Faster Deployment of Heat Pumps in Scotland: Settling the figures

For WWF Scotland

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Executive Summary

It is widely understood that the Scottish Government's ambitious targets to reduce all greenhouse gas emissions to net-zero by 2045 at the latest cannot be achieved without dramatic reductions in carbon emissions from heating. There are a number of technologies that could decarbonise home heating: solutions using electricity (produced from renewables), bioenergy and low-carbon gases, as well improved energy efficiency to reduce heating demand in buildings.

This study explored combinations of electric heating (primarily heat pumps) and energy efficiency to reduce emissions from heating, as these are the most mature technologies available and recommended for widespread adoption[1]. However, unanswered questions remain: what energy efficiency measures are needed alongside heat pumps? how much will it cost to install heat pumps in different types of home? what impact will this have on energy bills and fuel poverty?

What are the best low-emission heating systems for different types of home?

Modelling using dynamic simulation, coupled to optimisation work to reveal the most cost-effective low-emission heating systems, indicated that in 'unconstrained' dwellings (those without constraints due to small size, heritage/planning issues, or being located on the coast) the best solution is an air-source heat pump (ASHP) for homes starting with either oil or gas heating.

The majority of electrically-heated homes adopt air to air heat pumps, as these do not require changing to a wet central heating system with radiators, with larger homes adopting ASHP as air to air costs increase in proportion with home size. Annual carbon emissions fall by about 50% with heat pumps in comparison to storage radiators (including gains from improved fabric efficiency). In all cases, costs were calculated over 15 years, with discounting of costs in future years at 3.5%.

What energy efficiency measures are needed alongside heat pumps?

The modelling and optimisation revealed that homes require a good standard of energy efficiency to ensure efficient and cost-effective heat pump operation. Most dwellings end up with an annual space heating demand of 65-85kWh/m^2, which is suitable for installing a heat pump: enough for the houses to meet the desired level of heating on cold days, without very high flow temperatures (i.e above 50°C) that would make the heat pumps operate less efficiently.

To meet this level of energy efficiency, the analysis found that in almost all homes it is cost effective to insulate all cavity walls, fit double glazing and to improve draught proofing; and for homes with roofs to install 300mm of loft insulation. The analysis also found that it is cost effective to fit solid wall insulation to houses – despite high upfront costs it pays repays the investment within 15 years. The study found that it is technically possible to fit larger heat pumps to these homes without external wall insulation, but overall costs are higher. Total lifetime costs over 15 years (discounted) for these archetypes are on average 7% higher when a heat pump is installed without external wall insulation. Solid wall insulation was not found to be cost effective in tenements.

[1] See Climate Change Committee (2020) The Sixth Carbon Budget, London: CCC, and IEA (2022) The Future of Heat Pumps, Paris: IEA.

After fitting upgrades, all homes reach at least an Energy Performance Certificate (EPC) 'C' rating. These findings support the setting of minimum energy efficiency standards for all homes, as proposed by the Scottish Government. We recommend that the new metric for these standards be set using space heating demand per m^2/year, with a suggested target range of 65-85kWh/m^2. Some flexibility may be needed: not all archetypes meet the space heating demand range, and it may be necessary to vary standards according to dwelling age and size (with a lower target for smaller and more modern homes), to prevent excessive up-front costs.

Around 80% of all homes would require at least one upgrade to reach the cost-optimal level of energy efficiency. This is much higher than the proportion of homes below EPC C because the study assumes significant potential to improve air tightness with draught proofing. The proportion of homes requiring other insulation upgrades is likely to be similar to those below EPC C – around half of all homes.

Assuming that 80% of homes require at least one upgrade to meet the cost-effective level of energy efficiency sees an average cost of £2,820 per upgraded home. The majority of homes have costs of less than £1,000, which includes roughly half a million homes that do not require any upgrade at all, and many that simply require additional draught proofing. Conversely, there are roughly 175,000 homes requiring more expensive upgrades costing £10,000 or more.

How do overall heat pump costs compare for typical homes?

Considering upfront and running costs together, and excluding Government grants, the total costs of ownership over 15 years are higher than the base case for almost all house types, with present energy prices[2] and costs for fabric upgrades and heat pumps. Although in many cases running costs are lower with heat pumps, high capital costs lead to higher whole-life costs. This gap is what Government financial support needs to close in order to make converting to heat pumps more attractive to households.

Concerning the capital costs of adopting heat pumps, for the most common gas and oil-heated homes, heating systems range from £11,290 to £14,300. For electrically heated homes replacement heating systems (ASHP and A2A[3]) range from £10,480 to £19,980.

The most attractive proposition is upgrading homes that are currently heated with oil, closely followed by homes that currently have electric storage heaters. Most homes in both groups will see lower running costs by switching to heat pumps (an average saving of 25% for oil-heated homes and 28% for homes with electric heating). So the Scottish Government should prioritise replacing oil boilers (and other high carbon off-gas fuels) with heat pumps.

The impact for homes that currently have gas boilers is more nuanced, with homes varying between a 15% saving and a 5% increase in energy bills, on average, depending on their energy efficiency, layout and original boiler type. Flats are less likely than houses to see a benefit from heat pumps because they use proportionately more energy for hot water.

[2] April 2022 Ofgem energy price cap, with policy costs removed from electricity prices.
[3] One archetype selected storage radiators, but we omit this from the cost figures as it is much lower (£4,850) than the average for heat pumps.

What impact do recent energy price increases have?

This study used Ofgem Price caps for electricity and gas from April 2022 (when the analysis was conducted), with policy costs removed from electricity prices, in line with the UK Government's Energy Price Guarantee (EPG), introduced to protect consumers from rising energy prices. These prices are consistent with the medium-term forecasts for UK energy prices, although lower than current prices, driven by increased global demand for gas, and very significant reductions in European imports of gas from Russia following its war with Ukraine.

The EPG will maintain energy prices at a fixed level until April 2023, albeit at much higher prices than assumed in this study. This makes heating efficiency even more important and increases the savings to be made from improved energy efficiency.

The ratio of electricity to gas prices is a key factor determining heat pump running costs vs. gas, and this is a question we examined in this project. Current EPG energy prices would see increased heat pump running costs in comparison to gas. However, energy prices are forecast to fall in 2023[4] and with the continued removal of policy costs from electricity bills, the electricity to gas price ratio should return to levels that will mean many homes replacing gas boilers with heat pumps achieve lower running costs.

What are the prospects for heat pump costs in future?

