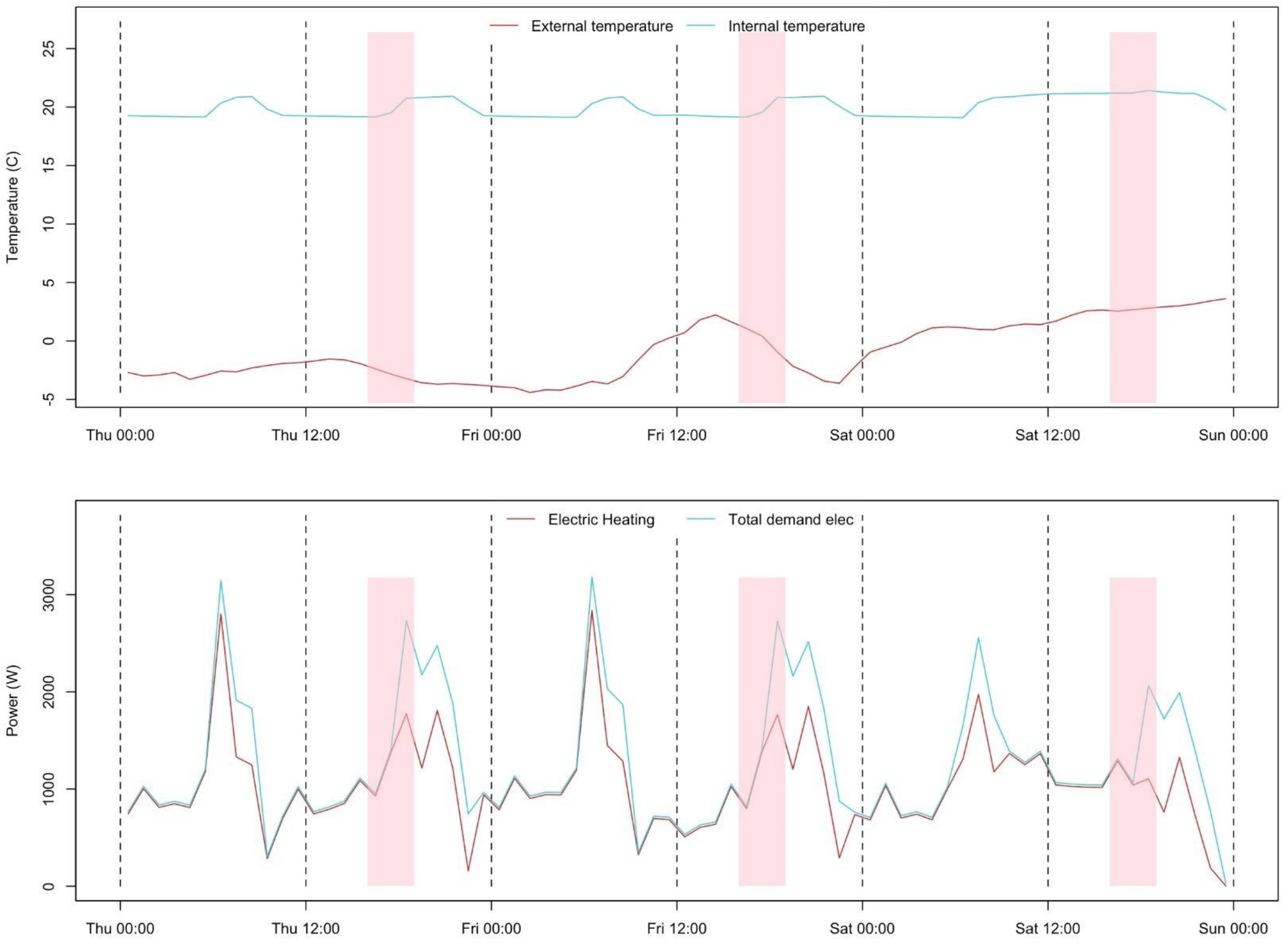
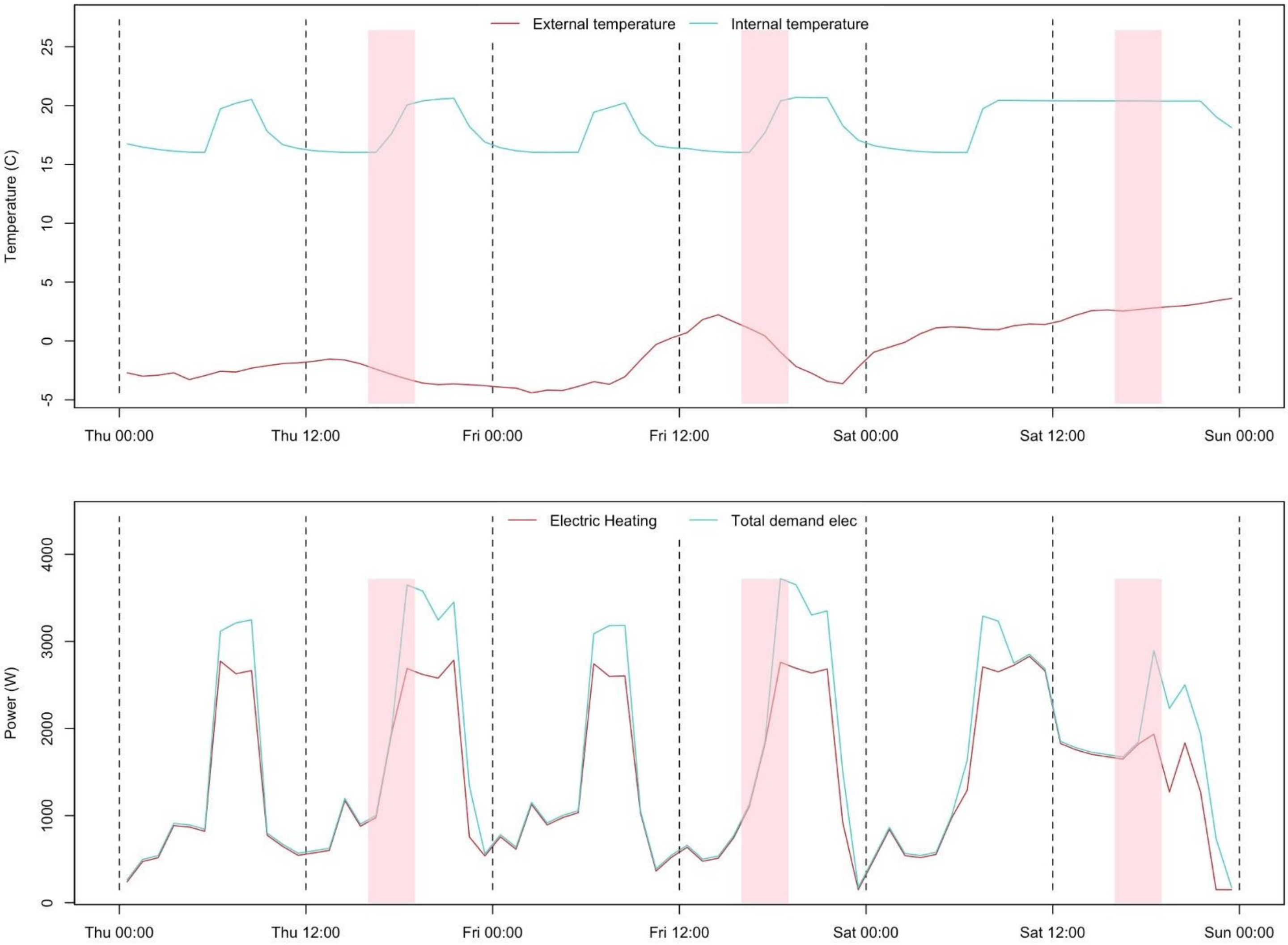


**Figure 5.11: Coldest day achieved temperatures – typical three-bedroom semi-detached house with high-temperature air-source heat pump**




# Why are there so few insulation measures?

Why are there so few fabric upgrades? The optimisation revealed that insulation measures are very seldom selected for any of the house types – apart from filled cavities and 100mm of loft insulation that were assumed for the base cases. This is because of the relationship between costs and savings from the insulation measures.

Figure 5.12 below compares costs and benefits for the Sprawling-S archetype with solid walls, for two different heating systems. Capital costs (orange) are shown to the right, and energy savings over 15 years are shown to the left (grey). Both operating costs and (to a lesser extent) capital costs are affected by the choice of heating system, and the optimised package of fabric measures that accompanies each heating system.

For triple glazing, the initial cost of installing glazing (£9,350) is at least six times the potential savings from the glazing over 15 years (£1,130 to £1,470). The potential savings are higher when triple glazing is installed in combination with storage heaters – because energy bills are higher. Ultimately, new high-performance windows would be unlikely to repay the capital expenditure within the lifetime of the glazing. In any house type, and even with the heating system with the highest energy costs, triple glazing is not justified on cost grounds. There would be much higher savings, of course, if windows in the base case were single rather than double-glazed.

The optimised external wall insulation (EWI) package at the bottom of Figure 4.13 costs from £7,440 to £8,100 more, when it is installed with storage radiators or air-to-air heat pumps, respectively. In both cases, installing EWI means that smaller heating systems are needed – which partly offsets the capital costs of the EWI. This explains why the costs differ between heating systems, since the costs of storage heaters and air-to-air heat pumps scale differently. The discounted savings in energy costs for EWI over 15 years, on the other hand, are £9,610 with the storage heaters, compared to £6,240 with the air-to-air heat pump. This means that EWI is justified (and included in the cost-optimal package) for storage heaters, but not for air-to-air heat pumps – or the other heat pump systems that have lower energy costs.

Readers should note that the Sprawling-S house type was chosen to illustrate this section of the report because it has solid walls and high heat loss through walls. Energy savings from EWI are higher for this house type than any other house type. (Floor insulation follows a similar pattern of high CapEx to install and relatively low resulting savings, to the point where it is not justified on cost grounds within 15 years for any of the house types.)

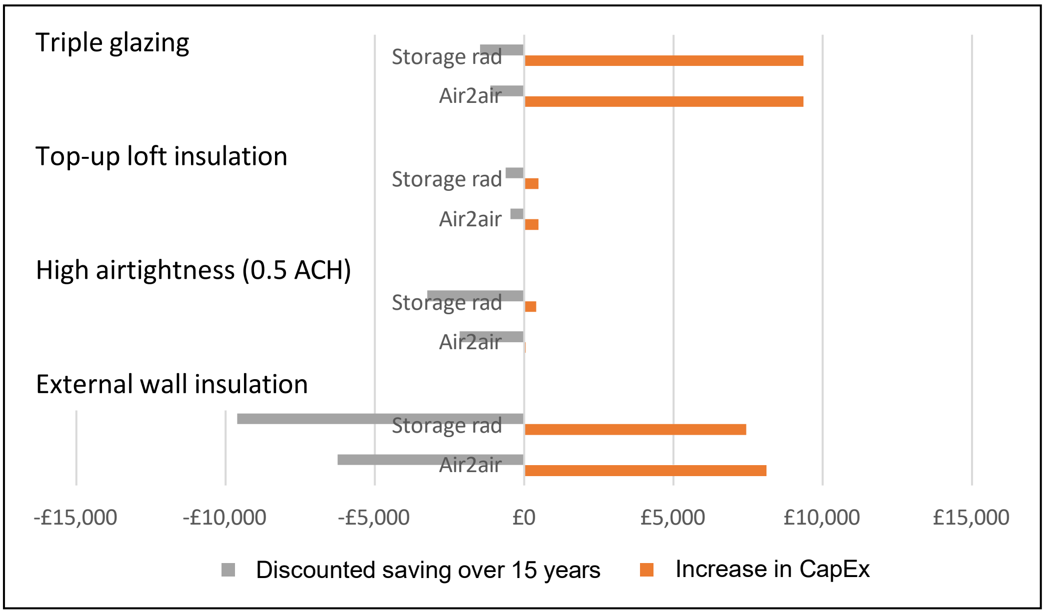
The ‘high airtightness’ upgrade is for high-quality draught-stripping that would reduce the air change rate from 0.96 (similar to most UK homes built before 1990) to 0.5 air-changes per hour. CapEx is actually negative for the high-temperature air-source heat pump (HT ASHP) because this level of airtightness means that a smaller heat pump is needed, and the savings in heat pump costs outweigh the modest cost of better airtightness. For the other two heating systems shown in the figure, the savings over 15 years easily outweigh the CapEx – this is why it is selected among the basket of measures for most of the heating systems applied to this house type (and, in fact, for all house types).

The installation costs of high airtightness are modest, but for nearly all house types the savings in energy costs dramatically outweigh the CapEx. This applies to all heating systems – which explains why high airtightness (“0.5 ACH”) is selected in nearly all the cost-optimal cases. In the examples in the chart, high airtightness increases CapEx by £400 when installed with storage radiators, but only £50 when installed with an air-to-air heat pump. Although the cost of installing airtightness measures alone is £400 in both cases, this is offset by a saving of £350 from being able to use a smaller air-to-air heat pump (22kW, compared to the 24kW heat pump that is needed without airtightness measures).

The energy-cost savings from airtightness are far higher (at least eight times more) than the increased CapEx in both cases: £3,240 over 15 years with storage heaters, or £2,160 with the air-to-air heat pump.

Like airtightness, top-up loft insulation has very modest installation costs (in this and all dwellings with roofs to insulate), and potential savings are also modest. For this house type it would cost £480 (with no knock-on impacts on other capital costs), while 15-year energy savings would be £620 with storage heaters or £450 for air-to-air heat pumps. Consequently, it is selected in the optimised package of cost-effective measures when paired with storage heaters, but not with heat pumps.

**Figure 5.12: Costs and savings from fabric measures for the typical three-bedroom house**




Costs and savings from fabric measures applied in combination with other heating systems followed a similar pattern, with radiant panels similar to the storage heaters shown in the figure, and air-source and ground-source heat pumps broadly similar to air-to-air heat pumps in the figure.

# The optimisation frontier: costs and energy use

Many decisions about how to improve the energy performance of existing homes involve trade-offs, and the main focus of this report is the trade-off between initial capital costs and ongoing energy and maintenance costs. However, we have already alluded to trade-offs between cost and energy use (and, ultimately, carbon emissions). This part of the report provides more detail about these trade-offs for a typical three-bedroom house with cavity walls.

Figure 5.13 below shows the total costs and electricity use of all of the optimisation runs for the Sprawling-C house type, and only the red points on the chart were selected as optimums. (Presenting the results this way, rather than as carbon emissions, avoids the problem of emissions per unit of electricity varying over time.) The optimiser was selecting for lowest total costs (with discounting applied to future costs), so electricity use was not part of the optimisation. There is one very clear message here: along the optimisation frontier, lower costs equate to higher energy use. The range in electricity use is from 1,800kWh up to 7,700kWh a year – a factor of more than three. But to achieve the lowest electricity use would cost considerably more than the ‘most cost-effective’ packages of measures discussed above. In this instance costs over 15 years would rise from just over £22,000 up to close to £70,000 (with future costs discounted at 3.5% a year, as before).

**Figure 5.13: Costs and annual electricity use for the typical three-bedroom house, all runs**

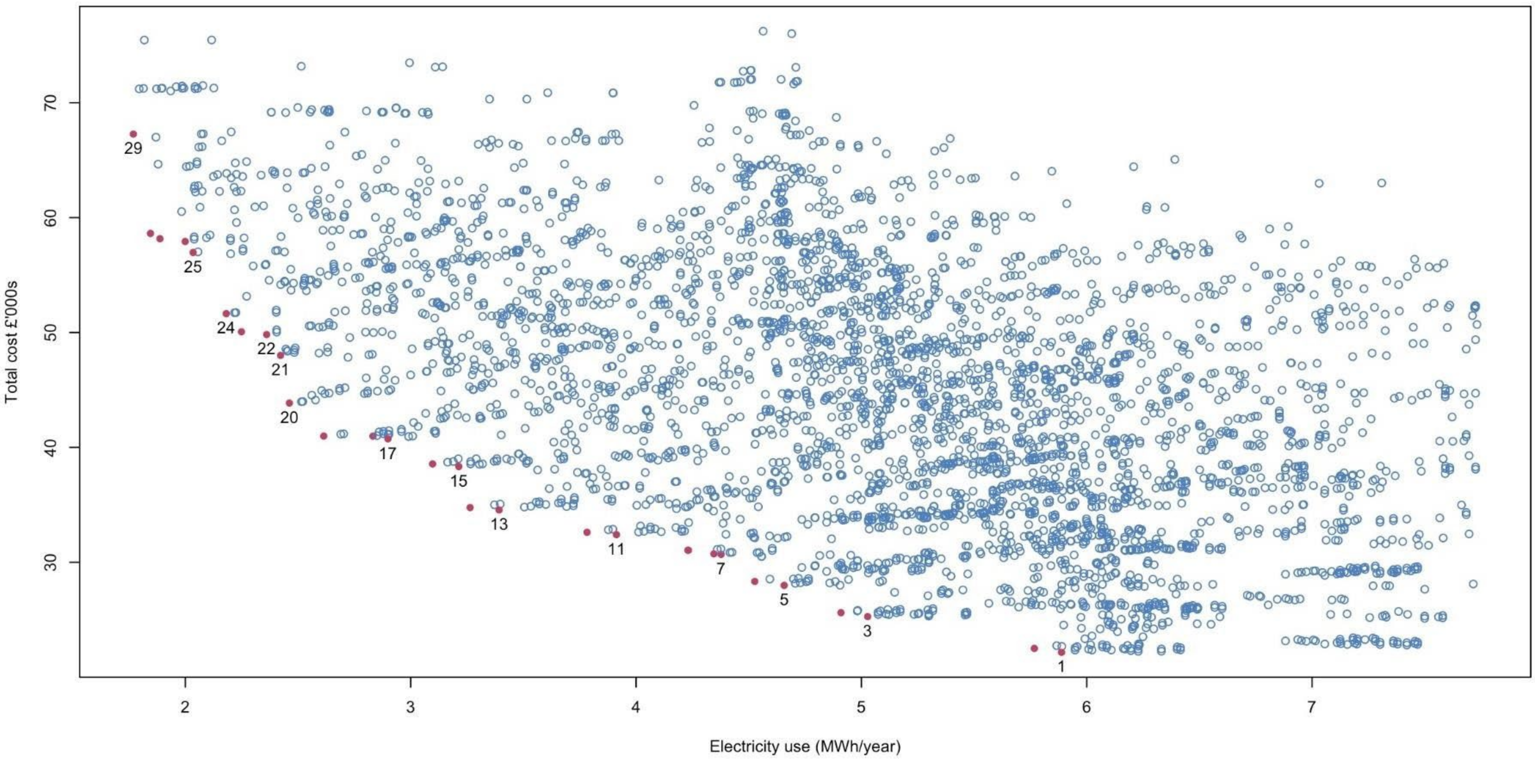


Figure 5.14 below shows the same plot presented as carbon emissions, using a simple, fixed emissions factor for electricity: 233 $gCO_2e/kWh$[50]. In reality emissions vary over time, so this is only indicative, and does not reflect falling emissions due to decarbonisation of the electricity grid. Nevertheless, the range in emissions is from 0.4 up to 1.37 tonnes$CO_2e$ a year – a factor of more than three, as before.

**Figure 5.14: Costs and greenhouse gas emissions for the typical three-bedroom house, all runs**

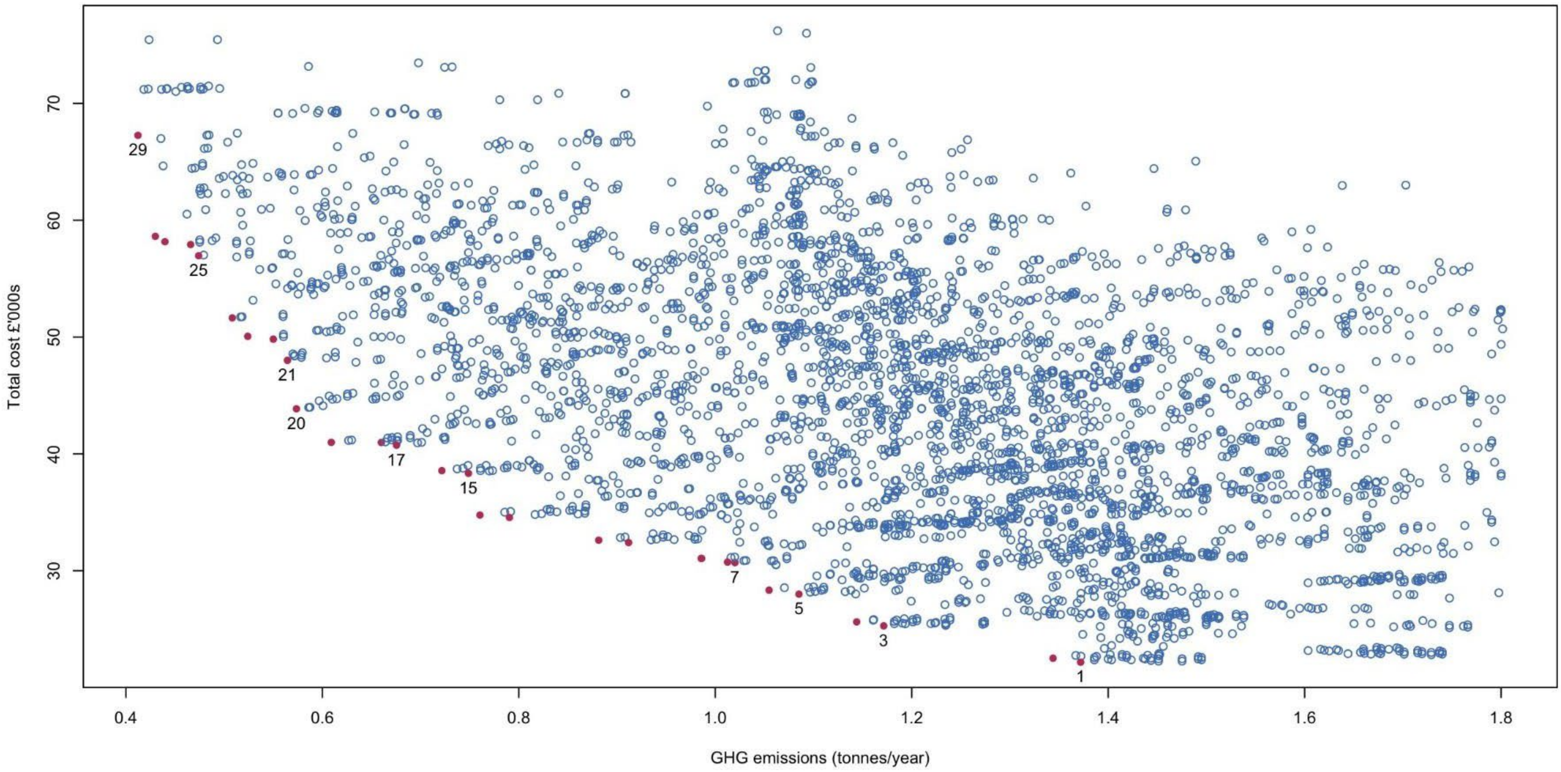



Table 5.2 below shows what each of the numbered optimums in Figure 5.14 represents, along with the associated costs and emissions (numbers run in sequence on the chart from 1, bottom-right, to 29, top-left, although some points are too close together for numbers to appear in Figure 5.13). Through to Optimisation 10 they all select the time-of-use tariff, while all select conventional tariffs from then onwards. From Optimisation 3 onwards they almost all select a 4kWp PV array, while from Optimisation 5 onwards they usually select a battery (either 4kWh or 8 kWh capacity). These combinations all bring electricity and emissions benefits that are not captured in the purely financial optimisation. This is why neither PV nor batteries appear in any of the optimised packages of measures described earlier.