For almost every house type, the up-front capital costs are what pushes the total cost of heat pumps over the baseline costs using a gas boiler. These capital costs may fall over time, as the market for installing heat pumps matures, and efficiencies may rise, which would reduce running costs.

Estimates of future costs are inherently uncertain, however, it seems likely that there will be economies of scale (affecting manufacturing costs and possibly installation costs), and learning effects (primarily affecting speed of installation, and so the cost of installation). Previous studies have indicated that the potential for upfront (CapEx) costs of heat pumps to fall in future by between 4% and 27% by 2030. At the most optimistic rate, average heat pump costs for the modelled archetypes would fall to below £10,000 per home in 2030.

The cost of replacing heat pumps in the future, after initial conversion from a different heating system, will be much lower than the costs outlined in this report. Unlike simple like-for-like replacement of a boiler, there are additional plumbing and equipment costs when a heat pump is installed for the first time. The full cost of these ancillary measures – including controls, buffer tanks and pipework, and in some cases new, larger radiators – are all included in the cost estimates in this report. However, these additional costs would be far lower when the heat pump comes to be replaced – say, in 15 to 20 years. New pipework and radiators should not be needed for the second and subsequent heat pump installations, and labour costs for installing should also be lower.

[4] https://www.cornwall-insight.com/predicted-fall-in-the-april-2023-price-cap-but-prices-remain-significantly-above-the-epg/

What are the options for heritage homes, and homes with limited space?

Approximately 10% of the overall housing stock is listed or in a conservation area, where planning requirements can affect what modifications are made to buildings. This study took account of these requirements, and insulating solid walls internally was provided as an alternative to external wall insulation for heritage homes. Internal wall insulation is significantly more expensive for very large dwellings (250m^2 and above), but is still cost-effective for smaller house types.

Internal space *may* be a constraint for some smaller house types which could struggle to fit an air source heat pump (and a hot water cylinder, if not already present). This could impact around 14% of the stock. Air to air (A2A) heat pumps (and instant hot water heaters) emerged as the most effective form of low-carbon heating in almost all 'space-constrained' homes. The two modern house types were exceptions, where storage radiators were more economical: although high cost to run they are still cheaper overall than the A2A heat pump solutions.

Capital costs are higher for space-constrained gas/oil homes – on average 9% more expensive for the A2A systems. This is due to the costs of removing radiators and their replacement with internal A2A units.

How suitable are individual systems for flats and tenements?

It is technically possible to fit heat pumps in almost all flats and tenements, with ASHP selected in most cases, and air to air units selected where internal and external space for ASHP equipment is limited (also in some flats with electric storage heaters). Fabric upgrades are similar to those for houses, except for the solid wall Pre-1919 tenement flat, which does not adopt external wall insulation. This measure is less cost effective than in houses because it has a lower ratio of external wall to floor area.

The capital cost of heating systems is slightly lower for flats than houses, given smaller system sizes. Post-upgrade improvements to running costs are also less significant than for houses – they are lower when moving away from electric and oil heating, but in all cases higher than gas. Again, this is due to a higher ratio of hot water to space heating demand (which lowers heat pump efficiency) and the better average thermal efficiency of flats, which reduces savings from energy efficiency measures.

How can Scotland meet its climate targets?

Every oil and gas boiler in Scotland generates carbon emissions. This modelling indicates that the most effective way to reduce carbon emissions from Scottish housing is to prioritise dwellings using oil-fired heating, and older homes with solid walls first, then gas-heated homes and bungalows, and finally newer dwellings built since 1982 and flats, where the potential savings are lower. This sequence is most cost effective, better for reducing emissions quickly, and for helping to tackle fuel poverty.

How to prioritise homes most effectively comes down to a political decision. If we wish to maximise carbon savings we would convert homes currently using oil-fired heating to heat pumps first and electrically heated homes last, but if we wish to maximise the benefit to households in fuel poverty we would convert homes on oil and electric heating first, and gas heating last.

Introduction

The Scottish Government has strong commitments to taking a lead role in addressing pressing environmental issues, including climate change mitigation and adaptation.[5] The Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 sets out ambitious targets to reduce all greenhouse gas emissions to net-zero by 2045 at the latest – with interim targets and annual budgets for different sectors of the economy.[6]

The Government is clear that Scotland's buildings must switch from gas and oil heating to very low-carbon heating systems. Without this it will be impossible to achieve the country's carbon-reduction targets. However, the Government (and the people of Scotland) lacked clarity about how to do this – and how much it is likely to cost to make the switch.

Scotland's Heat in Buildings Strategy[7] aims to double the number of heat pump installations each year, with one million homes using low-carbon heating by 2030. This is a very challenging target, and it will not be achieved without a major push from Government.

This project, commissioned by WWF-Scotland, is based on modelling and analysis of the key technology and policy options that can meet the scale of deployment that is required, at speed. Without this work there is a real risk that decarbonisation will come too slowly, or not at sufficient scale, or alternatively that carbon savings come at the expense of the poorest and most vulnerable households – who must be protected as Scotland decarbonises.

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[5] Scottish Government, *A Nation with Ambition: The Government's Programme for Scotland 2017-18*, 2017; and *Delivering for Today, Investing for Tomorrow: The Government's Programme for Scotland 2018-19*, 2018.
[6] http://www.legislation.gov.uk/asp/2019/15/contents/enacted
[7] Scottish Government, *Heat in Buildings Strategy: Achieving Net Zero emissions in Scotland's buildings*. 2021.