50 https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020

**Table 5.2: Costs and greenhouse gas emissions for the typical three-bedroom house, all runs**

| | Heating System | Air-tight-ness | EWI | Roof ins | Insul-ated floor | Triple glazing | Ther-mal store | PV | Bat-tery | Early heat start | Tariff | Total Cost | GHG Emissions (tonnes CO2e/year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | LT ASHP rad (12kW) Rad+50% | ✓ | | | | | | | | | TOU | £22,165 | 1.37 |
| 2 | LT ASHP rad (12kW) Rad+50% | ✓ | | ✓ | | | | | | | TOU | £22,507 | 1.34 |
| 3 | LT ASHP rad (12kW) Rad+50% | ✓ | | | | | | ✓ | | | TOU | £25,278 | 1.17 |
| 4 | LT ASHP rad (12kW) Rad+50% | ✓ | | ✓ | | | | ✓ | | | TOU | £25,617 | 1.14 |
| 5 | LT ASHP rad (12kW) Rad+50% | ✓ | | | | | | ✓ | ✓ | | TOU | £27,994 | 1.09 |
| 6 | LT ASHP rad (12kW) Rad+50% | ✓ | | ✓ | | | | ✓ | ✓ | | TOU | £28,332 | 1.05 |
| 7 | LT ASHP rad (12kW) Rad+50% | ✓ | | | | | | ✓ | ✓ | ✓ | TOU | £30,693 | 1.02 |
| 8 | LT ASHP rad (12kW) Rad+50% | | | ✓ | | | | ✓ | ✓ | | TOU | £30,734 | 1.01 |
| 9 | LT ASHP rad (12kW) Rad+50% | ✓ | | ✓ | | | | ✓ | ✓ | ✓ | TOU | £31,048 | 0.99 |
| 10 | LT ASHP rad (12kW) Rad+50% | ✓ | | ✓ | | | | ✓ | ✓ | ✓ | TOU | £31,051 | 0.99 |
| 11 | LT ASHP rad (12kW) Rad+50% | ✓ | | | | | | ✓ | ✓ | | Standard | £32,409 | 0.91 |
| 12 | LT ASHP rad (12kW) Rad+50% | ✓ | | ✓ | | | | ✓ | ✓ | | Standard | £32,611 | 0.88 |
| 13 | LT ASHP rad (12kW) Rad+50% | ✓ | | | | | | ✓ | ✓ | | Standard | £34,557 | 0.79 |
| 14 | LT ASHP rad (12kW) Rad+50% | ✓ | | ✓ | | | | ✓ | ✓ | | Standard | £34,763 | 0.76 |
| 15 | LT ASHP rad (12kW) Rad+50% | ✓ | | | ✓ | | | ✓ | ✓ | | Standard | £38,333 | 0.75 |

| | Heating System | Air-tightness | EWI | Roof ins | Insulated floor | Triple glazing | Thermal store | PV | Battery | Early heat start | Tariff | Total Cost | GHG Emissions (tonnes CO2e/year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16 | LT ASHP rad (12kW) Rad+50% | ✓ | | ✓ | ✓ | | | ✓ | ✓ | | Standard | £38,564 | 0.72 |
| 17 | LT ASHP rad (10kW) Rad+20% | | ✓ | | | | | ✓ | ✓ | | Standard | £40,744 | 0.68 |
| 18 | LT ASHP rad (10kW) Rad+20% | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | Standard | £40,977 | 0.66 |
| 19 | LT ASHP rad (10kW) Rad+20% | ✓ | ✓ | ✓ | | | | ✓ | ✓ | | Standard | £40,985 | 0.61 |
| 20 | LT ASHP rad (10kW) | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | | Standard | £43,858 | 0.57 |
| 21 | LT ASHP rad (8kW) | ✓ | ✓ | | | ✓ | | ✓ | ✓ | ✓ | Standard | £48,007 | 0.56 |
| 22 | LT ASHP uf (10kW) | ✓ | ✓ | | | | | ✓ | ✓ | | Standard | £49,820 | 0.55 |
| 23 | LT ASHP uf (10kW) | ✓ | ✓ | ✓ | | | | ✓ | ✓ | | Standard | £50,064 | 0.52 |
| 24 | LT ASHP rad (8kW) | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | | Standard | £51,642 | 0.51 |
| 25 | LT GSHP rad (8kW) | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | | Standard | £56,964 | 0.47 |
| 26 | LT ASHP uf (8kW) | ✓ | ✓ | | | ✓ | | ✓ | ✓ | | Standard | £57,923 | 0.47 |
| 27 | LT ASHP uf (8kW) | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | | Standard | £58,163 | 0.44 |
| 28 | LT GSHP rad (6kW) | ✓ | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | Standard | £58,622 | 0.43 |
| 29 | GSHP uf (8kW) | ✓ | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ | Standard | £67,268 | 0.41 |

# 6. Flexibility

*Batteries and thermal stores allow homes to shift demand for electricity from one period to another, which can relieve pressure on the electricity grid. Batteries can shift all electricity demand – including lights and appliances as well as heating – while thermal stores can only shift power demand for space heating. That means that the shifting potential in terms of power is lower for thermal stores than batteries. In both cases there is a great deal of variation between house types. The total energy that can be shifted (power x duration) depends on the size of the energy store.*

As the proportion of electricity from intermittent renewables increases, the value of demand side response (DSR) also increases. When the wind does not blow and the sun does not shine, we either need more power generation or reduced demand – DSR. Also, the need for DSR can be triggered by constraints on the distribution network rather than a shortage of power on the supply side. The need can occur at any time, not just at peak times. It can be measured as:

- the amount of power reduction (in Watts), and/or
- the length of time that power demand can be decreased (in hours).

The CODE models incorporate DSR using storage as an alternative energy source in two ways:

- Using a battery, the battery can provide power for the heating system and for all other requirements, until it is drained. In the battery model we assume fixed maximum discharge and charging rate (5 kW) and a fixed effective capacity (8 kWh). In practice these limits are dependent on each other and also environmental temperature.
- Using a thermal store, the store can provide heat until its temperature drops too low to supply the radiators. In CODE models, the thermal store is in addition to a conventional hot water cylinder, so the heat pump does not need to run for either hot water or space heating until one or other has dropped below an acceptable temperature. The effective storage potential in the thermal store model we are using is a little more than 6 kWh heat, though it varies depending on the temperature gradients in the store. With a low temperature heat pump and radiators, the thermal store is heated to 47°C and can usefully supply heat down to about 30°C, so the change in temperature ('delta T') would only be 17°C, even if the whole store was at a uniform temperature – which it is not. The heat stored corresponds to approximately 2.5 kWh electrical energy, depending on the external temperature: in colder weather the heat pump is less efficient, so it takes more power to heat the thermal store and the effective DSR power is higher.

In addition, using a hybrid heat pump with a gas boiler, all heat can be provided by the boiler for as long as required – entirely eliminating the need for electric heating. This is effectively

DSR by switching to an alternative fuel. The only remaining electrical demand is for appliances, lights and pumps. However, this also eliminates the emissions benefits of electric heating while gas heating is used.

These methods can also be combined. For example, a hybrid system or a thermal store can be combined with a battery so that appliances are powered using the battery, so reducing energy demand to zero until the battery is depleted. However, these systems all take up space, and having both a battery and a thermal store may not be acceptable to householders.

In this section of the report TOU tariffs are selected throughout because these give an incentive to householders to shift electricity use away from periods of peak demand. (Conventional flat electricity tariffs would be unlikely to achieve flexibility.) We did not adjust thermostat settings in dwellings to achieve DSR, because this would affect thermal comfort.

There are limitations on the modelling behind this section. We have used just one size of thermal store and one battery size, when in reality different sizes could be installed – possibly larger stores and batteries for larger dwellings and/or those with higher heating loads. We continue to use the central modelling assumption applied throughout the project of a thermostat setting of 21°C in the living areas and 20°C elsewhere. Individual dwellings may have higher or lower thermostat settings, providing correspondingly higher or lower potential to shift power.

## Quantifying flexibility

The following charts are based on the Sprawling-C detached house with cavity walls. They show electricity drawn from the grid, during the simulated test. External conditions and space heating requirements were fixed so that all cases are comparable.

- External temperature is constant (0°C unless otherwise stated).
- No solar gain (as if it was evening or a dull day).
- Heating runs continuously all day, from 06:00 until 22:00.
- DSR is requested from 12:00 until 21:00 (nine hours). This means the dwelling has been warm for some time before the test starts.

The handling of the DSR is the same as peak time with the dynamic tariff – where there is a battery, this is used to supply all electricity while it can. The DSR test case is compared with a baseline which has the same equipment, but functioning as it would with no DSR or peak tariff.

Figure 6.1 below shows the impact of a battery on power used for heating and lights/appliances. The battery (blue line) provides all the power needed for just over three hours. The battery reduces electricity use for heating from around 2500 W to zero as long as there is power available in the battery. The battery is programmed to charge overnight, not shown here. Overall, using the battery increases electricity consumption slightly (due to losses charging and discharging), but it shifts energy demand from daytime – when heat is needed –

to overnight. A larger battery would last longer – for example the Tesla PowerWall 2 has a capacity of 14.5 kWh[51], at least initially (the capacity degrades over time).

Charging and discharging losses dictate the "round-trip efficiency". This is of the order of 90%.

**Figure 6.1: Typical three-bedroom house – all electricity use, with and without a battery, at a constant 0°C outside temperature – DSR starting at noon**

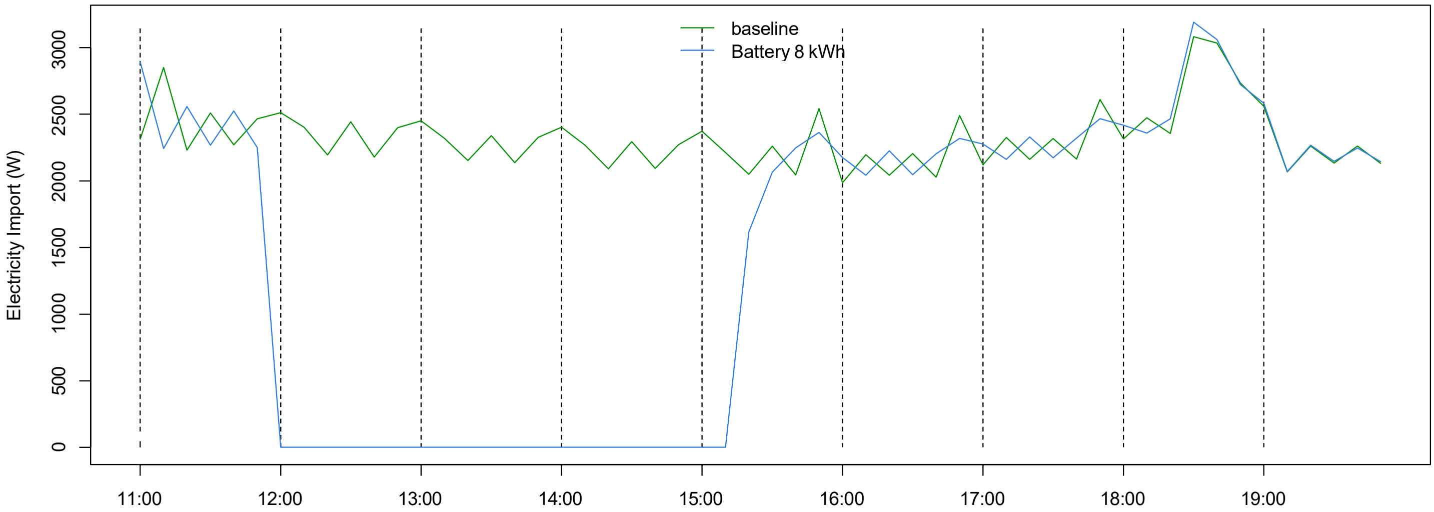



Figure 6.2 below shows the impact of a thermal store roughly the same size as a standard hot-water tank. During the DSR test, the heat pump is disabled and the thermal store supplies space heating – until the thermal store runs out of useful heat. The DHW cylinder continues to supply hot water.

In this example, the setback temperature for space heating has been increased to 18°C, which means that outside of the heating periods the thermostat is still set quite high. This means more heat is stored in the fabric of the house and the rooms do not cool so quickly. The higher setback is not because of the DSR – it is needed in this case to achieve the thermal comfort standard. Without it the house does not heat up quickly enough when the heating comes on, so occupants feel uncomfortable. The higher setback temperature adds about 3% to the annual electricity consumption.

The thermal store lasts for nearly two hours, not as long as the battery did. Then, as the temperature drops below the programmed threshold, the heat pump comes on to reheat it. When the thermal store is warm enough, the heat pump shuts off again. Readers should note that this time, when the heat pump comes on, it uses more electrical power than in the baseline case and more than it was doing before. It has to run at full power to reheat the thermal store, which in turn supplies the radiators. However, this effect is transient and overall there is little, if any, change in electricity demand. The smaller peaks in electricity use at 13:00 and again in the evening are for heating the hot water cylinder, which cools slightly over time whether it is used or not.  Demand also increases in the evening for lights and appliances.

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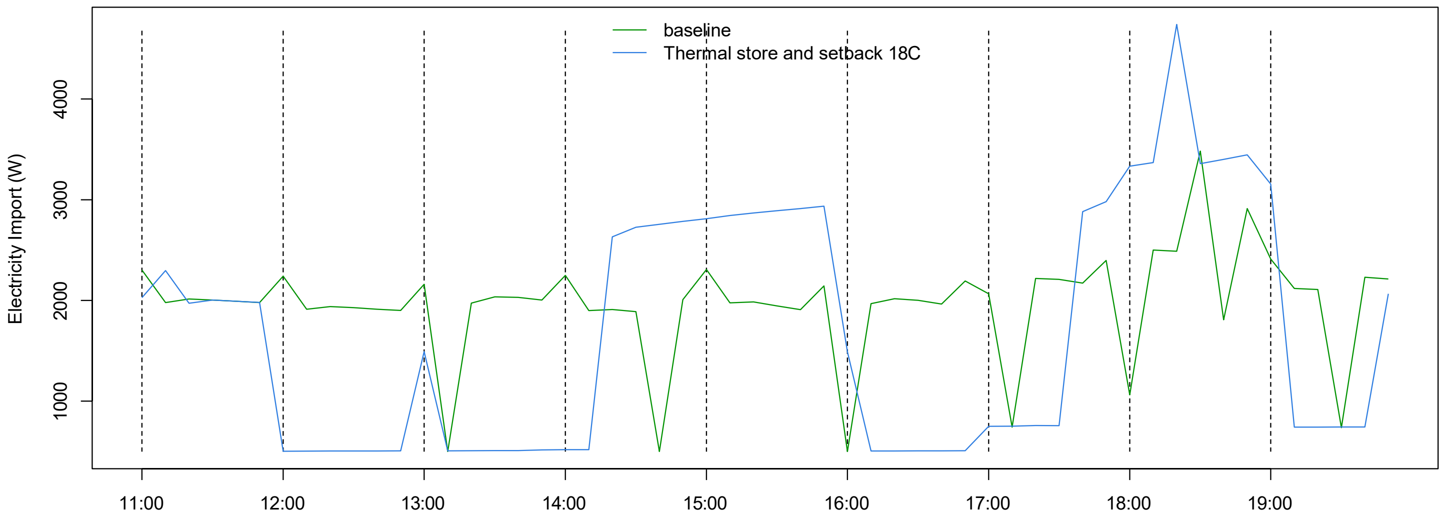
51 https://electriccarhome.co.uk/battery-storage/tesla-powerwall

**Figure 6.2: Typical three-bedroom house – all electricity use, with and without a thermal store and higher setback, at a constant 0°C outside temperature**




The duration of the DSR varies with the external temperature. When it is cold the dwelling needs more heat, so the stored energy does not last as long. In this study the power and duration for DSR is quantified as follows:

- Power is the difference between the mean power demand with- and without-the DSR, for the duration of the test.
- Duration is from the start of the test until either the end (12 hours) or the battery is fully discharged or the thermal store mean temperature has dropped to 30°C, which is not adequate for heating with a wet radiator system as we have here. An underfloor heating system could run with lower temperatures, but this would cost more than the cost optimal package selected for this analysis.

To summarise the findings, duration increases and power decreases with warmer weather, see Figures 6.3 and 6.4 below. For batteries, the product of power x duration is generally consistent between different temperatures, limited by the size of the battery. The battery in this case is 8 kWh, which typically delivers 7.5 kWh DSR. The thermal store is 6 kWh heat (with a temperature range of 17°C), storing water at up to 47°C, appropriate for a low-temperature air-source heat pump. This corresponds to 2.0 - 3.0 kWh electrical demand, more in colder weather and less when it is warm because the heat pump is more efficient. Arguably, with a high-temperature heat pump, the thermal store could be charged to a higher temperature (say 55°C), and this would increase the storage capacity, and so the potential for shifting demand. However, this would also mean a lower SCOP for the heat pump.

**Figure 6.3: Duration of Demand-Side Response at different outdoor temperatures, from a battery or thermal store (typical 3-bed house). At higher temperatures there is less demand for heat so the storage lasts longer.**

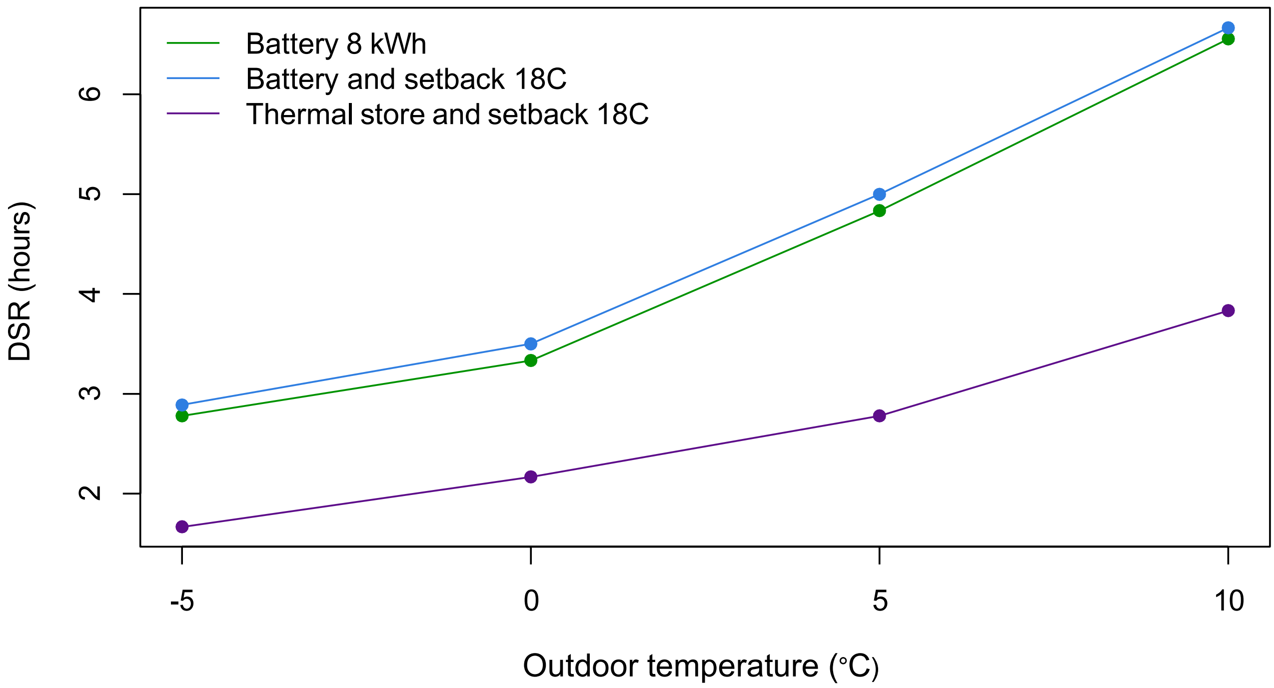
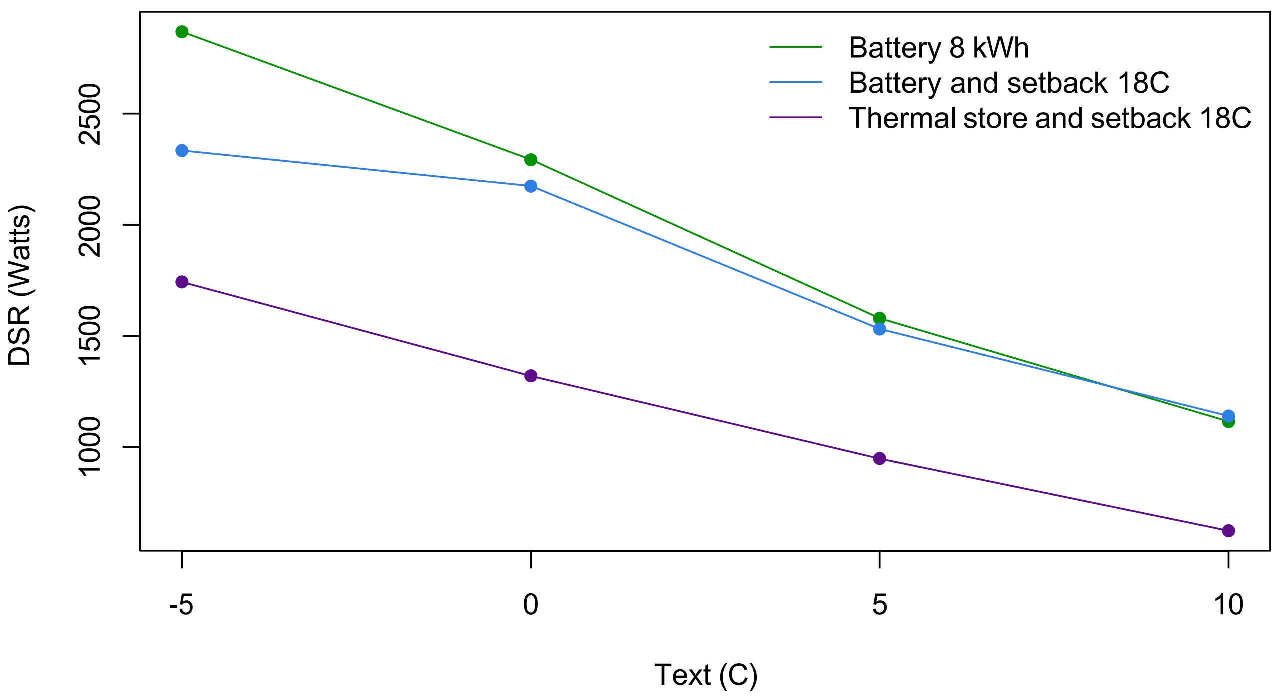



**Figure 6.4: Mean power shifted from Demand-Side Response at different outdoor temperatures, from a battery or thermal store (typical 3-bed house). At higher temperatures, the demand for heat is lower so there is less power demand to shift.**



# DSR potential and costs

This section considers thermal stores and batteries only. We have used the CODE models to examine the potential for providing flexibility from the cost-optimal packages discussed in earlier sections of this report. All of these packages include some energy efficiency measures, if only draught fixing. In all cases, TOU tariffs are selected because these give an incentive to householders to shift electricity use away from periods of peak demand.

For testing DSR potential, we have added either a battery or a thermal store to the cost optimal package. Thermal stores need to be connected to a wet heating system with radiators or underfloor heating. Where the cost-optimal heating system selected for a house type does not have radiators or underfloor heating (like air-to-air heat pumps) the heating system is replaced with a low-temperature ASHP for the thermal store analysis, and this can have a major impact on costs. External wall insulation was also added to all the solid wall cases, because without this the heating system response was too slow to meet the thermal comfort requirements. The slow response was due to adding the thermal store, since heat from the heat pump is shared between the thermal store and the radiators. It is does not affect a simple heat pump installation without a thermal store.

This analysis shows potential flexibility under the test conditions described above, when it is 0°C outside. Both power (in kW) and duration (in hours) are included. For colder weather, there is somewhat higher potential for kW savings, but for shorter periods. Similarly, to generalise across house types, dwellings with higher heating demand offer higher kW to shift between periods, but shorter duration of DSR potential. If larger tanks and batteries were used for larger dwellings, or dwellings with higher heating demand, the duration could be extended.

Table 6.1 below shows the DSR potential at 0°C for all the archetypes as described above. In the smallest dwellings the battery still had some charge left after 12 hours. In practice smaller batteries would probably be used in small dwellings.

The table also shows the Total Cost of adding the DSR equipment (along with the cost of wall insulation where needed and any necessary changes to the heating system). The Total Cost is the difference between the total cost of the DSR package and that of the cost optimal package, including capital, energy and maintenance costs. The storage capability combined with the TOU tariff brings savings by avoiding power use at peak times, and this partly offsets the extra installation cost. Costs are over the standard 15 years with discounting at 3.5%, and battery installations include a replacement after 10 years.

Battery systems usually lead to higher total costs than thermal stores over 15 years, because batteries cost more than thermal stores (£4,350 for a battery compared to £1,760 installed for a thermal store). However, for houses and bungalows – with higher electricity use and heating demand than flats – batteries have the potential to shift around three times more electricity at peak times, so there are more savings from the TOU tariff.

The total potential in kWh (power x duration) per day is approximately 2.5 kWh for thermal store and 7.5 kWh for the battery. This is similar across archetypes as it is governed by the size of the energy store rather than other parameters of the archetype or heating system. Dividing the annual cost by the kWh shifted in the test gives a measure of the cost of flexibility which can be used for comparing battery and thermal store cases. This is the Cost/kWh column in Table 6.1.

The thermal stores offer the best value flexibility in most cases: for houses and bungalows, around £500 increase in total costs over 15 years for every kWh that could be shifted each day. The costs cover up-front capital costs of the battery or thermal store, plus any other measures that are needed initially to make the storage systems work, and any impacts on subsequent running costs – energy or maintenance costs. However, this changes for flats with modest heating demand and where air-to-air heat pumps would be used ordinarily. Because low-temperature heat pumps must be used with thermal stores instead of air-to-air, and because LT ASHPs cost significantly more, this increases costs dramatically and it means that thermal stores work out much more expensive than batteries for the two small flats.

Thermal stores also work out more expensive for the solid-wall properties, because of the high capital cost of external wall insulation. In these cases, the total cost per kWh rises to £1300-£1400 for houses, but here there are other significant benefits (including major reductions in total energy use and emissions) apart from the flexibility benefits.

For cases where the baseline package did not have a higher setback temperature, we also tested the difference this makes to the flexibility in the system. The effect is actually very small. A higher setback temperature reduces the heating demand during the test slightly, as there is more heat stored in the building fabric to start with. This brings a slight reduction in the mean power shifted and a corresponding increase in duration. The higher setback temperature increases energy demand outside the heating periods, as the dwelling is warmer than it would have been. However, this test is conducted during heating period.

**Table 6.1: Potential duration and power of flexibility services (at 0°C temperature outside) provided to the grid, for each house type, with costs. Power is the mean power shifted for the duration. Costs are extra costs on top of the cost-optimal package in each case.**

| House Type | DSR system | kW | Hours | kWh | Total Cost* | Cost/ kWh |
|---|---|---|---|---|---|---|
| Flat small | Battery 8 kWh | 0.6 | 12 | 6.9 | £6,690 | £950 |
| Flat small | Thermal store | 0.5 | 5 | 2.3 | £6,030 | £2,620 |
| Flat ground | Battery 8 kWh | 1.1 | 6.8 | 7.3 | £5,280 | £720 |
| Flat ground | Thermal store | 0.6 | 4.3 | 2.5 | £3,780 | £1,510 |
| Flat mid | Battery 8 kWh | 1 | 7.3 | 7.6 | £6,000 | £790 |
| Flat mid | Thermal store | 0.5 | 5.1 | 2.4 | £1,390 | £580 |
| Flat top | Battery 8 kWh | 1.1 | 6.3 | 7.2 | £5,940 | £820 |
| Flat top | Thermal store | 0.8 | 3.1 | 2.5 | £2,580 | £1,030 |
| Bungalow | Battery 8 kWh | 1.6 | 4.6 | 7.2 | £5,680 | £790 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Bungalow | Battery and setback 18C* | 1.6 | 4.5 | 7.3 | £5,740 | £790 |
| Bungalow | Thermal store | 0.9 | 2.7 | 2.4 | £1,110 | £460 |
| Bungalow | Thermal store and setback 18C | 0.8 | 2.9 | 2.5 | £1,170 | £470 |
| Mid terrace-C | Battery 8 kWh | 1.6 | 4.7 | 7.4 | £5,740 | £780 |
| Mid terrace-C | Battery and setback 18C | 1.6 | 4.8 | 7.5 | £5,790 | £770 |
| Mid terrace-C | Thermal store | 0.8 | 3 | 2.4 | £1,200 | £500 |
| Mid terrace-C | Thermal store and setback 18C | 0.8 | 3.1 | 2.4 | £1,230 | £510 |
| Mid terrace-S | Battery 8 kWh | 1.7 | 4.3 | 7.5 | £5,710 | £760 |
| Compact (semi-d)*** | Battery 8 kWh | 2.5 | 3 | 7.4 | £5,220 | £710 |
| Compact (semi-d) | Battery and setback 18C | 2.4 | 3.2 | 7.5 | £5,350 | £710 |
| Medium-C (end-terr.) | Battery 8 kWh | 2.2 | 3.5 | 7.9 | £5,250 | £660 |
| Medium-C (end-terr.) | Battery and setback 18C | 2.1 | 3.7 | 7.8 | £5,310 | £680 |
| Medium-C (end-terr.) | Thermal store | 1.5 | 2 | 2.9 | £1,070 | £370 |
| Medium-C (end-terr.) | Thermal store and setback 18C | 1.2 | 2.2 | 2.7 | £1,140 | £420 |
| Medium-S (semi-d) | Battery 8 kWh | 2.4 | 3 | 7.2 | £4,410 | £610 |
| Medium-S (semi-d) | Battery and setback 18C | 2.3 | 3.3 | 7.6 | £4,540 | £600 |
| Medium-S (semi-d) | Thermal store | 1.2 | 2.5 | 3 | £3,910 | £1,300 |
| Medium-S (semi-d) | Thermal store and setback 18C | 1.1 | 2.5 | 2.8 | £3,980 | £1,420 |
| Sprawling-C (det.) | Battery 8 kWh | 2.3 | 3.3 | 7.6 | £5,530 | £730 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Sprawling-C (det.) | Battery and setback 18C | 2.2 | 3.5 | 7.6 | £5,730 | £750 |
| Sprawling-C (det.) | Thermal store and setback 18C | 1.3 | 2.2 | 2.9 | £1,180 | £410 |
| Sprawling-S (det.) | Battery 8 kWh | 2.7 | 2.7 | 7.2 | £4,380 | £610 |
| Sprawling-S (det.) | Battery and setback 18C | 2.6 | 2.8 | 7.3 | £4,540 | £620 |
| Sprawling-S (det.) | Thermal store | 1.2 | 2.6 | 3.1 | £4,240 | £1,370 |
| Sprawling-S (det.) | Thermal store and setback 18C | 1.1 | 2.7 | 3 | £4,330 | £1,440 |

*A setback temperature of 18C increases energy costs slightly because dwellings are warmer outside the usual heating periods. **Some house types did not achieve comfort criteria with a thermal store, so they are not included here. ***Compact Semi-D assumes the conservatory is unheated for the flexibility tests. If it was heated kW of flexibility would be higher, with commensurately lower duration.

Figure 6.5 below summarises the power and duration of DSR for all of the house types. (There are more than 12 of each because the 'higher setback' options are also shown.) The trade-off between power and duration discussed above causes the reduction in power shifted (in Watts), but for longer duration. This is because of the dwelling and heating characteristics rather than anything to do with the DSR technology.

**Figure 6.5: Duration and kW of DSR, all house types at 0°C outside temperature**

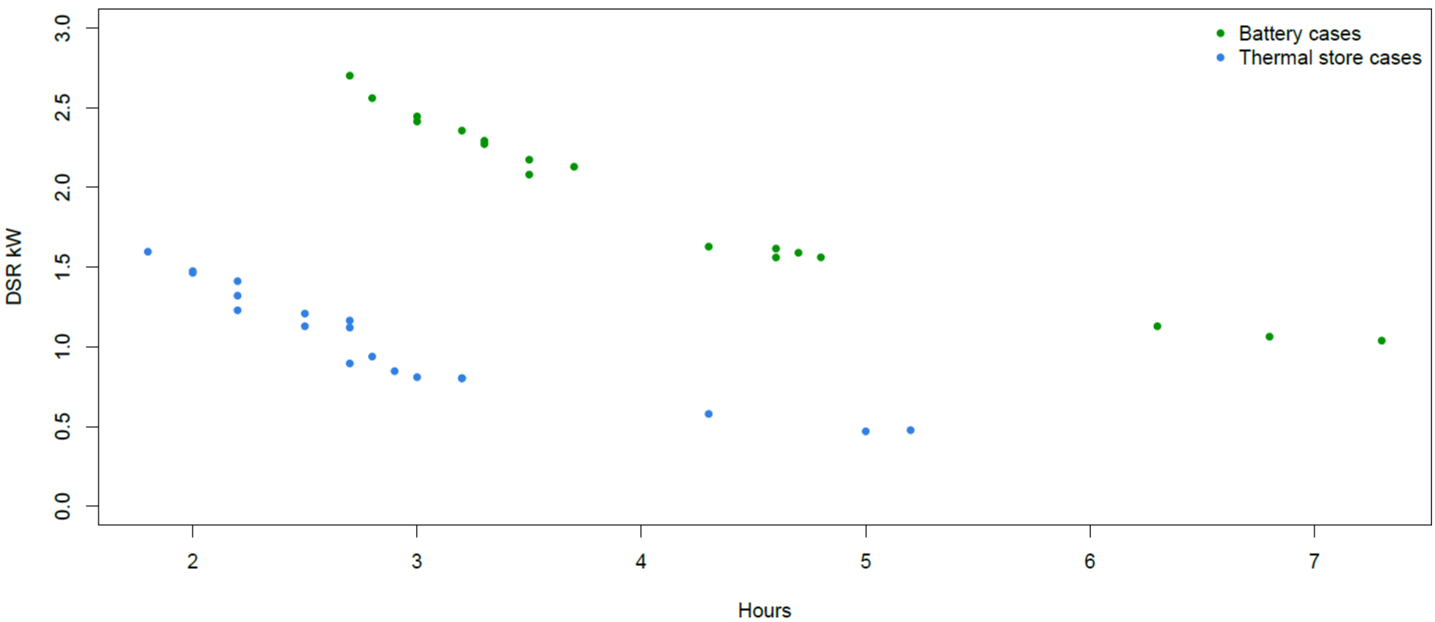
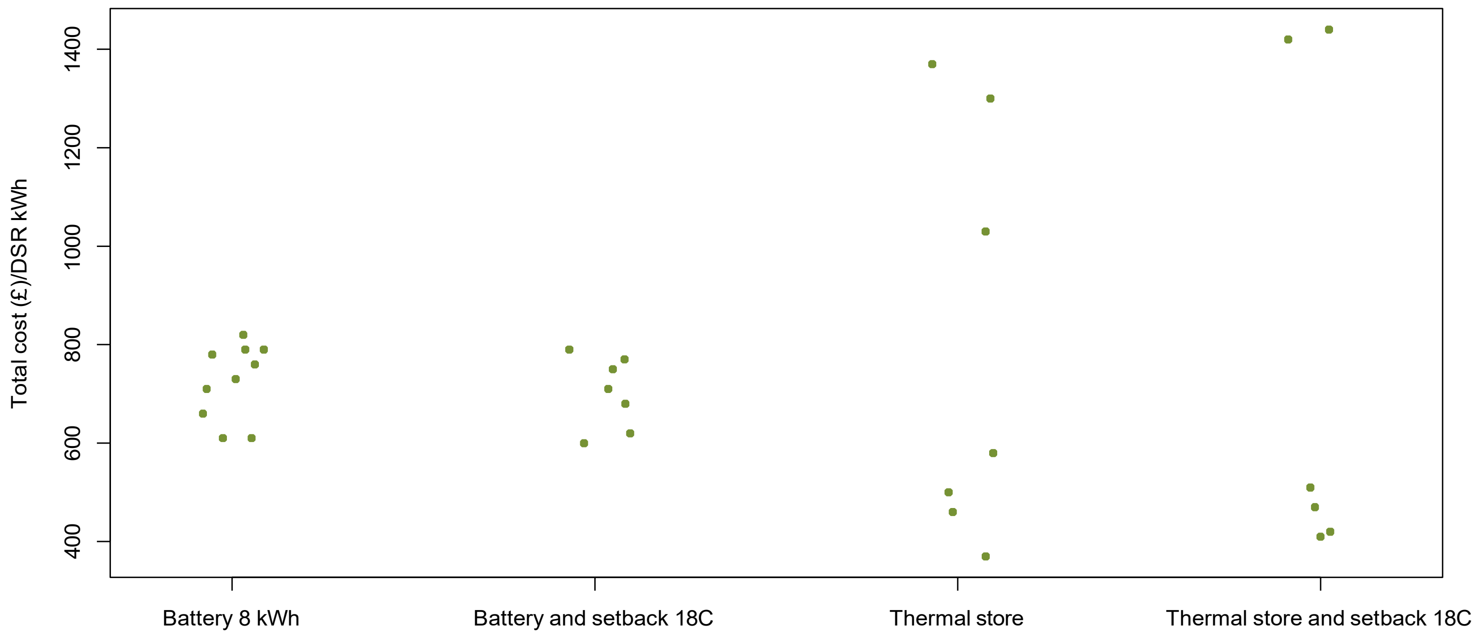


Figure 6.6 below shows the total cost per kWh (i.e. power x duration) from Table 6.1 above, split into batteries and thermal stores. Overall costs for battery systems and thermal stores are fairly similar across archetypes, except for five thermal store cases with much higher costs. The difference is due to the cost of external wall insulation applied to the solid wall house types, which is not needed without the thermal stores.

**Figure 6.6: Cost per kWh of flexibility available from batteries and thermal stores, all house types**




## Annual potential for DSR

Some simple assumptions allow estimates of the potential for flexibility from each combination of house type and DSR technology over a full calendar year. This section assumes, as above, that batteries provide up to 7.5 kWh a day for any electricity use, and thermal stores allow up to 2.5 kWh/day for electricity used for space heating. It further assumes:

- All flexibility services are during the day (06:00-22:00)
- The full flexibility potential is used every day.

On each day of the year, we calculated the relevant electricity used, and the energy stored in the DSR technology. The shifting potential is the lower of the two. Over the course of the year, the batteries shift 2,740 kWh for all house types apart from the Small flat (7.5 kWh a day, 365 days a year). For the Small flat, since less electricity is used in summer, they shift very slightly less: 2,730 kWh a year.

For thermal stores, the same assumptions and calculations lead to more variation in potential flexibility offered between house types. This is because flexibility from a thermal store is more closely related to the heating-demand profile. The range is from 700 kWh of electricity a year for the Small flat to 860 kWh a year for the Compact semi-detached house (the largest house type).

# 7. Sensitivity Analysis

*There are more than 130 assumptions and evidence-based inputs in the CODE models. Many of these have at least some uncertainty. BEIS asked us to look in detail at the impact of changing electricity prices, the capital cost of upgrades, discount rates, the quality of workmanship for fabric upgrades, and infiltration rates.*

## Which inputs are most significant?

In conventional sensitivity analysis for modelling work one or more input parameters for a model is varied, with the other inputs held constant, and the magnitude of variations typically related to the uncertainty affecting each input. Then the model is re-run with changes to the inputs, and the impact of each change on the model output is recorded and tabulated. [52] However, the CODE models have a very large number of different outputs: kWh, costs, $CO_2$ emissions, internal temperatures and others, and all of these are generated for tens of thousands of combinations of house type, heating system, fabric upgrade and tariff. Cost optimisation applied to the models also brings an additional layer of complexity because – arguably – the interesting findings from the work are the rankings of different combinations of measures rather than the absolute values of cost, kWh or emissions.

BEIS asked us to focus on the sensitivity of the models to seven parameters, shown in Table 7.1 below.

BEIS also asked us to examine the effect of a ‘low disruption’ scenario, where systems and upgrades that involve considerable disruption to occupants (internal wall insulation, floor insulation, replacing radiators, and excavating the garden to install ground-source heat pumps) are excluded. Finally, BEIS asked us to examine a ‘space constrained’ scenario, where bulky heating systems and insulation measures (like internal wall insulation) are excluded for small dwellings.

This part of the report addresses each of the scenarios in Table 7.1 in turn, and then describes findings relating to low disruption and space-constrained dwellings.