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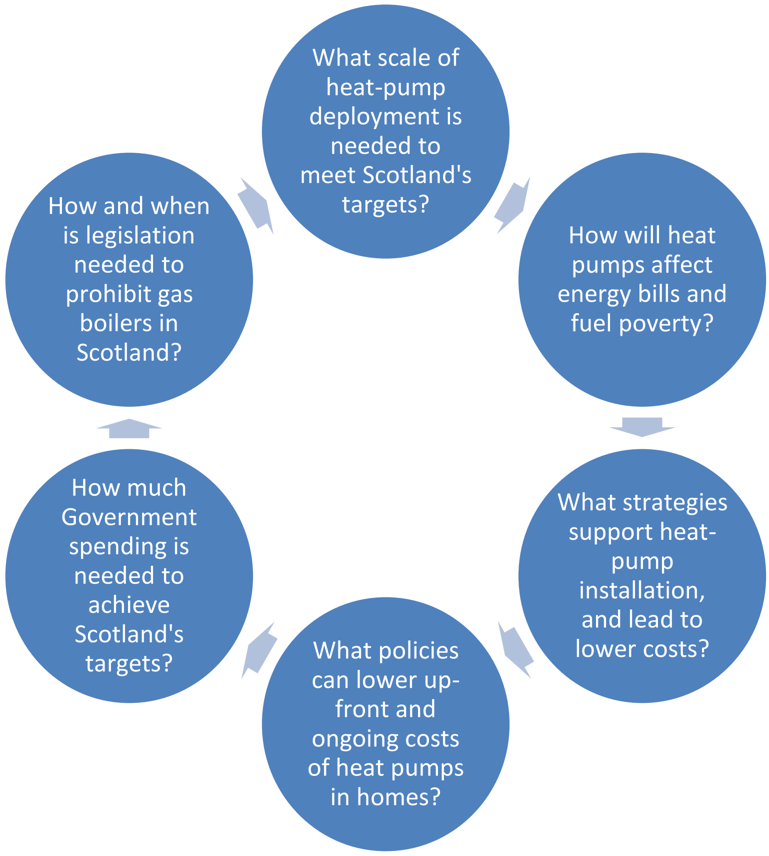
Key questions about deploying heat pumps in Scotland



Modelling

Much of the analysis presented in this report relies on modelling. CAR developed a new model for the work, ScotCODE, which drew on CAR's experience of building the CODE ('Cost Optimal Domestic Electrification') model for Great Britain[8]. ScotCODE is a full dynamic simulation model, built using EnergyPlus and drawing on the best-available evidence about costs and performance of energy efficiency and heat pumps. The model is described in detail in the next section.

Modelling applies energy efficiency and heat-pump upgrades to 12 representative house types, or 'archetypes'. These were developed to represent Scottish housing as closely as possible, based on detailed analysis of the Scottish House Condition Survey[9]. The representative house types are described in detail in 'Developing the Archetypes', p9.

Outputs from the model include:

- Installation costs of heat pumps in different dwelling types.
- Energy efficiency and other upgrades required to different archetypes and their costs, for optimal cost savings over a period of 15 years.
- Energy use for heating using gas (now) and electricity (future) for different house types, in kWh using the optimised measures described.

[8] https://www.gov.uk/government/publications/cost-optimal-domestic-electrification-code
[9] https://www.gov.scot/publications/scottish-house-condition-survey-2019-key-findings/pages/2/

- Carbon savings from installing heat pumps in different house types, which are used to determine deployment numbers required to meet government targets.

All modelling work includes checks on achieved thermal comfort – so that energy and carbon savings do not come as a result of under-heating or discomfort.

Photovoltaic solar panels (PV) are not part of the analysis, because these do not affect either heating or fabric energy efficiency. Batteries are also omitted, for the same reasons.

Overview of the model

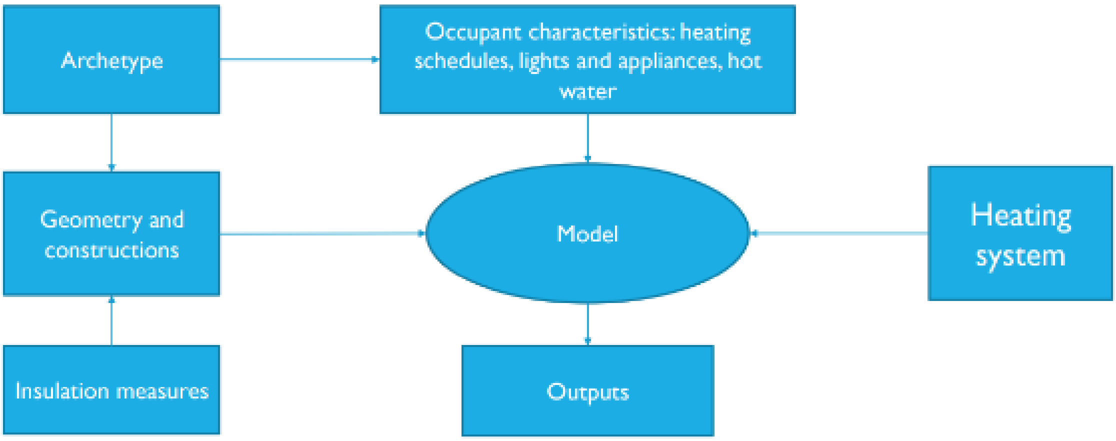
This research used a powerful and adaptable model of energy use in different archetypes, ScotCODE. This built on the Cost Optimal Domestic Electrification (CODE)[10] project CAR carried out for BEIS in 2020-21. Like CODE, this uses EnergyPlus, which was chosen among other energy-modelling tools because it is open source and it is extremely widely tested and used internationally. It is a full dynamic simulation model, carrying out calculations of air and surface temperatures at hourly intervals through the year – compared to only monthly calculations in simpler SAP-based models.

ScotCODE separately calculates flow temperatures and heating system efficiencies for space heating and domestic hot water – in contrast to much simpler assumptions about flow temperatures and heating efficiencies in other models. There are important issues linked to heat pump efficiency that cannot be addressed using a simple monthly model. Whereas some models do not include external air or ground temperatures, respectively, in calculating efficiencies of air- or ground-source heat pumps, ScotCODE does. It also incorporates measured efficiency curves showing heat pumps' coefficients of performance at different flow temperature. It demonstrates the trade-off between using a higher-capacity heat pump with intermittent heating, versus lower-capacity heating with constant heating. Overall, it is more closely linked to real-world performance than other stock models of heat pumps.

ScotCODE also allows calculation of fluctuating energy use through the day, which would be impossible using a monthly model. This is important for questions relating to the capacity of the electricity grid to provide sufficient power for the number of homes likely to convert to electric heating. Figure 1 below shows the main components of the ScotCODE model.

[10] https://www.gov.uk/government/publications/cost-optimal-domestic-electrification-code

Figure 1. Components of the energy performance model



Each home is included in the model as a housing 'archetype', representing a typical home – terrace, semi-detached, bungalow etc. The shape of each home and the type of walls, floor etc. is described by its geometry and constructions. This also includes baseline air tightness. Insulation measures can be added to make the building fabric more energy efficient. The occupants can be a single person, a couple or a family, and lights and appliances are used according to the number of occupants. Heating schedules are defined as two periods of heating, in the morning and evening, for all homes. The heating system can be a gas or oil boiler (with or without a hot-water cylinder) or an electric heating system of various kinds.