[52] M Hughes, J Palmer, V Cheng & D Shipworth (2013) Sensitivity and uncertainty analysis of England's housing energy model, Building Research & Information, 41:2, 156-167, DOI: 10.1080/09613218.2013.769146

**Table 7.1: Model parameters varied in CODE sensitivity testing**

| | Low | High |
|---|---|---|
| Electricity prices (high/low) | -50% | +50% |
| More extreme TOU tariffs (base case TOU tariff is a low tariff) | +10% peak electricity price | +20% peak electricity price |
| CAPEX of technologies (high/low) | -20% | +20% |
| Longer or shorter time horizon | 5 years | 25 years |
| Discount rates (high/none) | 0% | 7.5% |
| Insulation and thermal bridging (workmanship) | 15% higher (=worse) U-value for new insulation measures | - |
| Base case infiltration rates (high/low). If buildings were tighter before upgrade, savings from airtightness measures (draught stripping) fall. | -20% | +20% |

## High Electricity Price Scenario

The high electricity price scenario, where electricity prices rise 50% from current prices (for both standard and time-of-use tariffs), does not alter the optimum package of measures for 11 of the 12 house types (see Table 7.2 below). It does change the optimum packages for the Mid-floor flat: switching from an air-to-air heat pump to a low-temperature air-source heat pump with radiators twice as large as the original radiators. In this instance, higher electricity cost justifies the increased initial cost of using an air-source heat pump over the lower installation costs (for flats) of an air-to-air heat pump.

Naturally, total costs change for all house types and all packages of measures when electricity costs rise. For the optimum packages shown, the discounted cost rise over 15 years varies from £2,010 (22% of total costs) for the Mid-floor flat up to £7090 (26%) for the Sprawling-S house type.

**Table 7.2: Impact of the high energy price scenario on optimum measures and total costs over 15 years**

| House Type | Original Optimum Package | Original Optimum Cost | New Optimum Package | Optimum with New Costs |
|---|---|---|---|---|
| **Flat-small** | Air2air (6kW) 0.5 ACH TOU Setback18C | £10,100 | No change | £12,310 |
| **Flat-ground** | Air2air (8kW) 0.5 ACH TOU Setback18C | £14,770 | No change | £18,690 |
| **Flat-mid** | Air2air (6kW) 0.5 ACH TOU Setback18C | £17,890 | LT ASHP rad (6kW) Rad+100% 0.5 ACH TOU Setback18C | £21,100 |
| **Flat-top** | Air2air (10kW) TOU Setback18C | £16,990 | No change | £20,040 |
| **Bungalow** | LT ASHP rad (8kW) Rad+20% 0.5 ACH Ins-Roof TOU | £18,250 | No change | £21,960 |
| **Mid terrace-C** | LT ASHP rad (8kW) Rad+20% 0.5 ACH TOU | £19,670 | No change | £23,250 |
| **Mid terrace-S** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU Setback18C | £21,450 | No change | £25,230 |
| **Compact (semi-d)** | LT ASHP rad (12kW) Rad+20% 0.5 ACH Ins-Roof TOU | £23,350 | No change | £27,950 |
| **Medium-C (end-terr.)** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU | £23,310 | No change | £27,870 |
| **Medium-S (semi-d)** | Air2air (22kW) 0.5 ACH TOU | £25,130 | No change | £31,350 |
| **Sprawling-C (det.)** | LT ASHP rad (12kW) Rad+50% 0.5 ACH TOU | £22,160 | No change | £26,280 |
| **Sprawling-S (det.)** | Air2air (22kW) 0.5 ACH TOU | £26,880 | No change | £33,970 |

## Low Electricity Price Scenario

The low electricity price scenario, where electricity prices fall 50% from current prices, means that optimum packages of measures change more dramatically, see Table 7.3. With cheap electricity, there are changes to the cost-optimal packages for all-but-two of the house types, and storage radiators displace heat pumps as the most attractive heating system for most of the house types. Only the two house types with highest heating demand (Medium-S and

Sprawling-S, both with uninsulated solid walls) continue to benefit from heat pumps. Some of the fabric upgrades (like loft insulation for the Compact semi-D) are no longer justified on cost grounds with cheap electricity, but air-tightness measures continue to be justified even with low-cost electricity.

Again, total costs change for all house types and all packages of measures when electricity costs fall. For the optimum packages shown, the discounted costs fall over 15 years, between £3,420 (34%) for the Small flat up to £7100 (26%) for the Sprawling-S house type.

**Table 7.3: Impact of the low energy price scenario on optimum measures and total costs over 15 years**

| House Type | Original Optimum Package | Original Optimum Cost | New Optimum Package | Optimum with New Costs |
|---|---|---|---|---|
| **Flat-small** | Air2air (6kW) 0.5 ACH TOU Setback18C | £10,100 | Storagerad (4kW) 0.5 ACH TOU | £6,680 |
| **Flat-ground** | Air2air (8kW) 0.5 ACH TOU Setback18C | £14,770 | Storagerad (6kW) 0.5 ACH TOU | £9,860 |
| **Flat-mid** | Air2air (6kW) 0.5 ACH TOU Setback18C | £17,890 | Storagerad (6kW) 0.5 ACH TOU | £12,810 |
| **Flat-top** | Air2air (10kW) TOU Setback18C | £16,990 | Storagerad (6kW) 0.5 ACH Ins-Roof TOU | £13,040 |
| **Bungalow** | LT ASHP rad (8kW) Rad+20% 0.5 ACH Ins-Roof TOU | £18,250 | Storagerad (8kW) 0.5 ACH Ins-Roof TOU | £13,550 |
| **Mid terrace-C** | LT ASHP rad (8kW) Rad+20% 0.5 ACH TOU | £19,670 | Storagerad (8kW) 0.5 ACH TOU | £15,240 |
| **Mid terrace-S** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU Setback18C | £21,450 | Storagerad (8kW) 0.5 ACH Ins-Roof TOU | £16,110 |
| **Compact (semi-d)** | LT ASHP rad (12kW) Rad+20% 0.5 ACH Ins-Roof TOU | £23,350 | Storagerad (12kW) 0.5 ACH TOU | £17,550 |
| **Medium-C (end-terr.)** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU | £23,310 | Storagerad (10kW) 0.5 ACH TOU | £18,070 |
| **Medium-S (semi-d)** | Air2air (22kW) 0.5 ACH TOU | £25,130 | No change | £18,900 |
| **Sprawling-C (det.)** | LT ASHP rad (12kW) Rad+50% 0.5 ACH TOU | £22,160 | Storagerad (10kW) 0.5 ACH Ins-Roof TOU | £16,240 |
| **Sprawling-S (det.)** | Air2air (22kW) 0.5 ACH TOU | £26,880 | No change | £19,780 |

## Small Rise in Peak Electricity Price

What happens if only the peak electricity price rises? This is an entirely plausible scenario, because the Octopus Agile tariff this project's time-of-use tariffs are based on is very economical. Initially we modelled the impact of a small (10%) rise in peak-rate electricity prices: from 25.3p a unit up to 27.8p a unit. This had only a minor effect on the cost-optimal packages of measures: only two house types changed, one from an air-to-air heat pump to storage rads and one from an air-to-air heat pump to a low-temperature air-source heat pump (see Table 7.4 below). This was because total costs over 15 years for the mid-floor flat were similar for the air-to-air and air-source heat pumps, and the increased costs during the peak period just tipped the balance in favour of the air-source heat pump, with higher capital costs but lower running costs than air-to-air.

The impact on total costs over 15 years for all house types is very modest – an increase in costs between £140 (1%) for the Small flat and £520 (2%) for Sprawling-S.

**Table 7.4: Impact of 10% higher peak-electricity prices on optimum measures and total costs over 15 years**

| House Type | Original Optimum Package | Original Optimum Cost | New Optimum Package | Optimum with New Costs |
|---|---|---|---|---|
| **Flat-small** | Air2air (6kW) 0.5 ACH TOU Setback18C | £10,100 | Storage rad (4 kW) 0.5 ACH TOU<br>Ins-roof | £10,240 |
| **Flat-ground** | Air2air (8kW) 0.5 ACH TOU Setback18C | £14,770 | No change | £15,120 |
| **Flat-mid** | Air2air (6kW) 0.5 ACH TOU Setback18C | £17,890 | LT ASHP rad (6kW) Rad+100% TOU | £18,180 |
| **Flat-top** | Air2air (10kW) TOU Setback18C | £16,990 | No change | £17,230 |
| **Bungalow** | LT ASHP rad (8kW) Rad+20% 0.5 ACH Ins-Roof TOU | £18,250 | No change | £18,540 |
| **Mid terrace-C** | LT ASHP rad (8kW) Rad+20% 0.5 ACH TOU | £19,670 | No change | £19,940 |
| **Mid terrace-S** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU Setback18C | £21,450 | No change | £21,730 |
| **Compact (semi-d)** | LT ASHP rad (12kW) Rad+20% 0.5 ACH Ins-Roof TOU | £23,350 | No change | £23,710 |

| | | | | |
|---|---|---|---|---|
| **Medium-C (end-terr.)** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU | £23,310 | No change | £23,660 |
| **Medium-S (semi-d)** | Air2air (22kW) 0.5 ACH TOU | £25,130 | No change | £25,620 |
| **Sprawling-C (det.)** | LT ASHP rad (12kW) Rad+50% 0.5 ACH TOU | £22,160 | No change | £22,470 |
| **Sprawling-S (det.)** | Air2air (22kW) 0.5 ACH TOU | £26,880 | No change | £27,400 |

## Larger Rise in Peak Electricity Price

What happens if the peak electricity price rises more steeply? We went on to model the impact of a larger (20%) rise in peak-rate electricity prices: from 25.3p a unit up to 30.4p a unit. This had a slightly more pronounced effect on the cost-optimal packages of measures than the 10% rise. As before, the cost-optimum package for the mid-floor flat changed, from an air-to-air heat pump to a low-temperature air-source heat pump (see Table 7.5 below). In addition, for the 20% increase, the Sprawling-S case now selects an 18C set-back temperature (rather than the usual 16C for heat pumps), which results in using less electricity at peak time to come up to temperature. Again, the balance just tips in favour of this control strategy because the savings from avoiding higher peak electricity costs outweigh the increased cost from running heating higher at other times.

The impact on total costs over 15 years for all house types is exactly the same pattern as with the 10% peak tariff increase above. The increase is double the increase witnessed with the previous scenario: £250 (2%) more for the Small flat, rising to £1,030 (4%) for the Sprawling detached house with solid walls.

**Table 7.5: Impact of 20% higher peak-electricity prices on optimum measures and total costs over 15 years**

| House Type | Original Optimum Package | Original Optimum Cost | New Optimum Package | Optimum with New Costs |
|---|---|---|---|---|
| **Flat-small** | Air2air (6kW) 0.5 ACH TOU Setback18C | £10,100 | Storagerad (4kW) 0.5 ACH Ins-Roof TOU | £10,350 |
| **Flat-ground** | Air2air (8kW) 0.5 ACH TOU Setback18C | £14,770 | No change | £15,470 |
| **Flat-mid** | Air2air (6kW) 0.5 ACH TOU Setback18C | £17,890 | LT ASHP rad (6kW) Rad+100% TOU | £18,430 |
| **Flat-top** | Air2air (10kW) TOU Setback18C | £16,990 | No change | £17,470 |
| **Bungalow** | LT ASHP rad (8kW) Rad+20% 0.5 ACH Ins-Roof TOU | £18,250 | No change | £18,820 |

| | | | | |
|---|---|---|---|---|
| **Mid terrace-C** | LT ASHP rad (8kW) Rad+20% 0.5 ACH TOU | £19,670 | No change | £20,220 |
| **Mid terrace-S** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU Setback18C | £21,450 | No change | £22,010 |
| **Compact (semi-d)** | LT ASHP rad (12kW) Rad+20% 0.5 ACH Ins-Roof TOU | £23,350 | No change | £24,070 |
| **Medium-C (end-terr.)** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU | £23,310 | No change | £24,010 |
| **Medium-S (semi-d)** | Air2air (22kW) 0.5 ACH TOU | £25,130 | No change | £26,110 |
| **Sprawling-C (det.)** | LT ASHP rad (12kW) Rad+50% 0.5 ACH TOU | £22,160 | No change | £22,780 |
| **Sprawling-S (det.)** | Air2air (22kW) 0.5 ACH TOU | £26,880 | Air2air (22kW) 0.5 ACH TOU Setback18C | £27,910 |

## High Capital Cost Scenario

It is unlikely that any two homes undergoing the same package of measures for electric heating would incur exactly the same costs. Even if the dwellings are identical to start with, labour and materials costs vary over time, and different installers price work differently. This means it is difficult to give a single set of costs for installing measures. Moreover, the costs of installing electric heating systems could rise or fall over coming years depending on the supply of, and demand for, electric heating.

This scenario examines the effect of capital costs for all measures that are 20% higher than those in the standard models (see Table 7.6 below). This makes only two changes to the choice of cost-optimal packages of measures: for the small flat and the mid-floor flat the storage radiator solution now costs less than the air-to-air heat pump, although the difference between them in this scenario is only £40. This emphasises small increases in capital cost for all electric heating measures make little difference to the optimum packages selected.

Total costs (where there is a new heating system) rise by between £640 (6%) and £2,570 (11%) when CapEx increases 20%. The variation is largely, but not exclusively, driven by different sizes of dwellings.

There is a caveat to this sensitivity test: it assumes that CapEx rises evenly for all upgrades. In reality, this may not be the case. Different supply constraints could mean that some measures rise in costs while others remain constant or fall. Depending on the magnitude of increased costs, this would very likely bring changes to the cost-optimal packages of measures.

**Table 7.6: Impact of the high capital cost scenario on optimum measures and total costs over 15 years**

| House Type | Original Optimum Package | Original Optimum Cost | New Optimum Package | Optimum with New Costs |
|---|---|---|---|---|
| **Flat-small** | Air2air (6kW) 0.5 ACH TOU Setback18C | £10,100 | Storagerad (4kW) 0.5 ACH TOU | £10,780 |
| **Flat-ground** | Air2air (8kW) 0.5 ACH TOU Setback18C | £14,770 | No change | £15,900 |
| **Flat-mid** | Air2air (6kW) 0.5 ACH TOU Setback18C | £17,890 | Storagerad (6kW) 0.5 ACH TOU | £19,510 |
| **Flat-top** | Air2air (10kW) TOU Setback18C | £16,990 | No change | £18,910 |
| **Bungalow** | LT ASHP rad (8kW) Rad+20% 0.5 ACH Ins-Roof TOU | £18,250 | No change | £20,160 |
| **Mid terrace-C** | LT ASHP rad (8kW) Rad+20% 0.5 ACH TOU | £19,670 | No change | £21,910 |
| **Mid terrace-S** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU Setback18C | £21,450 | No change | £23,970 |
| **Compact (semi-d)** | LT ASHP rad (12kW) Rad+20% 0.5 ACH Ins-Roof TOU | £23,350 | No change | £25,920 |
| **Medium-C (end-terr.)** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU | £23,310 | No change | £25,880 |
| **Medium-S (semi-d)** | Air2air (22kW) 0.5 ACH TOU | £25,130 | No change | £27,400 |
| **Sprawling-C (det.)** | LT ASHP rad (12kW) Rad+50% 0.5 ACH TOU | £22,160 | No change | £24,690 |
| **Sprawling-S (det.)** | Air2air (22kW) 0.5 ACH TOU | £26,880 | No change | £29,150 |

## Low Capital Cost Scenario

Given that high CapEx makes a minor difference to the rankings and choice of cost-optimal packages, it seems likely that more economical installation costs would also make a small difference. Is this borne out by the sensitivity analysis?

The low-cost scenario explored costs 20% lower than those in the standard models (see Table 7.7 below). This time the Ground-floor flat is unchanged, but the cost-optimal package for the Mid-floor flat now has a different heating system. The original air-to-air heating system is replaced by the more efficient (but higher cost) low-temperature air source heat pump, with radiators double the original output. The 18C set-back temperature that was needed with the air-to-air heat pump is no longer required, so the set-back for the new package of measures is the default 16C applied to heat pumps in the models.

Total costs in this scenario, for cases with a change in heating system, drop by between £870 (9%) and £2,580 (11%) when CapEx falls by 20%. As before with high CapEx, capital costs vary as a fraction of total costs between house types and packages of measures.

The caveat on high capital costs applies equally (or more) here: CapEx may not fall evenly for all upgrades. It is likely that economies of scale and learning effects will act to reduce the costs of electric heating over time, as the market grows. However, these effects are unlikely to apply evenly – for example, the cost of labour-intensive measures like wall insulation is less likely to fall as rapidly as installing new heating systems. Similarly, innovations affecting any of the measures, in materials or installation methods, are unlikely to apply evenly across all measures. Such disparities across measures could very likely bring changes to the cost-optimal packages of measures that are not reflected here.

**Table 7.7: Impact of the low capital cost scenario on optimum measures and total costs over 15 years**

| House Type | Original Optimum Package | Original Optimum Cost | New Optimum Package | Optimum with New Costs |
|---|---|---|---|---|
| **Flat-small** | Air2air (6kW) 0.5 ACH TOU Setback18C | £10,100 | No change | £9,230 |
| **Flat-ground** | Air2air (8kW) 0.5 ACH TOU Setback18C | £14,770 | No change | £13,650 |
| **Flat-mid** | Air2air (6kW) 0.5 ACH TOU Setback18C | £17,890 | LT ASHP rad (6kW) Rad+100% TOU | £15,910 |
| **Flat-top** | Air2air (10kW) TOU Setback18C | £16,990 | No change | £15,080 |
| **Bungalow** | LT ASHP rad (8kW) Rad+20% 0.5 ACH Ins-Roof TOU | £18,250 | No change | £16,350 |
| **Mid terrace-C** | LT ASHP rad (8kW) Rad+20% 0.5 ACH TOU | £19,670 | No change | £17,430 |

| | | | | |
|---|---|---|---|---|
| **Mid terrace-S** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU Setback18C | £21,450 | No change | £18,940 |
| **Compact (semi-d)** | LT ASHP rad (12kW) Rad+20% 0.5 ACH Ins-Roof TOU | £23,350 | No change | £20,780 |
| **Medium-C (end-terr.)** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU | £23,310 | No change | £20,730 |
| **Medium-S (semi-d)** | Air2air (22kW) 0.5 ACH TOU | £25,130 | No change | £22,850 |
| **Sprawling-C (det.)** | LT ASHP rad (12kW) Rad+50% 0.5 ACH TOU | £22,160 | No change | £19,640 |
| **Sprawling-S (det.)** | Air2air (22kW) 0.5 ACH TOU | £26,880 | No change | £24,600 |

## Longer Time Horizon Scenario

Inevitably, investment decisions alter depending how far ahead the investor takes into account. The standard time horizon used in this project was 15 years, but in reality householders and others will be influenced by how long they intend to own a dwelling, as well as many other factors. What difference does it make how far ahead they look when they are making investment decisions? This scenario extends the time horizon to 25 years, and the scenario that follows shortens it to just five years.

Adopting a 25-year timeframe changes the cost-optimal heating system for eight of the house types, and all eight adopt storage heaters instead of heat pumps that were selected previously (see Table 7.8 below). This is because new storage heaters are not expected to incur maintenance costs or to need replacing within the next 25 years – whereas heat pumps are expected to need replacing, as well as relatively low-cost annual maintenance checks. Naturally, these ongoing running costs become more important when viewed over a longer time horizon, and the higher energy costs are more than offset by other costs of ownership.

Typically, the sizes of the storage radiator systems are smaller than the heat pumps they replace, because the output of the heat pumps falls in very cold weather, so a slightly larger system is needed to achieve comfort temperatures. The output from storage heaters, meanwhile, is unaffected by low outdoor temperatures. In five of these eight cases, top-up loft insulation is now also justified with the longer timeframe to recoup the up-front investment. However, even over 25 years neither wall insulation nor floor insulation are justified for cost reasons.

Total costs of ownership are considerably higher than standard model runs when the time horizon is extended to 25 years: from £2,930 (29% of original costs) for the Small flat to £11,780 (44%) for the Sprawling-S detached house with solid walls.

**Table 7.8: Impact of a 25-year time horizon on optimum measures and total costs**

| House Type | Original Optimum Package | Original Optimum Cost (15 years) | New Optimum Package | Optimum with New Costs (25 years) |
|---|---|---|---|---|
| **Flat-small** | Air2air (6kW) 0.5 ACH TOU Setback18C | £10,100 | Storagerad (4kW) 0.5 ACH TOU | £13,030 |
| **Flat-ground** | Air2air (8kW) 0.5 ACH TOU Setback18C | £14,770 | Storagerad (6kW) 0.5 ACH Ins-Roof TOU | £20,160 |
| **Flat-mid** | Air2air (6kW) 0.5 ACH TOU Setback18C | £17,890 | Storagerad (6kW) 0.5 ACH TOU | £22,560 |
| **Flat-top** | Air2air (10kW) TOU Setback18C | £16,990 | Storagerad (6kW) 0.5 ACH Ins-Roof TOU | £22,150 |
| **Bungalow** | LT ASHP rad (8kW) Rad+20% 0.5 ACH Ins-Roof TOU | £18,250 | Storagerad (8kW) 0.5 ACH Ins-Roof TOU | £25,990 |
| **Mid terrace-C** | LT ASHP rad (8kW) Rad+20% 0.5 ACH TOU | £19,670 | Storagerad (8kW) 0.5 ACH Ins-Roof TOU | £26,660 |
| **Mid terrace-S** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU Setback18C | £21,450 | Storagerad (8kW) 0.5 ACH Ins-Roof TOU | £28,770 |
| **Compact (semi-d)** | LT ASHP rad (12kW) Rad+20% 0.5 ACH Ins-Roof TOU | £23,350 | No change | £32,990 |
| **Medium-C (end-terr.)** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU | £23,310 | No change | £32,910 |
| **Medium-S (semi-d)** | Air2air (22kW) 0.5 ACH TOU | £25,130 | No change | £36,160 |
| **Sprawling-C (det.)** | LT ASHP rad (12kW) Rad+50% 0.5 ACH TOU | £22,160 | Storagerad (10kW) 0.5 ACH Ins-Roof TOU | £30,680 |
| **Sprawling-S (det.)** | Air2air (22kW) 0.5 ACH TOU | £26,880 | No change | £38,660 |

## Shorter Time Horizon Scenario

Re-running the model optimisation over five years witnesses the most radical change in the selection of cost-optimal heating system of all the sensitivity scenarios, see Table 7.9. All but one of the house types now select a different optimised package of measures. Once again most of the changes are substituting storage heaters for heat pumps that are preferred over 15 years. This time, however, the changes have nothing to do with long-term costs of ownership, but are entirely due to lower capital costs of storage heaters.

It is interesting to note that some house types now select top-up loft insulation in the cost-optimal basket of measures, while it was not chosen with a 15-year timeframe; whereas other house types moved the other way: they selected loft insulation before but do not with a shorter time horizon. Two house types where air-tightness measures were justified for cost reasons over 15 years can no longer justify the measures over five years (the Mid-floor flat and Medium-S). However, nine house types overall do include air-tightness measures and only 0.5 air changes per hour among the optimum packages of measures).

The choice of measures for the least efficient house type – the Sprawling-S detached house with solid walls, which has the highest energy costs overall – is unchanged by having a very short time horizon. This selects an air-to-air heat pump plus air-tightness measures (and nothing else) over either a 15 or five-year timespan. This heat pump has low initial costs compared to other heating systems, but apparently even the CapEx savings from storage heaters are not sufficient to cover the increased energy costs compared to the air-to-air heat pump.

**Table 7.9: Impact of a five-year time horizon on optimum measures and total costs**

| House Type | Original Optimum Package | Original Optimum Cost (15 years) | New Optimum Package | Optimum with New Costs (5 years) |
|---|---|---|---|---|
| **Flat-small** | Air2air (6kW) 0.5 ACH TOU Setback18C | £10,100 | Storagerad (4kW) 0.5 ACH TOU | £5,940 |
| **Flat-ground** | Air2air (8kW) 0.5 ACH TOU Setback18C | £14,770 | Storagerad (6kW) 0.5 ACH TOU | £8,680 |
| **Flat-mid** | Air2air (6kW) 0.5 ACH TOU Setback18C | £17,890 | Storagerad (6kW) TOU | £11,660 |
| **Flat-top** | Air2air (10kW) TOU Setback18C | £16,990 | Storagerad (6kW) 0.5 ACH Ins-Roof TOU | £12,000 |
| **Bungalow** | LT ASHP rad (8kW) Rad+20% 0.5 ACH Ins-Roof TOU | £18,250 | Storagerad (8kW) 0.5 ACH TOU | £12,110 |
| **Mid terrace-C** | LT ASHP rad (8kW) Rad+20% 0.5 ACH TOU | £19,670 | Storagerad (8kW) 0.5 ACH TOU | £13,910 |

| | | | | |
|---|---|---|---|---|
| **Mid terrace-S** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU Setback18C | £21,450 | Storagerad (8kW) 0.5 ACH Ins-Roof TOU | £14,670 |
| **Compact (semi-d)** | LT ASHP rad (12kW) Rad+20% 0.5 ACH Ins-Roof TOU | £23,350 | Storagerad (12kW) 0.5 ACH TOU | £15,840 |
| **Medium-C (end-terr.)** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU | £23,310 | Storagerad (10kW) 0.5 ACH TOU | £16,320 |
| **Medium-S (semi-d)** | Air2air (22kW) 0.5 ACH TOU | £25,130 | Air2air (22kW) TOU | £16,690 |
| **Sprawling-C (det.)** | LT ASHP rad (12kW) Rad+50% 0.5 ACH TOU | £22,160 | Storagerad (10kW) 0.5 ACH Ins-Roof TOU | £14,580 |
| **Sprawling-S (det.)** | Air2air (22kW) 0.5 ACH TOU | £26,880 | No change | £17,450 |

## No discounting scenario

A discount rate is usually applied to future costs and benefits in economic analysis, to reflect the time value of money (people prefer to have money today compared to in the future). This means that costs and benefits falling in the future carry less weight in decisions. This project uses a discount rate of 3.5%, but this scenario explored what happens if there is no discounting of future costs and benefits.

The impact of removing discounting is modest, and only one of the cost-optimum selections of packages changes as a result, see Table 7.10. This is for the Mid-floor flat, where a low-temperature air-source heat pump is now selected in preference to an air-to-air heat pump. Increased weight on future costs (mostly for purchasing energy) means that the more efficient – but higher capital cost – heat pump is now chosen ahead of the less efficient but lower CapEx heat pump.

The impact of removing discounting on total costs over 15 years for all house types rises from £1,480 up to £4,000, depending how much energy each house type uses with the cost-optimum package of measures. The percentage increase varies rather more between house types and packages, depending on the balance of initial capital costs to energy and maintenance costs incurred in future years. At the lower extreme, the Mid-terrace house with solid walls costs rise by just under 11%, whereas at the upper end costs rise by 16% for the Ground-floor flat as a result of removing discounting.

**Table 7.10: Impact of no discounting of future costs and benefits on optimum measures and total costs over 15 years**

| House Type | Original Optimum Package | Original Optimum Cost | New Optimum Package | Optimum with New Costs |
|---|---|---|---|---|
| **Flat-small** | Air2air (6kW) 0.5 ACH TOU Setback18C | £10,100 | No change | £11,580 |
| **Flat-ground** | Air2air (8kW) 0.5 ACH TOU Setback18C | £14,770 | No change | £17,130 |
| **Flat-mid** | Air2air (6kW) 0.5 ACH TOU Setback18C | £17,890 | LT ASHP rad (6kW) Rad+100% 0.5 ACH TOU | £19,940 |
| **Flat-top** | Air2air (10kW) TOU Setback18C | £16,990 | No change | £18,910 |
| **Bungalow** | LT ASHP rad (8kW) Rad+20% 0.5 ACH Ins-Roof TOU | £18,250 | No change | £20,510 |
| **Mid terrace-C** | LT ASHP rad (8kW) Rad+20% 0.5 ACH TOU | £19,670 | No change | £21,860 |
| **Mid terrace-S** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU Setback18C | £21,450 | No change | £23,740 |
| **Compact (semi-d)** | LT ASHP rad (12kW) Rad+20% 0.5 ACH Ins-Roof TOU | £23,350 | No change | £26,070 |
| **Medium-C (end-terr.)** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU | £23,310 | No change | £26,000 |
| **Medium-S (semi-d)** | Air2air (22kW) 0.5 ACH TOU | £25,130 | No change | £28,680 |
| **Sprawling-C (det.)** | LT ASHP rad (12kW) Rad+50% 0.5 ACH TOU | £22,160 | No change | £24,630 |
| **Sprawling-S (det.)** | Air2air (22kW) 0.5 ACH TOU | £26,880 | No change | £30,880 |

## High discounting scenario

The scenario above found that removing the discount on future costs and benefits made little difference to the ranking of packages of measures. However, what happens if a much higher discount rate is applied? We re-ran the optimisation with a discount rate of 7.5%. This rate was proposed by BEIS as a typical 'personal' discount rate: the level of discounting applied to personal investment decisions, and arguably the rate householders use (often implicitly) to consider financial investments. A higher discount rate means less weight is placed on future costs and benefits, and relatively more weight on up-front costs.

The impact of a higher discount rate (a little more than twice the standard rate of 3.5%) is slightly more pronounced than removing discounting, above. Three of the cost-optimum selections of packages change as a result – though one of these is a relatively minor change (see Table 7.11 below). The significant changes are once again for the Small flat and the Mid-floor flat, where storage radiators are now selected instead of the air-to-air heat pump. This is essentially the reverse of the change above, and now a lower CapEx option displaces the more expensive heat pump, because running costs over 15 years become less important.

There is also a change to the Sprawling detached house with cavity walls, where the higher discount rate means that improved air tightness is no longer justified by future savings in energy costs. So this disappears from the optimum package, but it is replaced by an early evening start time, to compensate for weaker comfort when air tightness is not improved.

Inevitably, higher discounting of future costs over 15 years means that total costs fall for all house types. The reduction varies from 8% to 14%, depending on house type and measures. In cost terms, the Sprawling-S detached house with solid walls saves most – £3,170 – and the Small flat saves least: £1,370.

**Table 7.11: Impact of 7.5% discounting of future costs and benefits on optimum measures and total costs over 15 years**

| House Type | Original Optimum Package | Original Optimum Cost | New Optimum Package | Optimum with New Costs |
|---|---|---|---|---|
| **Flat-small** | Air2air (6kW) 0.5 ACH TOU Setback18C | £10,100 | Storagerad (4kW) 0.5 ACH TOU | £8,730 |
| **Flat-ground** | Air2air (8kW) 0.5 ACH TOU Setback18C | £14,770 | No change | £12,910 |
| **Flat-mid** | Air2air (6kW) 0.5 ACH TOU Setback18C | £17,890 | Storagerad (6kW) 0.5 ACH TOU | £15,870 |
| **Flat-top** | Air2air (10kW) TOU Setback18C | £16,990 | No change | £15,480 |
| **Bungalow** | LT ASHP rad (8kW) Rad+20% 0.5 ACH Ins-Roof TOU | £18,250 | No change | £16,470 |
| **Mid terrace-C** | LT ASHP rad (8kW) Rad+20% 0.5 ACH TOU | £19,670 | No change | £17,940 |

| | | | | |
|---|---|---|---|---|
| **Mid terrace-S** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU Setback18C | £21,450 | No change | £19,640 |
| **Compact (semi-d)** | LT ASHP rad (12kW) Rad+20% 0.5 ACH Ins-Roof TOU | £23,350 | No change | £21,210 |
| **Medium-C (end-terr.)** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU | £23,310 | No change | £21,180 |
| **Medium-S (semi-d)** | Air2air (22kW) 0.5 ACH TOU | £25,130 | No change | £22,320 |
| **Sprawling-C (det.)** | LT ASHP rad (12kW) Rad+50% 0.5 ACH TOU | £22,160 | LT ASHP rad (12kW) Rad+50% TOU Heat on 14:00 | £20,210 |
| **Sprawling-S (det.)** | Air2air (22kW) 0.5 ACH TOU | £26,880 | No change | £23,710 |

## Workmanship scenario: what is the effect of poorly-installed insulation?

This scenario looked at the effect of relaxing the achieved U-values in the models when insulation measures are installed. This was intended to replicate the impact of insulation that is imperfectly installed – with gaps and/or thermal bridging that you would expect to be avoided with a good-quality installation, but which are commonplace today[53]. The scenario was implemented by raising the achieved U-value for insulation by 0.15 W/ $m^2$K – i.e. making the insulation performance not as good as the standard model run, when insulation measures are part of the upgrade package.

In fact, partly because so few insulation measures are selected in the cost-optimal packages (only loft insulation, and only for three dwelling types), the scenario made very little difference. It did not affect the cost-optimal measures whatsoever – not even those with loft insulation, which were still viable with poorer insulation performance.

We have not included the table for this scenario here, because there is no change to the packages of measures, and only a small change to the energy costs over 15 years. Poor workmanship increased the energy costs of the Small flat and the Bungalow by £30 over 15 years, and by £20 for the Compact semi-detached house. These are the only three house types with any insulation measure.

[53] Technology Strategy Board (2014) Retrofit for the Future: A guide to making retrofit work. Swindon: TSB. Retrofit for the Future: a guide to making retrofit work - GOV.UK (www.gov.uk)

## Air-tightness Scenario: high baseline infiltration

Infiltration and ventilation rates in dwellings are notoriously difficult and expensive to measure, and for this reason the empirical evidence about air-tightness is weaker than other aspects of energy efficiency – particularly for existing dwellings, built before air-tightness was added to Building Regulations. This means there is greater uncertainty about modelling assumptions and input data relating to air-tightness than for heating systems or insulation measures.

This scenario and the following one relax the base-case infiltration rates in each of the house types. First, we assumed infiltration rates 20% higher than the standard model runs (i.e. worse air-tightness than usual) for dwellings before any upgrade was applied. This meant that the base case air-change rates increased from 0.6-1.3 air changes per hour (depending on the house type) up to 0.72-1.56 air changes per hour. In all cases, the upgraded air-change rates improved to 0.8 or 0.5 air changes per hour, as per the standard model runs. (0.8 ac/h for modest air-tightness improvements, and 0.5 ac/h for more involved and more expensive air-tightness improvements.)

Higher infiltration rates for the base cases brought just two minor changes to the cost-optimal packages of measures. As for the standard optimisation run, 10 of the 12 house types selected the ‘extreme’ air-tightness upgrade resulting in 0.5 air changes per hour. The last one, the Top-floor flat, did not select the air-tightness upgrade, just like the standard run. However, the energy costs of this case are now £540 higher over 15 years (because the infiltration rate both before and after the upgrades were applied was 0.72 ac/h). Again, because there is no change to the cost-optimal measures we have not included the table for this scenario here.

## Air-tightness Scenario: low baseline infiltration

This scenario assumed infiltration rates 20% lower than the standard model runs (i.e. better air-tightness than usual) for dwellings before any upgrade was applied. This meant that the base case air-change rates decreased from 0.6-1.3 air changes per hour (depending on the house type) up to 0.48-1.04 air changes per hour. In all cases except the mid-floor flat, the upgraded air-change rates improved to 0.5 air changes per hour, as before.

This optimisation was more interesting: three of the cost-optimal packages changed (see Table 7.12 below). In all three cases – Flat-mid, Medium-S and Sprawling-C – the choice of heating system and insulation measures remained the same, but the airtightness measures were no longer justified on cost grounds.

Other changes to total costs resulting from the low baseline infiltration rates are also small: just £20 to £350 over 15 years.

**Table 7.12: Impact of low infiltration rates in the base case on optimum measures and total costs**

| House Type | Original Optimum Package | Original Optimum Cost | New Optimum Package | Optimum with New Costs |
|---|---|---|---|---|
| **Flat-small** | Air2air (6kW) 0.5 ACH TOU Setback18C | £10,100 | No change | £10,100 |
| **Flat-ground** | Air2air (8kW) 0.5 ACH TOU Setback18C | £14,770 | No change | £14,770 |
| **Flat-mid** | Air2air (6kW) 0.5 ACH TOU Setback18C | £17,890 | Air2air (6kW) TOU Setback18C | £17,760 |
| **Flat-top** | Air2air (10kW) TOU Setback18C | £16,990 | No change | £16,800 |
| **Bungalow** | LT ASHP rad (8kW) Rad+20% 0.5 ACH Ins-Roof TOU | £18,250 | No change | £18,250 |
| **Mid terrace-C** | LT ASHP rad (8kW) Rad+20% 0.5 ACH TOU | £19,670 | No change | £19,670 |
| **Mid terrace-S** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU Setback18C | £21,450 | No change | £21,450 |
| **Compact (semi-d)** | LT ASHP rad (12kW) Rad+20% 0.5 ACH Ins-Roof TOU | £23,350 | No change | £23,350 |
| **Medium-C (end-terr.)** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU | £23,310 | No change | £23,310 |
| **Medium-S (semi-d)** | Air2air (22kW) 0.5 ACH TOU | £25,130 | Air2air (22kW) TOU | £25,110 |
| **Sprawling-C (det.)** | LT ASHP rad (12kW) Rad+50% 0.5 ACH TOU | £22,160 | LT ASHP rad (12kW) Rad+50% TOU | £21,810 |
| **Sprawling-S (det.)** | Air2air (22kW) 0.5 ACH TOU | £26,880 | No change | £26,880 |

## Space-Constrained Scenario

This scenario examined the effects of smaller dwellings not implementing bulky measures, including all heat pumps (which are usually larger than the boilers they replace), with the exception of air-to-air heat pumps, which are usually easier to accommodate; and internal wall insulation, which is often ruled out by owners of small homes, who are reluctant to sacrifice space. The excluded measures are shown in Table 7.13 below. These were applied to all but the last five house types – Compact (semi-d), Medium-C (end-terrace), Medium-S (semi-d), Sprawling-C (detached), and Sprawling-S (detached) – because these are all over 100 $m^2$.

**Table 7.13: Measures excluded from 'Space constrained' and 'Disruptive' scenarios**

| **Fabric Measures** | Bulky measures (excluded for dwellings below 100 $m^2$ in the 'Space-constrained' scenario) | Disruptive (excluded in the 'Low disruption' scenario) |
|---|---|---|
| External wall insulation | | |
| Internal wall insulation | X | X |
| Roof insulation (pitched) | | |
| Roof insulation (flat roof) | | |
| Floor insulation | | X |
| Airtightness | | |
| Triple glazing | | |
| | | |
| **Heating System Measures** | | |
| Air-to-air heat pump | | X (exclude for all houses but not flats) |
| High-temperature ASHP | X | |
| Low-temperature ASHP | X | X |
| Low-temperature ASHP with u/floor heating | X | X |
| GSHP | X | X |
| GSHP with u/floor heating | X | X |
| Hybrid ASHP-gas boiler | X | |

| | | |
|---|---|---|
| Low-temperature ASHP with thermal store | X | X |
| High-temperature ASHP with thermal store | X | |
| GSHP with thermal store | X | |
| Radiant heaters | | |
| Infra-red panel heaters | | X (retained for electrically-heated flats, which have power cables and do not need radiators to be removed) |
| Electric storage heaters | | X (retained for electrically-heated flats, which have power cables and do not need radiators to be removed) |

Excluding bulky measures from smaller dwellings had no effect at all on the four flats (because they all selected either storage radiators or air-to-air heat pumps as the cost-optimal heating system, with no internal wall insulation). However, the effect on the three smaller houses – the bungalow and the two mid-terraces – was more pronounced, and all three switched from a low-temperature air-source heat pump to air-to-air heat pumps or storage radiators. The higher capacity needed for the air-to-air heat pumps is because the effect of reduced capacity in cold weather is greater for that technology.

These three houses saw higher total costs as a result of avoiding bulky measures: from £490 to £1,680 over 15 years.

**Table 7.14: Impact of the space-constrained scenario on optimum measures and total costs over 15 years**

| House Type | Original Optimum Package | Original Optimum Cost | New Optimum Package | Optimum with New Costs |
|---|---|---|---|---|
| **Flat-small** | Air2air (6kW) 0.5 ACH TOU Setback18C | £10,100 | No change | £10,100 |
| **Flat-ground** | Air2air (8kW) 0.5 ACH TOU Setback18C | £14,770 | No change | £14,770 |
| **Flat-mid** | Air2air (6kW) 0.5 ACH TOU Setback18C | £17,890 | No change | £17,890 |

| | | | | |
|---|---|---|---|---|
| **Flat-top** | Air2air (10kW) TOU Setback18C | £16,990 | No change | £16,990 |
| **Bungalow** | LT ASHP rad (8kW) Rad+20% 0.5 ACH Ins-Roof TOU | £18,250 | Air2air (10kW) 0.5 ACH Ins-Roof TOU Setback18C | £19,000 |
| **Mid terrace-C** | LT ASHP rad (8kW) Rad+20% 0.5 ACH TOU | £19,670 | Storagerad (8kW) 0.5 ACH Ins-Roof TOU | £21,350 |
| **Mid terrace-S** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU Setback18C | £21,450 | Air2air (14kW) 0.5 ACH TOU Setback18C | £21,940 |
| **Compact (semi-d)** | LT ASHP rad (12kW) Rad+20% 0.5 ACH Ins-Roof TOU | £23,350 | No change | £23,350 |
| **Medium-C (end-terr.)** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU | £23,310 | No change | £23,310 |
| **Medium-S (semi-d)** | Air2air (22kW) 0.5 ACH TOU | £25,130 | No change | £25,130 |
| **Sprawling-C (det.)** | LT ASHP rad (12kW) Rad+50% 0.5 ACH TOU | £22,160 | No change | £22,160 |
| **Sprawling-S (det.)** | Air2air (22kW) 0.5 ACH TOU | £26,880 | No change | £26,880 |

## Low Disruption Scenario

The low disruption scenario, where measures that would be very disruptive to occupants were excluded, did not alter any of the optimum packages for flats (see Table 7.15 below). However, the need to avoid replacing radiators with larger heat emitters precluded the use of low-temperature heat pumps, and avoiding air-to-air heat pumps in houses (where complicated ducting is usually needed), meant that high-temperature heat pumps were preferred. Inevitably, these run less efficiently, so the total cost over 15 years increased between £1,520 (8%) and £6,360 (24%), depending on the house type.