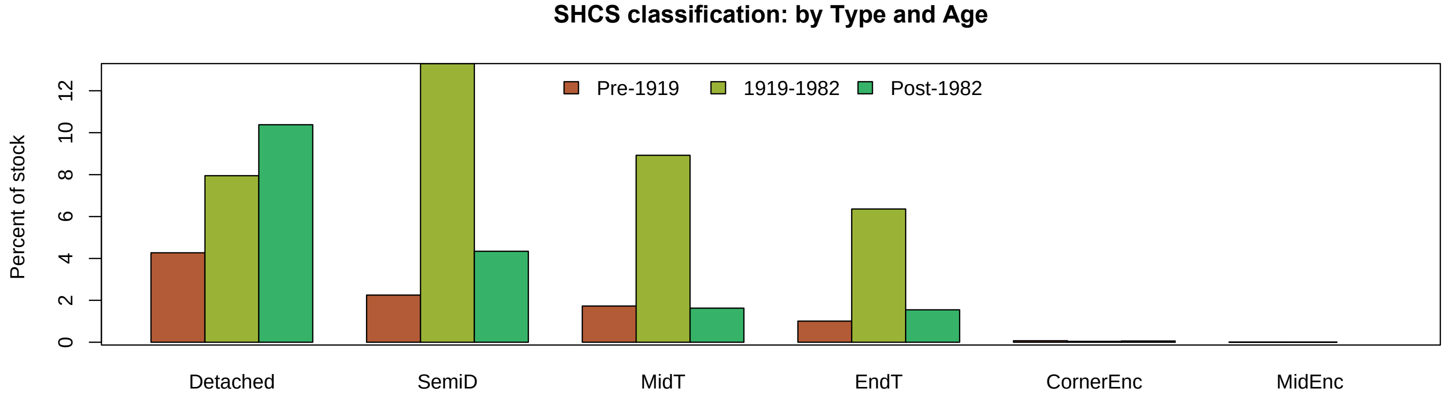
The EnergyPlus modelling system was developed in in the US as a collaboration between the Federal Government, academic institutions, and private firms. It allows us to parameterise both buildings and heating systems, and to simulate the running of homes in time-steps so that we can determine the dynamic performance. In this way we can check heating responsiveness and performance with different configurations.

Developing the Archetypes

We focussed on a relatively small number of typical homes in order to investigate a large number of variations in low carbon solutions, with detailed cost analysis of each. We derived twelve archetypes from the data in the Scottish House Condition Survey (2019) (SHCS) which represent between them 93% of the stock: all the main types except pre-1919 semi-detached, mid terrace, and bungalows, plus modern bungalows.

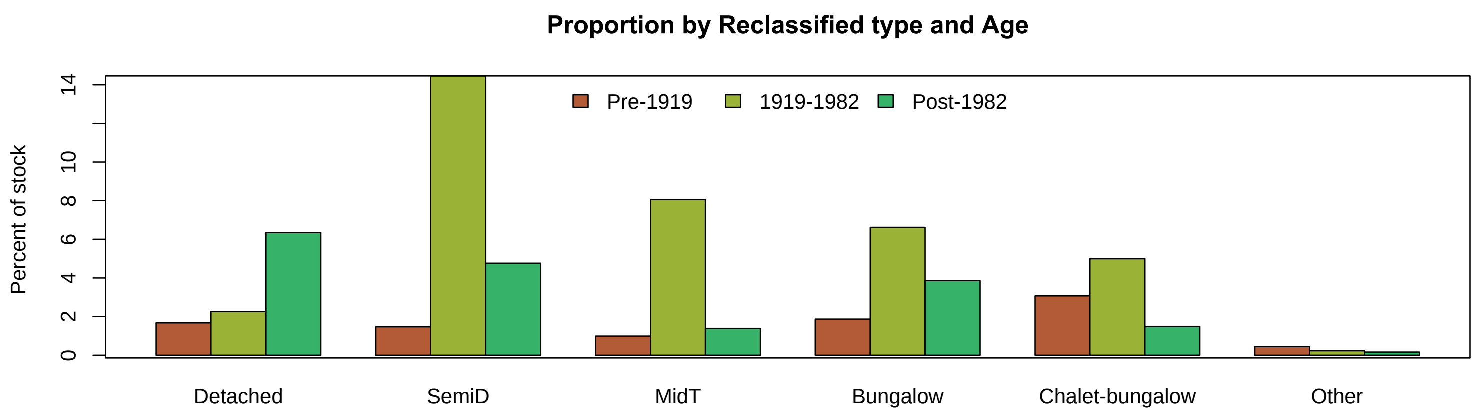
The SHCS records six types of house (not flats) including 'CornerEnc' (Corner-Enclosed) and 'MidEnc' (Middle-Enclosed) types – sometimes known as back-to-back terraces – which directly join up with other homes on at the back as well as the sides. However, there are very few cases of these types (see Figure 2 below) so they are omitted from the house types here.

Figure 2. Scottish housing stock by SHCS classifications



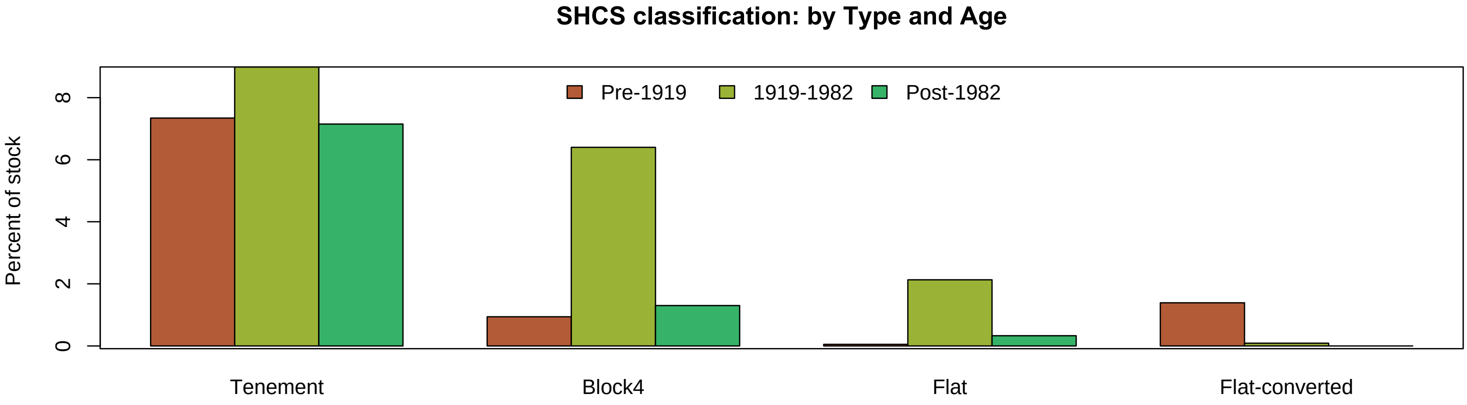
We reclassified these houses into slightly different groups based on building physics – principally the external wall to floor ratio and the roof to floor ratio. We merged End-terraces into Semi-detached houses because they are generally similar in both floor area and external wall ratio. Mid-terraces are different as they have a smaller wall area. We then separated single storey Detached, SemiD and EndT into bungalows, with and without attics. Bungalows without an attic have a much larger area for roof insulation than taller homes with the same floor area, while bungalows with an attic (chalet bungalows) have much smaller wall to floor ratio. Figure 3 below shows the resulting house types by age.