**Table 7.15: Impact of the low-disruption scenario on optimum measures and total costs over 15 years**

| House Type | Original Optimum Package | Original Optimum Cost | New Optimum Package | Optimum with New Costs |
|---|---|---|---|---|
| **Flat-small** | Air2air (6kW) 0.5 ACH TOU Setback18C | £10,100 | No change | - |
| **Flat-ground** | Air2air (8kW) 0.5 ACH TOU Setback18C | £14,770 | No change | - |
| **Flat-mid** | Air2air (6kW) 0.5 ACH TOU Setback18C | £17,890 | No change | - |
| **Flat-top** | Air2air (10kW) TOU Setback18C | £16,990 | No change | - |
| **Bungalow** | LT ASHP rad (8kW) Rad+20% 0.5 ACH Ins-Roof TOU | £18,250 | HT ASHP (8kW) 0.5 ACH Ins-Roof TOU | £19,770 |
| **Mid terrace-C** | LT ASHP rad (8kW) Rad+20% 0.5 ACH TOU | £19,670 | HT ASHP (8kW) 0.5 ACH TOU | £21,290 |
| **Mid terrace-S** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU Setback18C | £21,450 | HT ASHP (10kW) 0.5 ACH TOU | £23,450 |
| **Compact (semi-d)** | LT ASHP rad (12kW) Rad+20% 0.5 ACH Ins-Roof TOU | £23,350 | HT ASHP (14kW) 0.5 ACH TOU | £27,080 |
| **Medium-C (end-terr.)** | LT ASHP rad (10kW) Rad+20% 0.5 ACH TOU | £23,310 | HT ASHP (12kW) 0.5 ACH TOU | £27,080 |
| **Medium-S (semi-d)** | Air2air (22kW) 0.5 ACH TOU | £25,130 | HT ASHP (16kW) 0.5 ACH TOU | £30,530 |
| **Sprawling-C (det.)** | LT ASHP rad (12kW) Rad+50% 0.5 ACH TOU | £22,160 | HT ASHP (12kW) 0.5 ACH TOU | £23,970 |
| **Sprawling-S (det.)** | Air2air (22kW) 0.5 ACH TOU | £26,880 | HT ASHP (18kW) 0.5 ACH TOU Setback18C | £33,240 |

# 8. Scaling-up findings

*As well as insights about how individual house types can move to electric heating cost-effectively, this work has examined the cost of a wholesale electrification rolled out across the whole of Great Britain.*

The modelling findings described so far in the report are for individual house types. These provide useful insights relating to the most economical ways for consumers to electrify heating in specific kinds of housing. However, they provide limited value for understanding how transitioning to cost-optimal electric heating will affect the overall demand for electricity, or peak power demand, or how much it will cost in total to electrify British homes. This chapter of the report uses housing data from the 2017 English Housing Survey and the National Buildings Model to scale-up findings to the whole country.

The chapter begins by summarising findings for each house type, then we discuss the method of scaling up, then we show the aggregate effects of electrified heating in all homes. In each case we start with costs – capital costs, energy costs and maintenance costs – then move to annual energy consumption, and finally to peak electricity use with electric heating.

## Costs, energy and peak demand

Starting with costs for adopting electric heating in each of the 12 house types, Table 8.1 below shows capital costs and annual energy and maintenance costs for each house type. These costs are total costs for adopting cost-effective electric heating, including heating systems, new heat emitters where necessary, and fabric upgrades. We assume that cost-competitive time-of-use tariffs are applied throughout this chapter, which affects both the measures selected and the cost of energy. CapEx ranges from £4,380 to £12,860. Notice that there are very wide variations in capital cost and annual energy cost between house types, and CapEx ranges from seven times annual energy and maintenance costs for the Ground-floor flat up to 17 times annual energy and maintenance cost for the mid-terrace house with solid walls.

**Table 8.1: Capital and annual operating costs**

| House type | Cost-optimal measures* | Capital costs (heating and fabric measures) | Annual energy cost | Annual maintenance cost |
|---|---|---|---|---|
| **Small flat** | Air-to-air heat pump, air-tightness measures, high setback temperature | £4,380 | £370 | £110 |
| **Ground-floor flat** | Air-to-air heat pump, air-tightness measures, high setback temperature | £5,640 | £656 | £110 |
| **Mid-floor flat** | Air-to-air heat pump, air-tightness measures, high setback temperature | £9,290 | £610 | £110 |
| **Top-floor flat** | Air-to-air heat pump, high setback temperature | £9,590 | £510 | £110 |
| **Bungalow** | Low-temperature air-source heat pump with 20% larger radiators, air-tightness measures, roof insulation | £9,520 | £620 | £110 |
| **Mid-terrace with cavity walls** | Low-temperature air-source heat pump with 20% larger radiators, air-tightness measures | £11,200 | £600 | £110 |
| **Mid-terrace with solid walls** | Low-temperature air-source heat pump with 20% larger radiators, air-tightness measures, high setback temperature | £12,580 | £630 | £110 |
| **Compact semi-D** | Low-temperature air-source heat pump with 20% larger radiators, air-tightness measures, roof insulation | £12,850 | £770 | £110 |
| **End-terrace with cavity walls** | Low-temperature air-source heat pump with 20% larger radiators, air-tightness measures | £12,860 | £770 | £110 |
| **Semi-D with solid walls** | Air-to-air heat pump, air-tightness measures | £11,370 | £1,040 | £110 |
| **Detached with cavity walls** | Low-temperature air-source heat pump with 50% larger radiators, air-tightness measures | £12,620 | £690 | £110 |
| **Detached with solid walls** | Air-to-air heat pump, air-tightness measures | £11,370 | £1,190 | £110 |

*These are the cost-optimal packages for time-of-use tariffs. Optimal measures are different with standard, flat tariffs, and energy costs are higher.

The same house types and cost-optimal measures are shown in Table 8.2 below. The table shows what fraction of the housing stock is represented by each house type (derived from the National Buildings Model, see below). It also shows current gas and electricity use (for all uses, not just heating) for each house type, and modelled estimates of future electricity use (again, all uses), if each house type adopts cost-effective electric heating.

For the house types that have gas heating in the base case (i.e. excluding the two flats with electric storage heaters), gas consumption ranges from 6,460 kWh a year up to 24,120 kWh a year. Four times more gas is used each year by the larger, less efficient dwellings than the smaller efficient ones. However, electricity use in the 'current' base case is more consistent between dwellings: from 1,480 to 2,490 kWh a year for homes that start with gas heating, and much more for the two flats with electric storage heaters.

After switching to cost-effective electric heating, electricity consumption rises to between 3,350 and 10,060 kWh a year – with no gas use. Even very modest fabric improvements, along with the coefficient of performance of heat pumps, have the effect of reducing overall energy use in the dwellings considerably. The two large houses with un-insulated solid walls stand out as high-consumption homes after the upgrades.

**Table 8.2: Annual energy consumption (kWh)**

| House type | Proportion of homes | Current annual gas use | Current annual electricity use | Annual electricity use with cost-optimal electric heating |
|---|---|---|---|---|
| **Small flat** | 4% | n/a | 7,780* | 3,350 |
| **Ground-floor flat** | 8% | n/a | 12,180* | 5,380 |
| **Mid-floor flat** | 3% | 6,460 | 2,000 | 4,670 |
| **Top-floor flat** | 3% | 7,610 | 1,480 | 4,290 |
| **Bungalow** | 9% | 13,150 | 2,360 | 5,370 |
| **Mid-terrace with cavity walls** | 9% | 10,890 | 2,380 | 5,180 |
| **Mid-terrace with solid walls** | 10% | 12,140 | 1,980 | 5,450 |
| **Compact semi-D** | 16% | 15,140 | 2,640 | 6,460 |
| **End-terrace with cavity walls** | 13% | 16,260 | 3,090 | 6,560 |
| **Semi-D with solid walls** | 7% | 20,610 | 2,740 | 8,940 |
| **Detached with cavity walls** | 14% | 12,680 | 2,090 | 5,890 |
| **Detached with solid walls** | 2% | 24,120 | 2,490 | 10,060 |

*First two flats are electric-only.

How do these combinations of capital investments and ongoing energy costs translate into total costs of ownership? Table 8.3 below gives total costs over 15 years, including maintenance costs in each case. As before, future costs are discounted at 3.5%. For current costs, it also includes the cost of replacing boilers in the house types that start with gas heating – since modern boilers typically last 15 years, and they are very likely to need replacement within 15 years.

The total costs of owning the cost-effective electric heating are not so much more than the cost of sticking with the existing heating system – on average 46% higher. For the Ground-floor flat that started with electric storage heaters the costs are only a little higher (£550 over 15 years), even allowing for new and more controllable heating. Part of this saving is due to using time-of-use tariffs, which are more attractive than current Economy 7 tariffs. Ownership costs change more dramatically for the large houses and dwellings where little or no fabric upgrades are selected through optimisation.

**Table 8.3: Total costs over 15 years**

| House type | Cost-optimal measures | Current total cost over 15 years* | Total cost over 15 years with cost-optimal electric heating |
|---|---|---|---|
| **Small flat** | Air-to-air heat pump, air-tightness measures, high setback temperature | £8,610 | £10,100 |
| **Ground-floor flat** | Air-to-air heat pump, air-tightness measures, high setback temperature | £14,220 | £14,770 |
| **Mid-floor flat** | Air-to-air heat pump, air-tightness measures, high setback temperature | £9,340 | £17,890 |
| **Top-floor flat** | Air-to-air heat pump, high setback temperature | £9,240 | £16,990 |
| **Bungalow** | Low-temperature air-source heat pump with 20% larger radiators, air-tightness measures, roof insulation | £13,830 | £18,250 |
| **Mid-terrace with cavity walls** | Low-temperature air-source heat pump with 20% larger radiators, air-tightness measures | £12,570 | £19,670 |
| **Mid-terrace with solid walls** | Low-temperature air-source heat pump with 20% larger radiators, air-tightness measures, high setback temperature | £12,540 | £21,450 |
| **Compact semi-D** | Low-temperature air-source heat pump with 20% larger radiators, air-tightness measures, roof insulation | £15,210 | £23,350 |

| | | | |
|---|---|---|---|
| **End-terrace with cavity walls** | Low-temperature air-source heat pump with 20% larger radiators, air-tightness measures | £16,770 | £23,310 |
| **Semi-D with solid walls** | Air-to-air heat pump, air-tightness measures | £18,680 | £25,130 |
| **Detached with cavity walls** | Low-temperature air-source heat pump with 50% larger radiators, air-tightness measures | £13,020 | £22,160 |
| **Detached with solid walls** | Air-to-air heat pump, air-tightness measures | £20,140 | £26,880 |

*Comprising capital costs for upgrades and replacing the existing boiler at the end of its service life, energy and maintenance costs. Future costs discounted at 3.5%.

Table 8.4 below shows the impact of converting to all-electric heating on power drawn from the electricity grid during the critical 4-7pm evening peak on the coldest day of the year, when most power is used nationally. It is the homes with highest annual demand for electricity that have the highest peak power demand – up to 5.6 kW in the case of the Detached house with solid walls. This is a large rise from today's average power during the peak of 0.4 kW, and it would have significant implications for grid reinforcement to be able to power a street of such homes if they all switched to electric heating.

Changes to peak demand for other house types are less marked, but still significant, even for flats that were previously heated by electricity. Notice that the peak electricity demand by the Small flat and Ground-floor flat increases significantly even though they are assumed to use storage heaters in the base case. This is because both flats are not using electricity to charge their storage heaters from 4-7pm (which also explains why their power draw is limited). In both cases, after upgrading, most of the electricity use during the peak period is for domestic hot water, and the timing of this water heating (linked to different internal temperatures) alters as an unintended consequence of the change.

**Table 8.4: Average demand for electricity during 4-7pm peak (kW)**

| House type | Current peak period demand** on the coldest day | Peak period demand on the coldest day with cost-optimal electric heating |
|---|---|---|
| **Small flat*** | 0.15 | 1.06 |
| **Ground-floor flat*** | 0.90 | 1.60 |
| **Mid-floor flat** | 0.33 | 2.08 |
| **Top-floor flat** | 0.25 | 1.89 |
| **Bungalow** | 0.51 | 1.86 |
| **Mid-terrace with cavity walls** | 0.51 | 1.83 |
| **Mid-terrace with solid walls** | 0.33 | 2.01 |

| | | |
|---|---|---|
| **Compact semi-D** | 0.44 | 2.19 |
| **End-terrace with cavity walls** | 0.97 | 2.76 |
| **Semi-D with solid walls** | 0.59 | 3.51 |
| **Detached with cavity walls** | 0.35 | 2.13 |
| **Detached with solid walls** | 0.42 | 5.56 |

*Note the first two flats are electric-only in the base case and use electric storage heaters and an immersion heater for hot water. Both space and water heating are carried out overnight in base case, so do not affect electricity use in the peak period. This changes after they install heat pumps, and they require some heating during the peak.

**Average peak demand is defined as average kW of electricity drawn during the peak 4-7pm period. This avoids spikes in demand caused for very short periods, such as a kettle boiling. The coldest day is the day with the coldest recorded mean temperature (-3°C), which in the weather data used in modelling occurred on 27th December 1984.

The preceding four tables are summarised graphically in Figures 8.1 to 8.3 below. These allow easy visual comparisons between current and cost-optimal electric heating, for total cost of ownership, annual energy consumption, and peak power demand.

**Figure 8.1: Total cost of ownership (CapEx, energy costs and maintenance, over 15 years)**

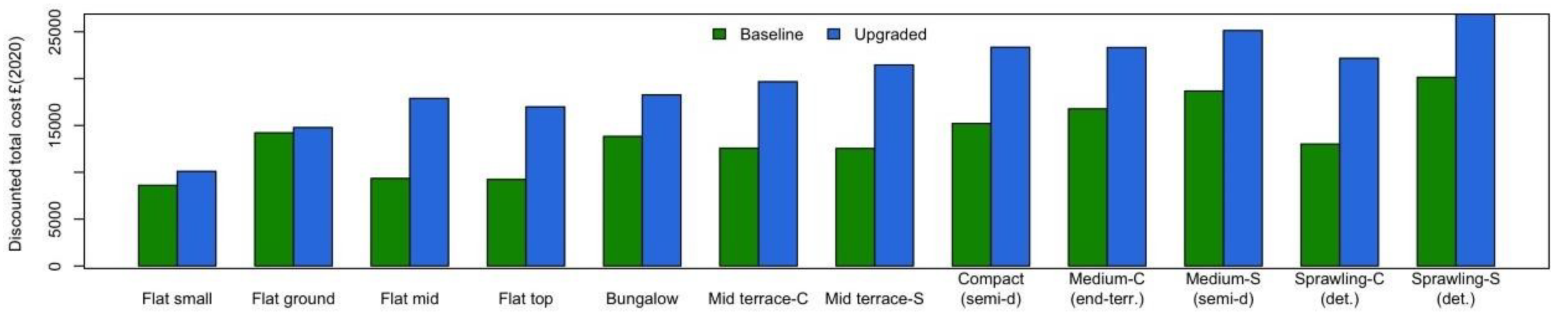



**Figure 8.2: Annual electricity use (kWh)**

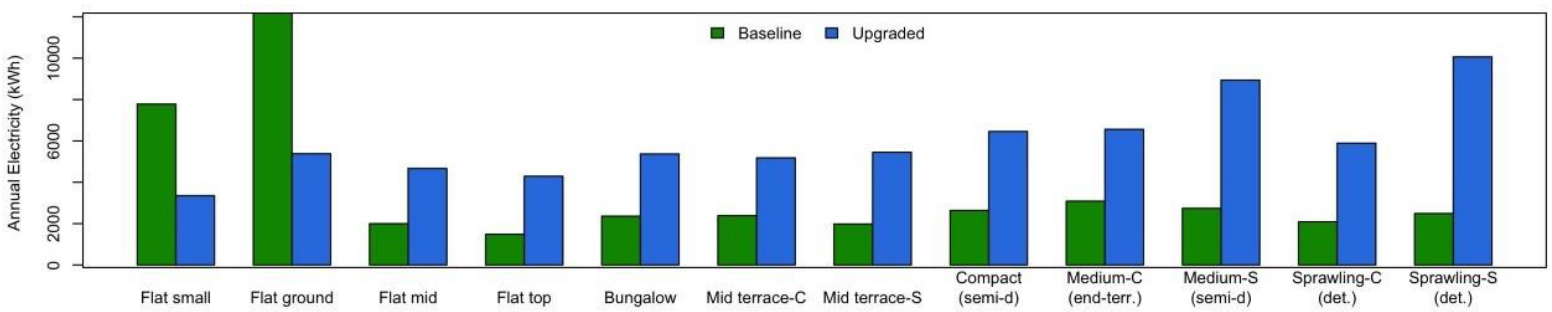
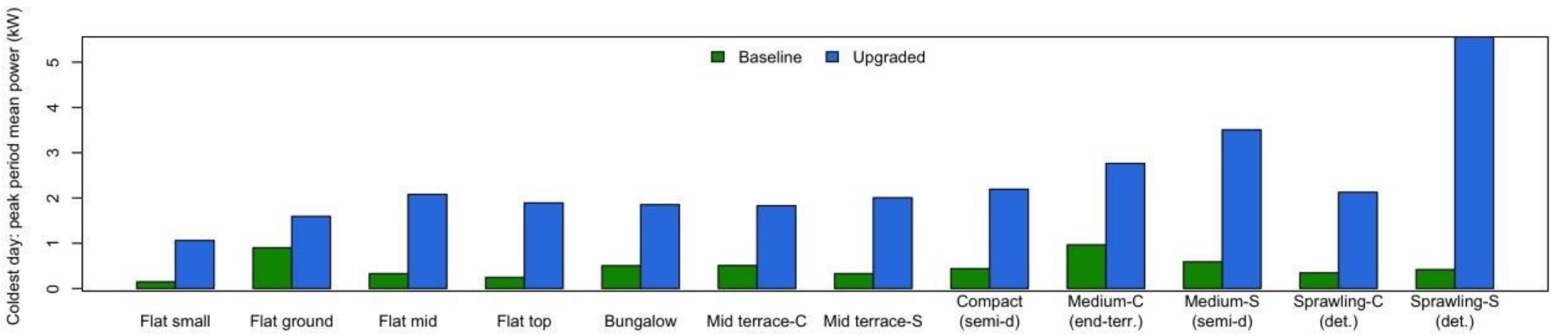


**Figure 8.3: Average peak demand (4-7pm) with electric heating, coldest day**




# Scaling-up

It is helpful to understand how electric heating could be adopted by individual house types as a building block, but the wider implications of cost-effective electric heating only become clear on considering what happens if large numbers of British homes convert to electric heating. Part of our brief on commencing this project was to scale up to all GB homes and assess the effects on costs, electrical demand and greenhouse gas emissions.

Data provided by BEIS describing the National Buildings Model (NBM), and provided by the UK Data Archive describing the English Housing Survey[54], were used to calculate weightings for each of the 12 house types used in modelling. The NHM data described floor areas, house types, internal volumes, and main fuel type. We used this with simple rules to allocate each of the 12,320 dwellings in the NHM to one of the 12 house types.

The rules were:

- Properties recorded as **bungalows** are automatically allocated to the 'bungalow' type.
- For **flats** (including converted and high rise)
    - If the ground contact area is more than 1/10th of the floor area, then they are deemed to have a ground floor.
    - If the roof area is more than 1/10th of floor area then they have a roof.
    - No ground floor or roof means they are 'Flat-mid'.
    - If they have a floor but no roof they are 'Flat-ground'.
    - If they have a roof but no floor they are 'Flat-top'.
    - Any top-floor flat with a floor area below 55 $m^2$ is 'Flat-small'.
- For **mid terrace**
    - If ceiling height is larger than 2.65m or the Heat Loss Parameter is greater than 3 they are 'Mid-terrace with solid walls'.
- For **detached houses**

[54] English Housing Survey - GOV.UK (www.gov.uk) (Commissioned jointly by MHCLG and BEIS)

    - If ceiling height is larger than 2.65m or the Heat Loss Parameter is greater than 4.5 they are ‘Sprawling detached with solid walls’, otherwise detached with cavity walls.

- For **end terrace** and **semi detached**
    - If the ceiling height is greater than 2.65m or the Heat Loss Parameter is greater than 4.5 they are ‘Medium detached with solid walls’.
    - Otherwise they are split on facade ratio (wall area/floor area): façade ratio below 0.9 means they are ‘Compact semi-D’, or ‘End-terrace with cavity walls’.
- Finally, a fuel check was applied, where cases that have mains gas in the house types but where the NHM data has no gas or bulk LPG are excluded (this is where most of the exclusions come).

This allowed us to match 21,101,042 dwellings from the National Buildings Model, or 88% of the stock (as a weighted sum). Then the NHM dwelling weightings were used and combined with dwelling data for Scotland and Wales to scale up to Great Britain, including a 12% adjustment to account for homes that were not matched in the NHM.

Most of the dwellings we were unable to match did not meet the matching rules because they did not have the same fuel defined in the relevant house type: either they had oil-fired or solid-fuel heating, or they were houses with all-electric heating. (The 12 house types include two electrically-heated flats but no houses, since only a small proportion of houses are heated electrically.)

# National impact

How does energy consumption over a year factor up across all homes? Table 8.5 below shows that overall household energy (gas and electricity) falls quite dramatically as a result of adopting cost-optimal electric heating. However, electricity demand would increase by 75% if all dwellings converted to electric heating.

**Table 8.5: Annual electricity and gas use (GWh), all GB homes**

| House type | Current annual gas use * | Current annual electricity use * | Annual electricity use with cost-optimal electric heating |
|---|---|---|---|
| **Small flat** | n/a | 8,590 | 3,700 |
| **Ground-floor flat** | n/a | 27,710 | 12,240 |
| **Mid-floor flat** | 5,720 | 1,770 | 4,140 |
| **Top-floor flat** | 7,170 | 1,390 | 4,040 |
| **Bungalow** | 32,580 | 5,850 | 13,310 |
| **Mid-terrace with cavity walls** | 28,060 | 6,130 | 13,350 |
| **Mid-terrace with solid walls** | 35,700 | 5,820 | 16,030 |
| **Compact semi-D** | 68,930 | 12,020 | 29,410 |
| **End-terrace with cavity walls** | 61,160 | 11,620 | 24,680 |
| **Semi-D with solid walls** | 41,030 | 5,460 | 17,800 |
| **Detached with cavity walls** | 51,410 | 8,470 | 23,880 |
| **Detached with solid walls** | 13,940 | 1,440 | 5,810 |
| **TOTAL** | **345,690** | **96,270** | **168,360** |

*Modelled gas and electricity use.