Figure 3. Proportions of Scottish houses of different types



We treated apartment buildings in a similar fashion. The overwhelming majority of apartments are Tenements or 4-in-a-block, as shown in Figure 4 below.

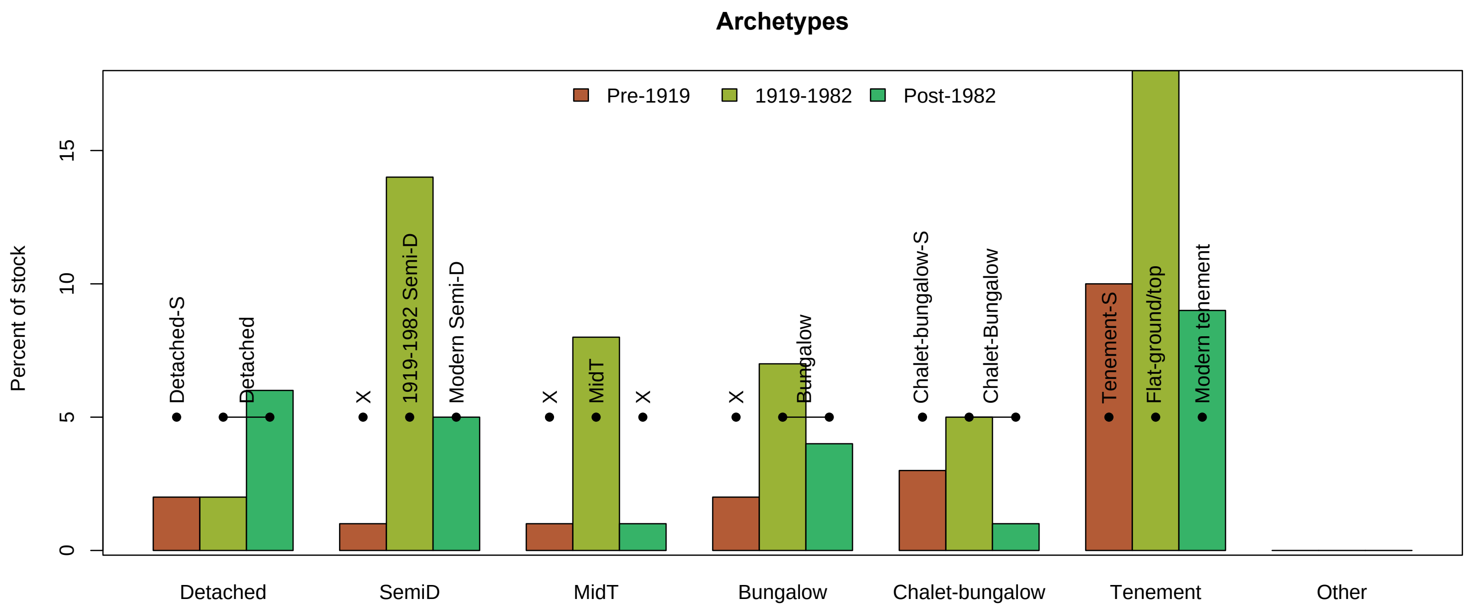
Figure 4. Proportions of Scottish apartments of different types



Although tenements and 4-in-1-block apartments are arranged differently, they are actually very similar in terms of the ratio of external walls to floor. The most important differences between apartments are whether they have a roof or a ground floor, their age, and hence their construction. Hence we derived four archetypes from these, representing top floor and bottom floor apartments for the most common age group, and two mid floor cases with two ages.

The final set of 12 archetypes is illustrated in Figure 5 below. From this you can see that the excluded cases (marked with an 'X') are Pre-1919 Semi-detached, mid terrace and bungalows, plus modern Mid-terraces. These four cases only represent 1% to 2% of the stock each, and they sum to 7%, which is how we calculate the 93% stock coverage. In three cases we have an archetype representing both modern and mid-century constructions – in the case of the Detached home, the archetype has more modern features as this age is more common, whereas for the bungalows the mid-century versions are more common.

Figure 5. Mapping archetypes onto the whole Scottish housing stock



*X-axis shows SHCS archetype classifications, the final study archetypes are marked in black above

The constructions and energy-efficiency measures of each archetype are based on typical values for the stock.

- Cavity wall insulation: 75% of homes have cavity walls, and 73% of these have already been insulated. The majority of homes in each SHCS archetype classification are filled.
- Solid wall insulation – 25% of homes have solid walls and only 18% of solid or 'other wall types' have been insulated.
- Fully double glazed: the overwhelming majority of all of the archetype classified homes have double glazing. This worst case is the Pre-1919 tenement, where only two thirds are fully double glazed.
- Loft insulation: the majority of archetypes have at least 150mm of loft insulation, apart from Chalet bungalows and Pre-1919 tenements. For the chalet bungalows, the majority have 100mm of loft insulation. For the tenement case, about half have at least 150mm.

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Final Archetypes

There are general descriptions of the final archetypes in Table 1 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 living areas have windows to the front (west) and rear. The size and the general shape of each archetype, including the ratio of external walls to floor area, has been calibrated to typical values according to the SHCS.

All the older house types are masonry construction, while post-1982 homes are timber-frame construction (which have lower U-values and thermal mass). Pre-1919 homes have solid walls, and later homes have filled cavity walls. All homes have suspended timber floors with carpets; in the post-1982 homes these floors are insulated. All homes are fully double glazed. The proportion of external wall area occupied by windows varies according to the age and size of the home. It is between 18% and 22% except where indicated. Infiltration rates vary depending on age and type, typically from 0.72 ACH (air changes per hour) in the most modern homes to 1.12 ACH in the oldest.[11] Living area fraction (the fraction of floor area that is heated to the living zone temperature, 20°C) varies between 18% and 25%, depending mainly on size. Other rooms like bedrooms, kitchen and bathrooms, are taken to be heated to 19°C.

For apartments, 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. Living area fraction is higher for these, 24% to 35%.

All of the dwellings are modelled with gas/oil wet heating systems with standard radiator sizes in the base case (180 W/m^2 unless otherwise stated) and high flow temperatures (60-80°C). They are also modelled with electric storage heaters, to represent electrically heated homes.

[11] Ventilation/infiltration rates are based on Johnston, D and Miles-Shenton, D (2009) Airtightness of UK dwellings. In: Proceedings of the Construction and Building Research Conference. UNSPECIFIED, London, 271 - 280. ISBN 095523901X, 9780955239014. http://eprints.leedsbeckett.ac.uk/644/
And J Love et al (2017) 'Hitting the target and missing the point': Analysis of air permeability data for new UK dwellings and what it reveals about the testing procedure. Energy and Buildings Volume 155, 15 November 2017, Pages 88-97.

Table 1. General description of archetype dwellings

House type, size, proportion of stock		Description
1	Pre-1919 Detached 257 m^2 1.6%	This is a draughty 5-bedroom detached house with solid walls. These are uninsulated in the base case. The proportion of windows in the wall (the 'glazing ratio') is low, at 14%. The main house is square but with a large two-storey projecting element at the rear. The ceiling on the ground floor is high, as is typical for Victorian construction. Part of the roof is converted to an attic room. This is the largest home and we assume that not all rooms are fully heated. To allow for this we model non-living areas to be heated to 19°C instead of the usual 20°C. The living area is 18% of the total floor area. The radiators in all rooms are slightly larger than normal, at 200W/m^2 which was necessary before the walls were insulated. Although this house type is a small proportion of the stock, it was included because energy use and carbon emissions are substantial, and also because these dwellings are more likely to use oil-fired heating, which has high cost and emissions.
2	Post 1919 Detached 158 m^2 8.4%	This is a 3-bedroom detached home, rectangular in shape with timber-frame construction. The glazing ratio is high, at 25%. The living-area fraction is 19%. This house has good air tightness, good insulation (including floor insulation), and high-performance windows.
3	1919-1982 Semi-D 102 m^2 14.2%	This is a 3-bedroom semi-detached home with filled cavity walls. It is rectangular in shape. The living-area fraction is 21%, and the glazing ratio is 17%.

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	House type, size, proportion of stock	Description
4	Post-1982 Semi-D 98 m^2 4.8%	This is a 3-bedroom semi-detached home with timber-frame construction. It has a single-storey projecting element to the rear. The glazing ratio is only 13%. This house is well insulated, has good air-tightness and high-performance windows. The living area fraction is 18%.
5	1919-1982 Mid terrace 94 m^2 9.3%	This is a 3-bedroom terraced house. It is the smallest of the house archetypes and quite compact. Hence the ratio of external walls to floor is low and a high proportion of those walls is occupied by windows (24%). The living area fraction is 21%.
6	Post 1919 Bungalow 105 m^2 10.1%	This is a single-storey, three-bedroom house partially joined to another on the north side, and entirely detached on the other sides. There is a small projecting element. The living area fraction is 25%.
7	Pre-1919 Chalet bungalow ("Chalet bungalow S") 157 m^2 2.8%	This bungalow is quite similar in layout to the Bungalow above, with the north wall partly connected to the neighbour, but it is older, with solid walls, and larger, with two rooms in an attic. The living area fraction is 25%. The attic roof insulation is only 100mm because headroom is at a premium.
8	Post 1919 Chalet Bungalow 137 m^2 4.9%	This chalet bungalow is a little smaller than the older one, and is almost square. However, it also has rooms in the attic and to make headroom for them it is has steeper roof pitch than the others: 40° instead of 37°. It also has only 100mm of roof insulation at rafter level in the attic. The living area fraction is 25%.

The flats are similar. All are fully double glazed and the top-floor flat has 150mm of loft insulation. The ground floor flat has a suspended timber floor.

Apartment type/size/ proportion of the stock		Description
9	Pre 1919 Tenement 82 m^2 9.4%	This is a mid-floor flat with solid walls that are not insulated. The ceilings are high, as is typical for the age, and the apartment is larger than the other three. There are semi-exposed walls to unheated access areas, as well as external walls to East and West, and party walls North and South. The living area fraction is 25%, and the glazing ratio is 23%.
10	Post 1982 Tenement 69 m^2 8.2%	This modern tenement dwelling is mid-floor in a building with timber frame construction, is compact and energy efficient with high performance windows. It is the only archetype achieving EPC grade B in base case. It only needs small radiators: 90 W/m^2. The living area fraction is 35%.
11	1919-1982 Ground floor flat 70 m^2 8.4%	This apartment is on the ground floor of a four-in-a-block arrangement. with party walls to the North and East. It is arranged in an L-shape and the short leg of the L has external walls on three sides. Even so, with no heat loss in the roof it does not need full size radiators: only 144 W/m^2. The living area fraction is 30%.
12	1919-1982 Top floor flat 70 m^2 8.4%	This apartment is above the ground floor flat, in the four-in-a-block arrangement, so it has the same shape and the only difference is it has a roof instead of a ground floor. It has standard-sized radiators. The living area fraction is 24%.

Table 2 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. Images of archetype dwellings

Houses	Image
1. Pre 1919 Detached	
2. Post-1919 Detached	
3. 1919-1982 Semi-D	

Houses	Image
4. Post-1982 Semi-D	
5. 1919-1982 Mid-terrace	
6. 1919-1982 Bungalow	

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Houses	Image
7. Pre-1919 Chalet bungalow (“Chalet bungalow S”)	
8. 1919-1982 Chalet Bungalow	

Apartments	Image
9. Pre-1919 Tenement	
10. Post-1982 Tenement	
11. 1919-1982 Ground-floor flat	
12. 1919-1982 Top-floor flat	

*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. The percentage of the stock represented by each archetype does not reflect the construction age or styles listed in these tables.