# 9. Conclusions

*This research and modelling addressed complex relationships between capital and running costs of different forms of electric heating. There are many strands to the work, and many outputs. This part of the report draws out key findings.*

Transitioning to electric heating is a major plank in the UK Government's strategy to achieve Net Zero Carbon by 2050. The UK has a national target to install 600,000 heat pumps a year by 2028.[55] However, until now there were uncertainties about the most cost-effective balance of new heating technologies and energy efficiency measures like insulation. There were also uncertainties about which forms of electric heating are cost optimal for different house types (from the perspective of the home owner). This research and modelling answers many of those questions.

The objective of this study was to assess costs based on the perspective of the consumer. It therefore only considers costs that directly impact the consumer: the upfront cost of equipment, energy costs and maintenance costs. The wider energy system is represented by proxy through the energy costs, but it does not take into account future energy system costs in generation or distribution infrastructure. These may be required as a result of homes switching to electric heating. In this study 'Cost optimal' therefore refers to the optimum for the consumer in the present day, and not necessarily what may be cost optimal from a future energy system perspective.

## On the balance of heating technologies to insulation measures

- The work focused on total costs of ownership over 15 years. For most house types and most electric heating systems, the cost-optimal packages of measures have very limited fabric improvements – most commonly just draught-sealing and top-up loft insulation. High-cost improvements, like internal or external wall insulation, hardly ever repay the capital costs over 15 years.

## On the cost-optimal electric heating systems

- Detailed modelling of energy costs and evidence-based assumptions about capital costs found only small differences in costs over 15 years between low- or high-temperature heat pumps, or air-to-air heat pumps, or storage radiators. Typically the difference was only 10% between the highest and lowest cost.

- Low-temperature air-source heat pumps and air-to-air heat pumps are cost-optimal for most house types when TOU electricity tariffs are applied.

[55] PM outlines his Ten Point Plan for a Green Industrial Revolution for 250,000 jobs - GOV.UK (www.gov.uk)

- When conventional tariffs (standard flat-rate tariffs and Economy-7 tariffs) are applied, storage radiators displace the air-to-air heat pumps as the cost-optimal system for one of the house types included in the study: the Small flat.

## On the factors that would alter the cost-optimal measures

- Sensitivity testing examining the impact on cost-optimal packages of measures showed that the time-horizon used for total costs or ownership is crucial, and this makes a major difference to the choice of cost-optimal measures. Extending beyond 20 years makes heat pumps less attractive because (unlike other electric heating systems) they are likely to need to be replaced.
- Avoiding very disruptive measures – such as replacing radiators with larger ones – also has a major effect on results, and this makes high-temperature heat pumps more attractive.
- Lower electricity costs would also make a dramatic difference to the cost-optimal measures. Eleven out of 12 house types have a different cost-optimal heating system with lower power costs. (Higher electricity costs have a less pronounced impact.)
- Applying different discount rates to future electricity and maintenance costs (from the central 3.5% discount rate down to 0% or increased to 7.5%) did not make a major difference to the cost-optimal packages.

## On the potential for flexibility from electric heating

- The work indicated that two technologies that could provide flexibility in electricity demand (batteries or thermal stores) were never cost-optimal at current energy costs and capital costs for these systems.
- However, if an 8kWh battery were installed in a dwelling, it could provide approximately 7.5kWh of flexibility a day in cold weather, and this is similar across different house types because the scale of flexibility is governed by the size of the energy store.
- The flexibility provided by installing a thermal store similarly depends on the size of the thermal store, and differs little between house types.
- Thermal stores offer better value flexibility than batteries, at current costs. Typically, they cost around £500 per kWh that could be shifted per day, compared to £700-£800 per kWh for batteries. However, thermal stores cost more to install in dwellings where air-to-air heat pumps are cost-optimal without them – since thermal stores cannot be used with air-to-air heat pumps, so the heating system has to change.

# Appendix 1: Hybrid systems

Hybrid heating systems were also modelled as part of this project. These have the existing boiler paired to an air-source heat pump, with the boiler providing domestic hot water. Hybrids offer the option of using a time-of-use tariff and using the boiler during the expensive peak periods. Here the heat pump provides heating at all other times. However, these are qualitatively different from the other all-electric heating systems because they use gas in addition to electricity. Strictly, they do not meet the objective of ‘electrified’ heating, and they do not offer the prospect of zero-carbon heating without major changes to the gas supply system. Consequently, we have separated the results of model runs including hybrid systems.

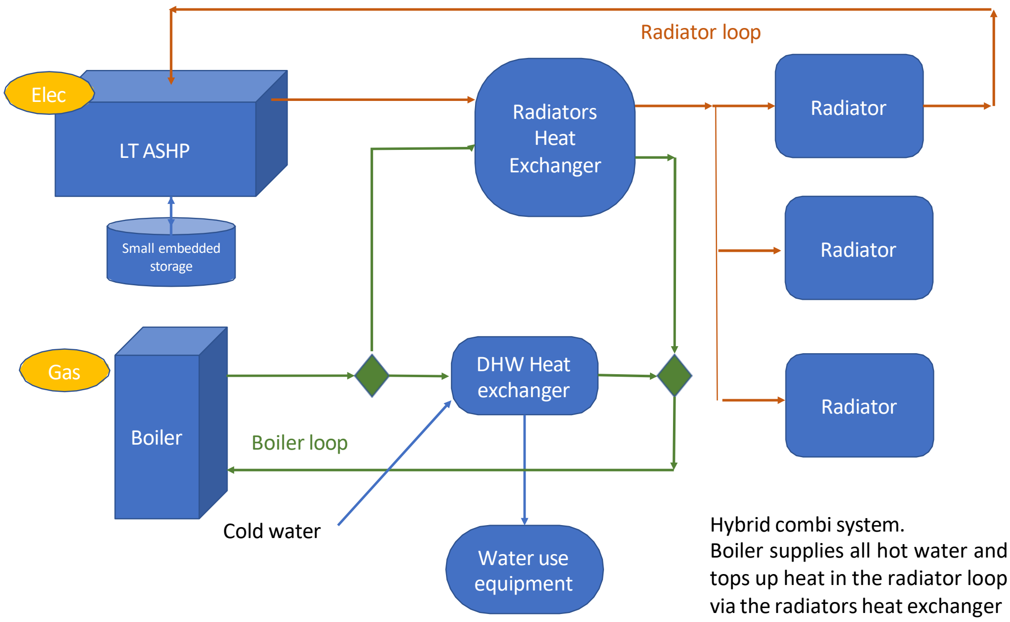
## Hybrid Heat Pump Model

The hybrid heat pumps are modelled only for archetypes which have a boiler in the baseline, since they already have gas boiler and a gas supply. There are two variants:

- Running with an existing combi boiler
- Running with an existing system boiler

The most common configuration at present, as a retrofit, is to continue using the existing DHW system (whether combi boiler or system boiler with a cylinder), then to add a heat pump to provide space heating – with the existing gas boiler providing top-up on cold days. This means that model components need to include the base case DHW system (combi or system boiler+cylinder) PLUS an ASHP as above. In our models the boiler provides all water heating and the heat pump supplies space heating, with support if needed. The CODE models are defined with the same size heat pump as in the standard case, so it should be able to supply all the space heating. (If it is not able to achieve comfort conditions it will fail the CODE ‘unmet hours’ test, described in ‘Thermal Comfort’ section, below.) However, when a variable tariff is used the ASHP is effectively switched off during peak times 4-7pm. Figure A1.1 shows the combi boiler case. In the system boiler case, the boiler heats a DHW cylinder rather than providing hot water on demand.

**Figure A1.1: The Hybrid Heat Pump-Combi-Boiler case has separate heat exchangers for space and water heating (like combi boilers do currently), and the boiler continues to provide domestic hot water**




Key features:

**Boiler**

- Setpoint 70°C
- Capacity as per the original boiler: 24 or 30 kW
- **Heat Pump as for low temperature ASHP**
- Turned off during peak times when there is a variable tariff – at these times the boiler supplies space heating when necessary.
- **DHW cylinder (system boiler case)**
- Sized 110, 140 or 210 litres depending on dwelling/family size
- Setpoint 55°C

## Hybrid heat pump costs

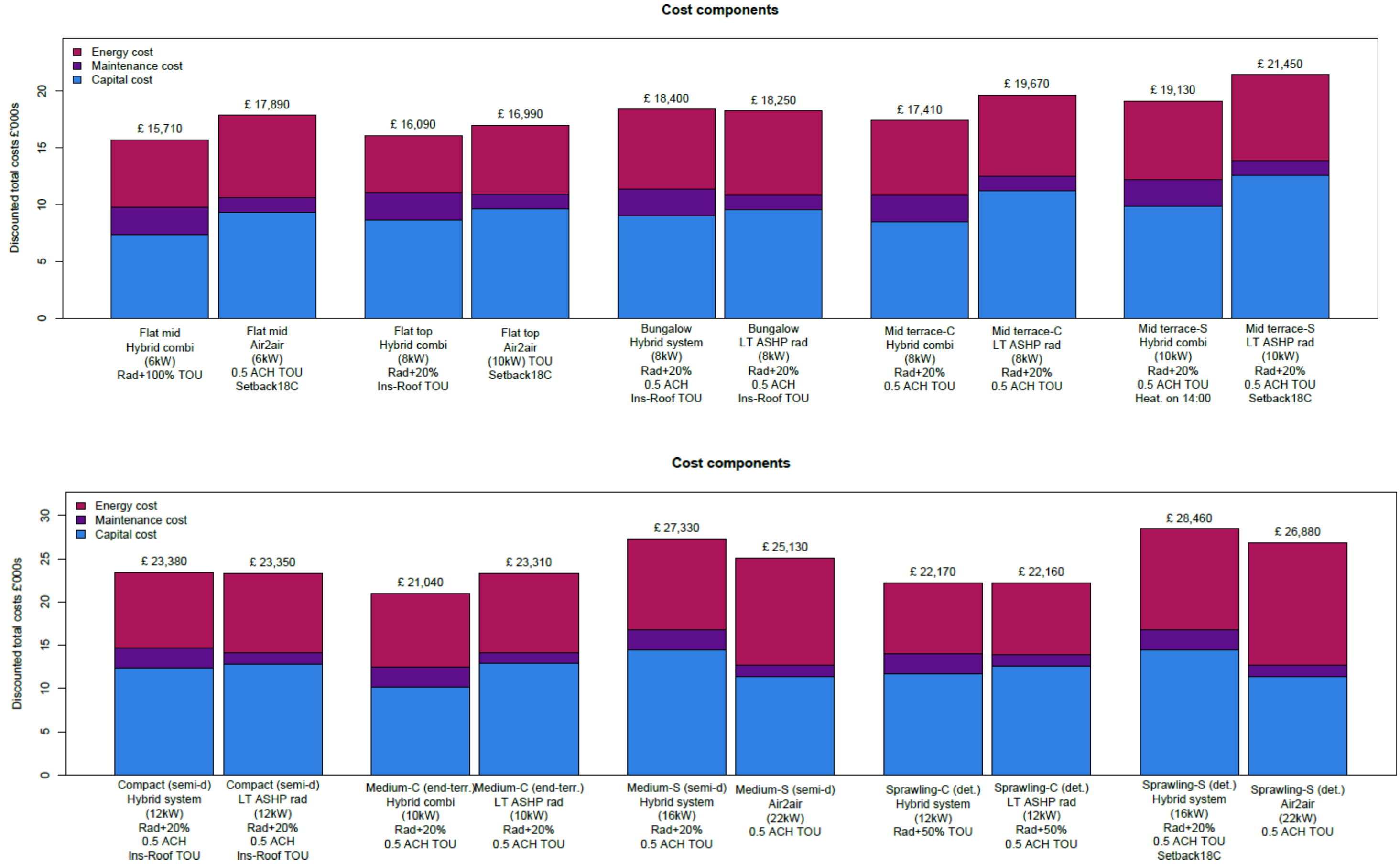
When hybrid systems are included in the range of possible heating systems alongside heat pumps and other electric-only systems, they often displace the all-electric systems as the lowest-cost option. This is for two reasons. First, capital costs can be lower because there is no need to add a new hot water cylinder to go with the heat pump (the old boiler provides the hot water), and often smaller heat pumps are needed than with heat pumps alone. Second, running costs can be lower because gas is presently much cheaper per kWh than electricity – only a quarter of the price per unit of standard-rate electricity, and only a fifth compared to the peak-rate price for a time-of-use tariff.

The combined effect of these two savings can mean a pronounced change to total costs over 15 years, when using the hybrid system: £2,180 lower cost for the optimum package of measures in the mid-floor flat (see Figure A1.2 below). The Small flat and Ground-floor flat are omitted from the chart because neither of these have a gas boiler or gas connection in the base case, so installing a hybrid system would be complicated and expensive.

The cost-optimal package of measures is often a hybrid system in place of an air-to-air or air-source heat pump. Notice that the hybrid system is not always lower cost over 15 years: for the Bungalow, Medium-S semi-D with solid walls, and the Sprawling-S detached house with solid walls it would actually cost more, so this would not emerge as the cost-optimal heating system. For Compact (semi-D) and Sprawling-C the 15-year cost is almost identical, so there is nothing to choose between the packages in the chart – based on costs alone. Including or excluding hybrid systems in the optimisation makes very little difference to fabric upgrades that are selected. Just Flat-top has different insulation (top-up loft insulation for the hybrid heating package – which is not quite justified based on energy cost savings with the air-to-air heat pump).

Hybrid systems do not make any difference to the choice of time-of-use tariffs. These are preferred in the optimisation in all cases, whether or not hybrid systems are used.

**Figure A1.2: Cost breakdown over 15 years for the cost optimal hybrid solution (left) and the cost optimal electric-only solution (right)**




One concern about hybrid systems is the split of gas and electricity use: if gas continues to be used to meet the majority of the space heating load there is little benefit from installing an electric heating system too. Table 7.15 below shows the annual electricity and gas consumption in kWh when the cost-optimal hybrid heating system is used in each house type, with standard electricity tariffs. On average across the house types, 44% of heating energy use comes from electricity, and 66% from gas. However, the proportion varies somewhat between house types, depending on the characteristics of each house type and the package of upgrade measures selected through optimisation. Flat mid is the extreme-low case, where just 25% of space and water heating energy is electric. Medium-C (end terrace) is the extreme-high case, with 56% of heating energy supplied by electricity.

Note that heating provided by electricity has the benefit of a coefficient of performance (COP) so that 1kW of electricity provides more than 1kW of heating. This varies from case to case, but might be from 2.0 to more than 3.0 for air-source heat pumps. Electricity use for lights and appliances is unaffected by the choice of heating system or fabric upgrade measures, and this averages 2,350 kWh a year across all house types.

Although gas use remains significant for the hybrid systems, it is dramatically lower than it is with a standard gas boiler only. Average (mean) gas use across the hybrid cases in the table is

2,330 kWh a year, compared to 13,910 kWh a year of gas for the base case dwellings (with no fabric improvements).

**Table A1.1: Electricity and gas use over a year for hybrid systems**

| House Type | Package of Measures | Lights & Appliances (kWh/y) | Electricity for heating (kWh/y) | Gas (kWh/y) |
|---|---|---|---|---|
| **Flat mid** | Hybrid combi (6kW) Rad+100% 0.5 ACH | 2000 | 880 | 2580 |
| **Flat top** | Hybrid combi (8kW) Rad+20% Ins-Roof | 1480 | 1390 | 1660 |
| **Bungalow** | Hybrid system (8kW) Rad+20% 0.5 ACH Ins-Roof | 2360 | 1750 | 2140 |
| **Mid terrace-C** | Hybrid combi (8kW) Rad+20% 0.5 ACH | 2380 | 1550 | 1660 |
| **Mid terrace-S** | Hybrid combi (10kW) Rad+20% 0.5 ACH Heat. on 15:00 | 1980 | 1940 | 2140 |
| **Compact (semi-d)** | Hybrid system (12kW) Rad+20% 0.5 ACH Ins-Roof | 2640 | 2350 | 3270 |
| **Medium-C (end-terr.)** | Hybrid combi (10kW) Rad+20% 0.5 ACH | 3090 | 2130 | 1700 |
| **Medium-S (semi-d)** | Hybrid system (10kW) 0.5 ACH EWI | 2740 | 1950 | 2160 |
| **Sprawling-C (detached)** | Hybrid system (12kW) Rad+50% | 2090 | 2690 | 2760 |
| **Sprawling-S (detached)** | Hybrid system (12kW) 0.5 ACH EWI | 2490 | 2010 | 3230 |

# Appendix 2. Literature review

*There is a large body of published research relating to electric heating and modelling the energy used for heating homes. This project began with a review of past work, aimed at drawing out learning to apply to the CODE Models.*

The CODE project set out to develop a set of linked dynamic simulation models that would explore the cost and energy-use implications of different British house types adopting different forms of electric heating. The models had to incorporate energy-efficiency improvements to the fabric of homes, and thermal and battery storage, and photovoltaics, as well as the electric heating systems. They also had to consider the effect of different electricity tariffs. The objective was to overlay on top of the models an optimiser that could select the most cost-effective combinations of measures for different house types. This went a long way beyond building and applying dynamic models.

We examined publications relating to these aims from the UK and internationally, and established a database of relevant work. We particularly focused on work published recently, since electric heating is developing rapidly. It is not appropriate to list or summarise all of the work in this report, but this chapter flags some significant reports that provide context for this project.

The chapter starts by considering past modelling of electric heating, then it turns to flexibility and work aimed at understanding the potential for flexibility services from homes. Then we summarise important past work on cost-effective electric heating, including assumptions that other researchers and modellers have made. Next we draw out what others have said about modelling heat pumps in particular, including hybrid heat pumps (where a heat pump works alongside a conventional gas boiler). The chapter closes by summarising what others have said about modelling electric storage heaters.

## Past modelling of electric heating

Glasgo et al.'s work (2017[56]) concluded that compared to actual homes, EnergyPlus models (as used in this project) tend to over-estimate use for more efficient homes, due to inaccurate simulation of use of non-heating appliances use. They said models were accurate for air infiltration, window areas and orientations, occupancy schedule, thermostat settings and the number of occupants – but weaker in other areas.

Badiei et al. (2019)[57] also used EnergyPlus models, and compared their results against RdSAP for energy use, based on data from EPC extracts for semi-detached homes. The models were very simple – each house shape was just a box with floors and appropriate windows. Adiabatic walls (with no heat transfer to the wall) and zero-thermal-mass areas were used to adjust the

[56] Glasgo, Hendrickson and Azevedo (2017) Assessing the value of information in residential building simulation: Comparing simulated and actual building loads at the circuit level. Applied Energy v203pp 348-363.
[57] Badiei, A., Allinson, D., & Lomas, K. J. (2019). Automated dynamic thermal simulation of houses and housing stocks using readily available reduced data. Energy and Buildings, 203.

model to match the EPC for floor area and wall area. Again, just two thermal zones were used.

Taylor et al.'s 2013 conference paper[58] described their use of a detailed model as a baseline. They concluded that a model with just two thermal zones was sufficient to get within 10% for energy use. They said the model does need a true footprint and windows with the correct frames.

Other researchers (Dogam, 2017[59]) suggested using the Shoeboxer software to model the building stock as simple 'shoebox' models. This groups buildings according to shape parameters: floor/façade, roof/floor, ground/floor and core/perimeter ratios, which was an insight we could apply to CODE.

## Measuring flexibility

Salpakari et al.'s study (2017[60]) measured the potential for flexibility to reduce costs for house owners. They found that large costs savings (30% to 50%) are possible for householders using their PEV (plug-in electric vehicle) battery to load shift heating energy demand and electricity from PV panels (using large PV arrays, in Sweden in very cold weather). The modelling of battery performance is detailed and this analysis warned not to avoid battery degradation in estimating benefits of PEV for battery storage. It found that cost savings from vehicle to grid services can be negated by shortening battery life. The focus was on householder costs through increasing self-consumption.

Dominkovic et al.'s 2018[61] work on flexibility, focused on winter peak load problems – demand side management events. They measured flexibility as the number of hours of no-heating before the internal temperature drops from thermostat temperature to 18°C. These results were from a model but using Modelica, not EnergyPlus. They also identified a post-event power spike.

Reynders' 2017 study[62] looked at using thermal storage for active demand response – storing heat when energy is cheap, for use later. Thermal storage was characterised by energy capacity, power and efficiency. For example, if heat is stored in advance of a peak period when demand must be reduced, how much extra heat is demanded overall? More thermally efficient homes were found to have less storage capacity, but more storage efficiency. Temperatures are allowed to vary by 2°C from the thermostat set point.

[58] Taylor, Allinson, Firth and Lomas (2013) Dynamic energy modelling of UK housing: evaluation of alternative approaches.13th Conference of International Building Performance Simulation Association.
[59] Timur Dogan, Christoph Reinhart (2017) Shoeboxer: An algorithm for abstracted rapid multi-zone urban building energy model generation and simulation. Energy and Buildings v140, pp140-153,
[60] Jyri Salpakari, Topi Rasku, Juuso Lindgren, Peter D.Lund (2017) Flexibility of electric vehicles and space heating in net zero energy houses: an optimal control model with thermal dynamics and battery degradation. Applied Energy v190 pp800-812.
[61] Dominkovic et al. (2018) Integrated Energy Planning with a High Share of Variable Renewable Energy Sources for a Caribbean Island. Energies 11(9): 2193.
[62] Renders et al. (2017) Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings. Applied Energy v198 pp192-202.