Quantitative details

Quantitative information about the archetype dwellings, including floor areas, the number of occupants, the number of bedrooms and boiler types, are shown in Table 3 below.

Table 3. Quantitative description of archetype dwellings

	Archetype	Floor area (m^2)	No. rooms[a] (Bedrooms)	Adults (Children)	Occupancy	Boiler type	Hot water cylinder size[b] (litres)
1	Pre-1919 Detached	257	12 (5)	2 (1)	In all day	system boiler	210
2	Post-1919 Detached	158	10 (3)	2	In all day	system boiler	140
3	1919-1982 Semi-D	102	8 (3)	2 (1)	Out on weekdays	combi boiler	140
4	Post-1982 Semi-D	98	8 (3)	2 (2)	Out on weekdays	system boiler	140
5	Mid terrace	93.5	8 (3)	2	In all day	system boiler	140
6	Bungalow	105	8 (3)	2	In all day	system boiler	140
7	Chalet bungalow S	157	10 (3)	2	In all day	system boiler	140
8	Chalet bungalow	137	10 (3)	2	In all day	system boiler	140
9	Pre 1919 tenement	82	6 (2)	2	Out on weekdays	combi boiler	110
10	Post 1982 tenement	69	6 (2)	2	Out on weekdays	combi boiler	110
11	Ground floor flat	70	6 (2)	2	In all day	combi boiler	110
12	Top floor flat	70	6 (2)	2	In all day	combi boiler	110

[a] This total includes non-habitable rooms. It is all rooms that have a radiator.
[b] For homes with a combi system initially, this is the size of cylinder that is installed when it is needed.

Table 4. Insulation and air tightness of archetype dwellings

	Archetype	Wall	Roof	Windows	Air tightness (ACH)	Floor
1	Pre-1919 Detached	Solid - uninsulated	100mm (attic room)	Fully double glazed	1.12	Uninsulated
2	Post-1919 Detached	Cavity - insulated	150mm	Fully double glazed	1.12	Uninsulated
3	1919-1982 Semi-D	Cavity - insulated	150mm	Fully double glazed	1.28	Uninsulated
4	Post-1982 Semi-D	Cavity - insulated	150mm	Fully double glazed	0.72	Insulated
5	Mid terrace	Cavity - insulated	150mm	Fully double glazed	1.12	Uninsulated
6	Bungalow	Cavity - insulated	150mm	Fully double glazed	1.12	Uninsulated
7	Chalet bungalow S	Solid - uninsulated	100mm (attic room)	Fully double glazed	1.12	Uninsulated
8	Chalet bungalow	Cavity - insulated	100mm (attic room)	Fully double glazed	1.28	Uninsulated
9	Pre 1919 tenement	Solid - uninsulated	n/a	Fully double glazed	1.12	Uninsulated
10	Post 1982 tenement	Cavity - insulated	n/a	Fully double glazed	0.72	Insulated
11	Ground floor flat	Cavity - insulated	n/a	Fully double glazed	1.28	Uninsulated
12	Top floor flat	Cavity - insulated	150mm	Fully double glazed	1.28	Uninsulated

Fabric U-values

Table 5 below describes the fabric constructions used in the archetypes in base case (before any upgrades) and their U-values. EnergyPlus constructions are specified as layers of different materials and do not permit specifying the U-values directly. The modelled layers have been turned to approximate the U-values in SAP.

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Table 5. Insulation and U-values before any upgrades

Fabric element	U-value (W/m²K)	Notes
Masonry cavity walls (filled)	0.65	RdSAP uses 0.7 up to 1975, then 0.4. The modelled value is between these but closer to the older, more common value.
Timber-frame construction walls	0.29	These are used for the modern archetypes, where stated.
Solid walls (insulated)	0.33	This matches RdSAP for 100mm insulation.
Solid walls (no insulation)	1.8	
Double glazed windows (normal/High performance)	2.9/2.0	2.9 is between the RdSAP values for PVC frames (2.7) and metal frames (3.3).
Roof insulated at joists 150mm (initial)/300mm (with top-up insulation)	0.29/0.14	The RdSAP value for a slate/tile roof with 150mm of insulation is 0.3, 300mm of insulation is 0.14.
Room in roof insulation	0.4	This is the same as RdSAP with 100mm insulation. Gable ends are insulated to the same U-value.
Floors (no insulation)	0.63	EnergyPlus models floors differently from SAP, and the SAP U-value varies depending on the perimeter ratio. This is an approximation of the equivalent value in SAP, but it varies between archetypes.
Floors (with insulation)	0.34	As above, this is an approximation to the SAP equivalent value. Building Regulations require < 0.45 from 1982 and < 0.25 from 2003.

Occupancy patterns

To model heating, each dwelling is divided into zones, which can have different heating settings – set using simple radiator valves that control the flow rate through radiators, or modern thermostatic radiator valves. The assumptions echo SAP, and take it that people set radiators outside the living room lower than their living area. Three zones were included in the model for flexibility in later use, however are only two different settings were defined. Living areas are heated to 20°C while the other zones are heated to only 19°C, matching recent research on indoor temperatures in Scotland (Pullinger, 2022[12]). (For the Pre-1918 detached house, the size of the house and the number of rooms is so large that we assumed some rooms are unheated and use a lower setting, 18°C, in the other zones to account for this.)

We used a twice daily heating pattern on all days for all homes, even though some are occupied during the day and others not, because this is by far the most common practice. The pattern we used is based on recent data from Scottish homes (Pullinger et al, 2022). The living area zone is heated 6-9am and 4.30-10pm, while other zones are heated for one hour less in the evening: 6-9am and 5.30-10pm.

[12] Pullinger, Martin; Berliner, Niklas; Goddard, Nigel and Shipworth, David (2022) Domestic heating behaviour and room temperatures: Empirical evidence from Scottish homes, Energy and Buildings. https://doi.org/10.1016/j.enbuild.2021.111509

Outside of heating hours, the thermostat is set to the setback temperature and in the baseline this is 12°C, which effectively means no heating. When heat pumps are installed this is increased, in accordance with recommendations for running heat pumps. The higher setback allows for lower flow temperatures, smaller radiators, and a smaller heat pump, reducing capital cost and increasing efficiency. There is a trade-off between these savings and higher heat demand. The model allows values of 16°C or 18°C for the setback temperature, but modelling indicated that the overall costs are lower at 18°C.