## What did past research find to be the most cost-effective solutions?

Slonski and Schrag (2019[63]) found that air-source heat pumps are most cost-effective for homes with good energy efficiency, and ground-source heat pumps only really make sense economically for homes with high heat loss.

Element Energy and UCL (2019[64]) found that communal heat pumps were most cost-effective in most of the 13% of dwellings they defined as 'space-constrained' (small). They also found that top-up loft insulation was cost effective in 17.4 million UK dwellings – along with solid wall insulation for 4.9 million dwellings and cavity wall insulation for 4.8 million. Element and UCL provide cost estimates for different forms of electric heating (including water heating), from different starting points.

The Committee on Climate Change (2019[65]) suggested the cost of installing an air-source heat pump is 52% of the cost of a ground-source heat pump (£8,478 vs £4,404 in 2025). It estimated hybrid heat pump costs of £5,677 in 2025 for homes on gas, and £5,187 for homes off the gas grid. It also suggested costs of a hot water cylinder of £1,060, and £1,720 for a heat battery (falling to reach parity with a cylinder by 2030).

Hitachi noted in 2019[66] that gas standing charges, servicing costs and boiler replacement costs are important factors in cost-benefit assessments for electric heating. However, savings on gas standing charges and servicing are lost if cooking equipment continues to run on gas. They also said that electric batteries are not economically viable because there are other cheaper ways to provide flexibility services. Although there were unusual circumstances (access to minewater at 20.3°C) they found costs could be lower by using energy centres each serving 100 homes – rather than every home having its own heat pump. There would be similar benefits from a stable source of communal heating, which could also reduce the cost to households.

## What assumptions have other studies made?

Bloomberg (2020[67]) assumed for purposes of estimating domestic DSR that well-insulated homes are capable of storing heat for 3 hours. This study also assumed that some form of time-of-use tariffs will be introduced before 2050 in order to provide an incentive for domestic DSR.

The Committee on Climate Change (2019[68]) assumed that a phase-change heat battery no larger than a slimline dishwasher will be large enough to provide hot water in typical homes. Also that the proportion of low-carbon heating systems can rise from 1% now to 25% by 2030. The Committee also assumed that air-source heat pumps (ASHPs) will last 18 years, ground-

[63] Slonski and Schrag (2019) Linear Optimisation of a Settlement Towards the Energy-Plus House Standard. Energies v12(2) pp1-12.
[64] Element Energy & UCL (2019) Analysis on abating direct emissions from 'hard-to-decarbonise' homes, with a view to informing the UK's long term targets. London/Cambridge: Element Energy.
[65] Committee on Climate Change (2019) Net Zero Technical Report. London: CCC.
[66] Hitachi Europe (2019) Caerau Valley District Heating Local Energy Market Options and ICT Architecture. London: Hitachi Europe.
[67] Bloomberg NEF (2020) Sector Coupling in Europe: Powering Decarbonisation - Potential and policy implications of electrifying the economy. London: Bloomberg.
[68] Committee on Climate Change (2019) Net Zero Technical Report. London: CCC.

source heat pumps (GSHPs) 20 years, and hybrid heat pumps 15 years. They further assumed that hybrid heat pumps can meet 80% of the space heating load, and none of the hot water demand.

# Considerations for modelling heat pumps

Delta-EE's 2018 report[69] for BEIS indicated that 70% of (rural) homes are suitable for low temperature air-source heat pumps with current levels of insulation, and adding more insulation increases this to over 90%. They suggested that high temperature ASHPs are not much better in terms of potential uptake. The authors argued that practical constraints limit the number of homes that are suitable for heat pumps, terraced homes and flats - because of internal space.

Marini et al's 2019 paper[70] discussed the operation of ASHPs with different sizes of thermal store. They included a detailed diagram of the configuration modelled (using TRNSYS rather than EnergyPlus). The larger the thermal store, the larger the heat pump that can be installed without inefficient cycling at part load. In turn, this allows the required service to be provided more completely.

Mitsubishi's 2019 data book[71] included essential information on products including coefficients of performance and capacity under different conditions (flow temperature, ambient temperature, and thermal demand).

## Hybrid heat pumps

Element Energy's 2017 report[72] for BEIS said that hybrid heat pumps (which were excluded from the main results of this project because they do not achieve zero carbon) can be configured in two ways: switching between gas and heat pump or in parallel: using gas to top up the heat pump. When the schedule is all day and the heat pump is appropriately sized, there is little difference. But if the heat pump is small or the heating schedule is twice a day, like a gas boiler, then the heat pump can supply as little as 15% of heat demand, while the parallel setup would deliver 39%.

The Freedom Project's 2018 report[73] described the setup used and carbon savings achieved on a large field trial of a hybrid ASHP/gas boiler system. The main focus was in reducing costs. The system had an ASHP, a gas boiler and in some cases a hot water cylinder. Usually, hot water came from the gas boiler and space heating from either this or the ASHP. Different scenarios considered different fuel cost ratios, time of use tariffs and restricted consumption periods.

[69] Delta-EE (2018) Technical Feasibility of Electric Heating in Rural Off-Gas Grid Dwellings: Final report. London: BEIS.
[70] Dashamir Marini, Richard. A. Buswell, Christina. J. Hopfe (2019) Sizing domestic air-source heat pump systems with thermal storage under varying electrical load shifting strategies. Applied Energy v255 pp1-14.
[71] Mitsubishi Electric (2019) Air to water heat pump systems data book. London: Mitsubishi. Ecodan ATW Databook 2019 - Document Library - Mitsubishi Electric
[72] Element Energy (2017) Hybrid Heat Pumps. London: BEIS.
[73] Freedom Project (2018) Freedom Project Final Report. Bridgend: WPD/Wales and West Utilities.

# Considerations for modelling night storage heaters

Boait et al.'s 2017 paper[74] suggested that electric storage heaters could be given smart controls and charge during the day as well as at night when there is excess supply. However, even well insulated storage heaters do not keep their charge for long – they lose at least a quarter of their heat in 24 hours.

Delta Energy and Environment's (Delta-EE) 2016 report[75] also examined the potential for doing more with electric storage heaters: they said 1.8 million homes have night storage heaters, where heat is stored in ceramic blocks. Modern heaters have insulation to reduce heat loss when not needed and a fan to drive heat out when it is.

Delta-EE said that Dimplex's storage capacities range from 10kWh to 20 kWh, and typical costs were £800 per heater, including installation.

[74] Boait, P.J., Snape, J.R., Darby, S.J., Hamilton, J. and Morris, R.J.R. (2017) Making legacy thermal storage heating fit for the smart grid. Energy and Buildings, v138, pp630-640.
[75] Delta Energy and Environment (2016) Evidence Gathering: Thermal Energy Storage Technologies. London: BEIS.

# Appendix 3. Defining house types

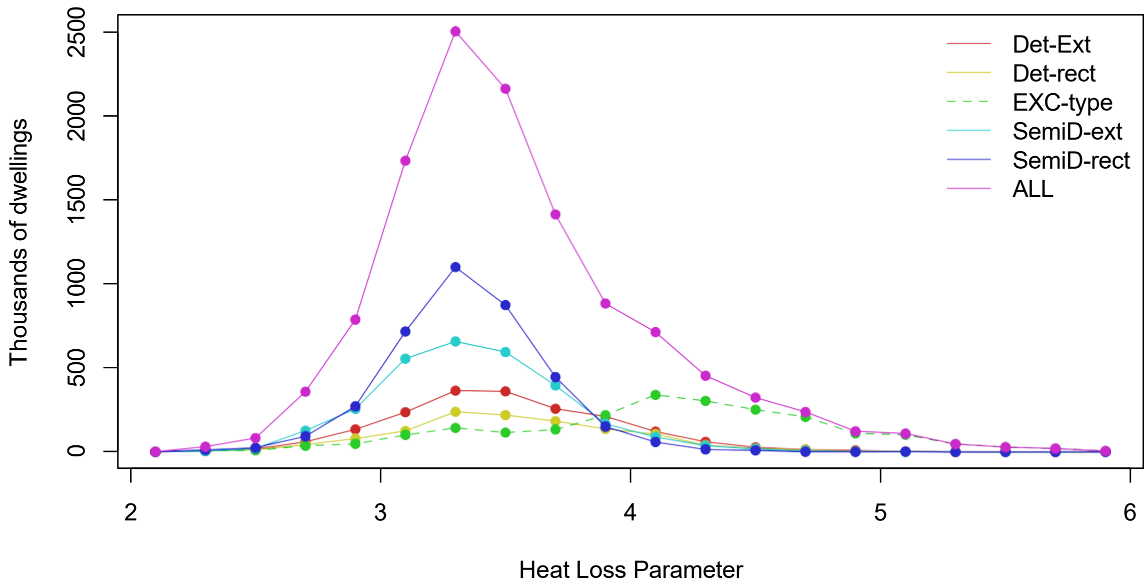
*This appendix gives a more detailed description of our methods for defining CODE house types.*

## Form factor-based approach

Initially we considered using building sub-types, for example, separating out mid-terrace homes with an extension or with an attic (room in roof). We proposed grouping end-terrace and semi-detached together as they both have one party wall. However, this gave a large number of variants – even after discarding the ones that are less common. (There were 23 sub-types, though 11 of these accounted for 80% of dwellings in the stock.) There was also a large overlap between different forms in terms of thermal performance.

Heat loss is the most critical feature of dwellings for this study, as heat loss has a large impact on the suitability of different kinds of heating systems. Therefore, the next step was to use the CHM to calculate the heat loss parameter (HLP, measured in W/K/ $m^2$, which normalises for floor area) for each dwelling, after adjusting them all to be in the same region and the same age and with similar construction – solid floor with no insulation, pitched roof with 150mm insulation, double-glazed windows and cavity walls (unfilled). Shape was still not the only remaining driver for heat loss, as ventilation rates and draughts still vary. Figure A3.1 below shows there is a large overlap in performance for detached homes and semi's. In fact, there is scarcely any difference between those which have extensions (-ext) and those which do not (-rect).

**Figure A3.1: Histogram showing frequency counts for dwellings with different heat-loss parameters (W/K/$m^2$).** Semi-detached, end-terrace and detached dwellings all have at least two floors. The groupings are Detached with and without extension or SemiD/EndT with and without an extension. Although this is a histogram lines are used rather than bars to show overlaps more clearly.




The large overlap in performance of each sub-type meant that it was not sensible to select any particular case to use to represent the whole class. A different method of classifying that yields more distinct performance characteristics would provide better coverage. However, it was not sensible to simply use the HLP to categorise dwellings since good or bad performance can have different drivers, requiring different approaches for low carbon heat.

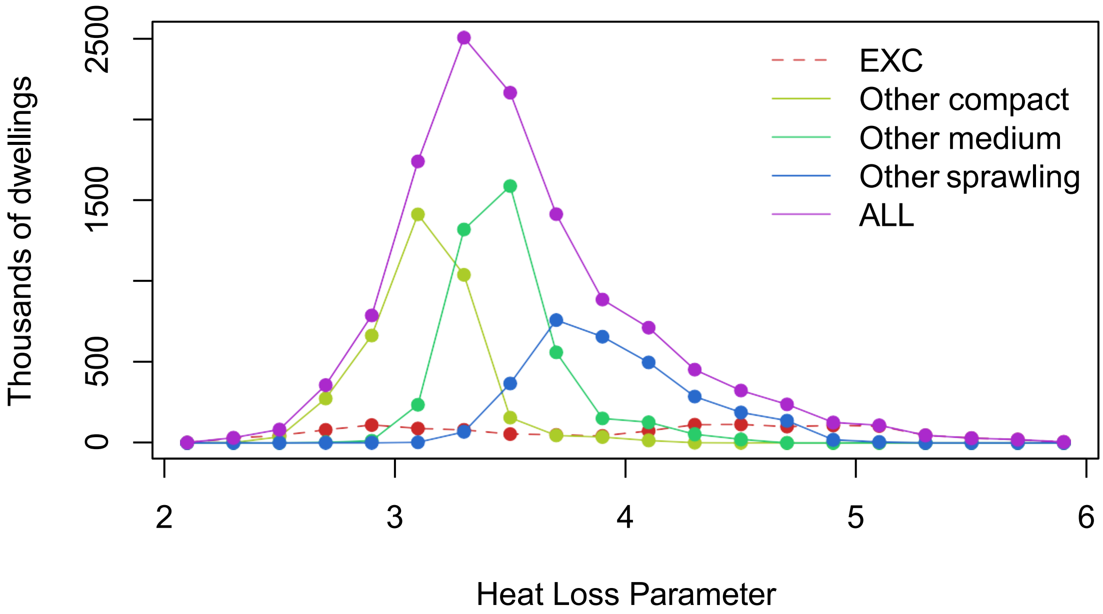
Following on from the approach used in Shoeboxer, (Dogam, 2017) we decided to try classifying based on ratios of walls to floor etc. The parameters we settled on are shown in Table 2.2 in the main body of this report. These gave the best power of prediction of the thermal performance. We settled on internal floor area (IFA, excluding basement and room in roof) as the best measure of building size. We excluded basement flats (67,000 in total) because the ground floor area is zero for those cases.

We tested the power of these parameters to predict the thermal performance (HLP), using a linear regression model. For example, considering the same dwelling categories as above (semi detached, detached and end terrace) only two parameters are needed to describe 87% of variation in HLP. This is not surprising given the way the energy model works.

Next we carried out cluster analysis based on these parameters. This consistently identified five clusters mapping closely to five types: the three kinds of flats, bungalows and mid-terraces. However, the 'other' dwellings - semi detached, detached and end terrace - were split across several clusters. Unfortunately, these clusters were not well defined and ultimately these groups had to be clustered manually to simplify reporting and to optimise coverage of the stock.

Accordingly, we divided the 'semi-Ds, end-of-terrace, and detached' cases into three groups: compact, medium and sprawling. We did not separate by size, as only a tiny fraction of this category was below the cut-off for space constraints - only 0.4% of the stock. The groups are further defined by limits on façade ratio and windows ratio, excluding dwellings with a ratio of windows to floor area of 0.5 or more. Figure A3.2 below shows the impact on HLP. There is now considerable separation between compact and less compact groupings. This means that the archetypes for each group are functionally more distinct and the groups are more tightly defined.

**Figure A3.2: Histogram showing frequency counts for dwellings with different heat-loss parameters ($W/K/m^2$)**




# Construction-based approach

## Roofs

Analysis of the stock determined that roofs are overwhelmingly pitched for all groups – even top-floor flats mostly have pitched roofs. Loft insulation is more variable, but the average thickness of loft insulation does not differ much between groups, see Figures A3.3 and A3.4 below. This is why we propose to model all archetypes with an initial 100mm of loft insulation.

**Figure A3.3: Loft insulation thickness across the whole stock (EHS, 2014)**

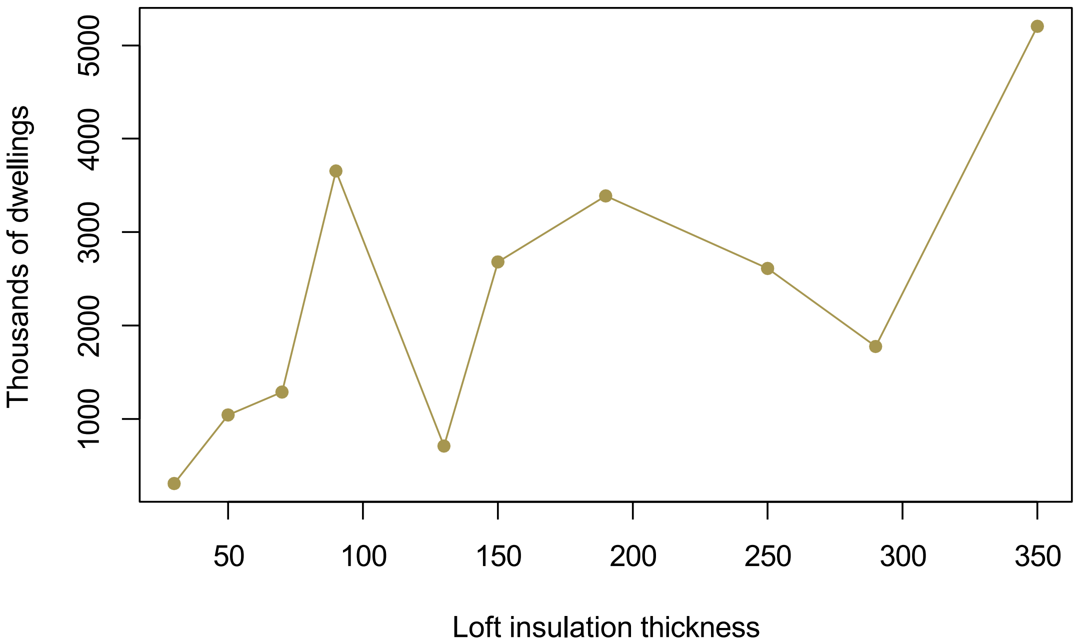
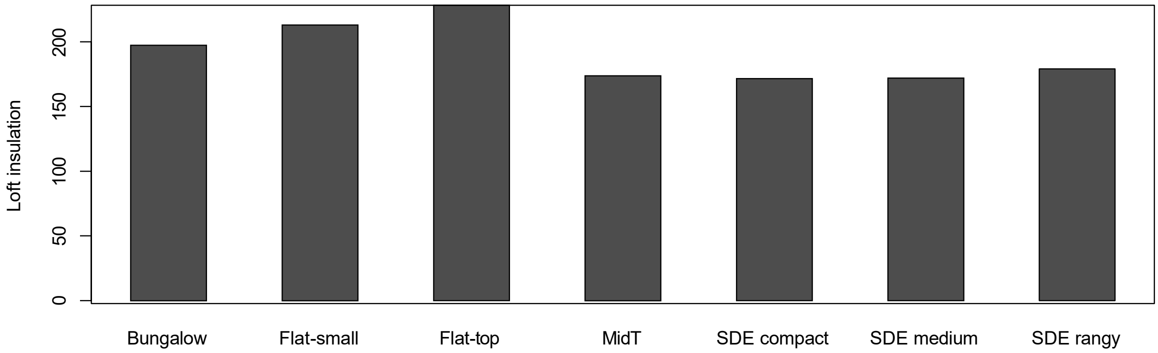


**Figure A3.4: Average (weighted) mean loft insulation by archetype group (excluding flats without a roof)**

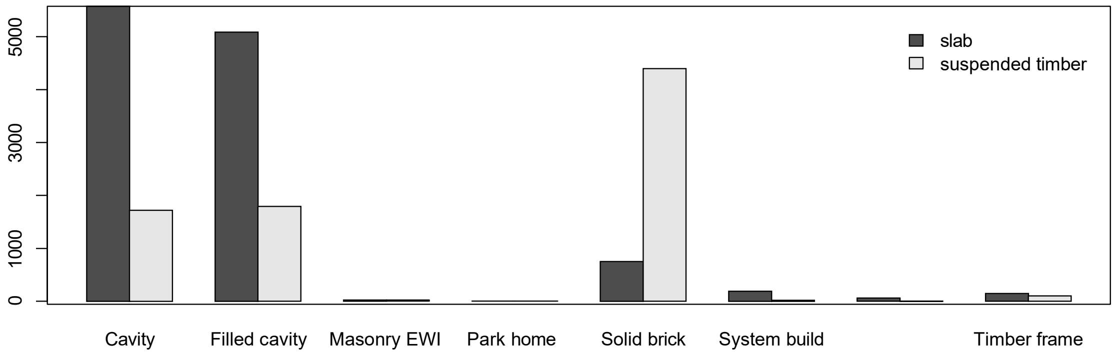



## Floors

Floor type is related to wall type – see Figure A3.5 below. However, suspended timber floors are in the minority for all types except for the 28% of dwellings with solid walls. We decided to model all solid-wall properties with suspended timber floors.

In addition, floors were built with no insulation up to at least the 1990s, so in all cases floors were modelled with no insulation in the base case.

**Figure A3.5: Floor construction by wall construction, whole stock**




## Windows

Windows are on average 90% double glazed for all groups, but in the vast majority of cases they are 100% double glazed. Consequently they were all modelled as 100% double glazed.

## Walls

For walls, the age and construction type both strongly affect the U-value, so walls were classified as high/low U-value (high is > 0.7) for cavities, solid walls and system build. There are very few timber frame dwellings in the EHS. However, if necessary, they could be considered similar to system build, with low thermal mass but good insulation. There is significant variation between groups. Table A3.1 below shows the weighted frequencies by group in 1000s, where this is greater than 50,000.

The final decision was to model all the archetype forms with Cavity walls (low U-value) and in addition, solid wall constructions for three of the forms, shown in red boxes below.

**Table A3.1: Dwelling counts (1000s) for wall classifications by U-value (W/K/m$^2$) and group.** Red borders indicate use for an archetype, so in the final analysis we have nine cases with Cavity walls and low U-values, plus three solid walls with high U-value.

| | Cavity High U | Cavity Low U | Solid High U | System High U |
|---|---|---|---|---|
| Bungalow | 340 | 1,164 | 75 | |
| Flat-small | 315 | 688 | 86 | |
| Flat-ground | 168 | 439 | 100 | |
| Flat-mid | 131 | 326 | 140 | 57 |
| Flat-top | 183 | 359 | 118 | |
| Mid-terrace | 554 | 1,005 | 1,700 | 55 |
| Compact house | 942 | 1,944 | 712 | 62 |
| Medium house | 860 | 2,296 | 804 | |
| Sprawling house | 525 | 1,633 | 777 | 52 |

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