The archetypes are defined with different family sizes (shown in the table above), and this affects use of hot water, cooking and appliances. The demands for these are based on SAP except that for the 'in-all-day' cases there is extra use of appliances during the day. Appliances (including lighting and cooking) account for between 1,700 kWh and 5,000 kWh per year. In gas heated homes hot water accounts for between 1,600 kWh and 2,900 kWh/year, while space heating accounts for between 3,300 kWh/year (for the modern tenement) and 50,000 kWh/year for the Pre-1919 detached) with a weighted mean of 12,800 kWh/year. The heating demands in kWh for electrically heated homes are a little less, because electricity is 100% efficient at the point of use, compared to boiler efficiencies of around 85%.

Cooking is assumed to be all electric in all cases, both before and after upgrades, and emissions from this are included in all totals. However, cooking is only a small proportion of energy use – modelled at 257-330 kWh a year, depending on the number of occupants, which in most cases is only around 2% of annual gas use.

Limitations of archetypes

The house types used for this project were constructed very carefully to match the Scottish House Condition Survey findings, and ultimately represented 93% of Scotland's homes. However, there are limitations of using house types, which cannot perfectly represent the full diversity of Scotland's homes. The 12 house types used here capture all of the common dwelling types in Scotland – especially when further divided by heating fuel and tenure – creating effectively 108 (12 house types x 3 heating fuels x 3 tenures) archetypes in total.

The remaining 7% of Scottish homes that fall outside the archetypes are unusual for one reason or another – house types that are rare pre-1919 or unusual types such as corner enclosed or back-to-back dwellings. No homes were excluded because of high or low levels of insulation, so we would not expect notable differences between the insulation or air tightness of these homes compared to dwellings that were included. Pre-1919 semi-Ds, bungalows and terraces are similar in terms of wall to window ratio to the Detached, Semi-Ds and Chalet bungalow house types, respectively. The Post-1982 terraces that were not included are most similar to Post-1982 tenements, although they have less external wall areas. Overall, floor areas of the excluded house types are broadly similar to the modelled house types – we would not expect any systematic bias from omitting these dwellings.

We would not suggest that our house types perfectly represent the wide range of different characteristics within each house type. For example, the 1919-1982 semi-detached house could not possibly represent the full diversity of all 393,000 semi-detached homes built over this 63-year period in Scotland, or the hundreds of different combinations of numbers of occupants and heating regimes used in these dwellings. However, it is a good and robust example of the *average* or *typical* Scottish house of this type – as all of the archetypes are. The modelling was also calibrated against overall energy use in Scotland, so we know that modelling – when scaled up to all homes – is a good match against total heating energy and electricity use.

We could not possibly claim that model outputs would give accurate energy use or carbon emissions for a specific, individual dwelling in Scotland. But in aggregate, across many homes, energy use and carbon emissions estimated by the model are as close as existing evidence allows us to get.

Similarly for upgrade costs, there is a wide range of cost for efficiency measures and new heating systems, varying according to a hundred different considerations for one specific dwelling: the location, where the insulation or heat pump needs to go, how easy it is to access pipework, where the homeowner wants to locate the external unit of the heat pump, how hard it is to access the loft, and so on. The estimates of costs presented here could not possibly be accurate for a specific installation, but they are the best estimate possible of the *average* install costs, based as they are on more than 10,000 heat pump installations across Scotland (see below).

Scaling up

The Scottish House Condition Survey was used to scale up from the 12 house types to the number of each archetype with different fuels, see Table 6 below. All house types are predominantly heated by gas, although some house types are more common in rural areas and less common in urban areas, which means that non-gas heating is relatively more common. Conversely, modern tenement flats almost never have oil heating.

Overall, 84% of Scottish homes have gas-fired heating, while just 5% have oil heating, and 11% have electric heating – nearly all of these using storage heaters.

Figures in Table 6 are scaled from the archetypes' 93% coverage to 100% of Scotland's homes, including the constrained house types.

Table 6: Scaling up from baseline archetypes to all Scottish homes, split by fuel

	Baseline archetypes				
		Gas	Oil	Electric	Total
1	Detached Pre 1919, solid walls	17,400	19,600	2,760	39,760
2	Detached Post 1919	217,860	11,040	3,870	232,770
3	Semi-D 1919-82	364,480	6,900	21,810	393,190
4	Modern Semi-D	119,840	830	10,490	131,160
5	Mid-terrace house 1919-82	234,420	3,870	19,600	257,890
6	Bungalow Post 1919	194,390	45,010	39,210	278,610
7	Chalet-bungalow Pre 1919, solid walls	49,980	20,160	5,800	75,940
8	Chalet-bungalow Post 1919	118,450	10,490	4,970	133,910

9	Tenement-flat (mid) Pre 1919, solid walls	226,690	1,660	32,310	260,660
10	Modern Tenement flat (mid)	162,910	-	63,780	226,690
11	4-in-block flat (ground) 1919-82	196,870	550	34,790	232,210
12	4-in-block flat (top) 1919-82	196,870	550	34,790	232,210
	Totals	2,100,160	120,660	274,180	2,495,000

Constrained homes

For each house type we modelled other situations that affect what upgrades are feasible: heritage status (either being listed, or in a conservation area, which affect a proportion of older homes) and space constraints (where there is insufficient space for the internal unit of a heat pump and/or a hot-water cylinder, or internal wall insulation) which affect a proportion of the smaller homes. We also modelled the impact of being in proximity to the sea, which brings a higher corrosion risk and so increases the cost of a suitable heat pump. In total, 25.9% of the stock is modelled to have at least one constraint, see Table 7 below. Estimates for the number of homes potentially affected by these constraints were informed by previous research conducted for Scottish Government[13].

Table 7. Summary of constraints, and which dwellings are affected

Constraint	Impact	Homes affected
Heritage home Home is either listed or in a conservation area.	No external wall insulation allowed.	Affects solid wall archetypes. 6.4% of total stock – 159,450 homes.
Space constrained Home at risk of lacking space for internal heat pump equipment & hot water tank, and/or internal wall insulation.	Only air to air heat pumps can be selected. Where a combi boiler is present in the base case, instant hot water heater(s) are specified.	Homes with average habitable rooms below 18m^2 – terrace, single-storey bungalow and semi-detached archetypes. 13.8% of total stock – 343,920 homes. 65% are houses, the rest flats or tenements.
Coastal environment Homes within 5 miles of the sea, which poses a higher corrosion risk to external heat pump equipment.	Added cost (£1000) for corrosion-resistant heat pumps.	5% of total stock - 124,660 homes.

[13] Element Energy (2020) Technical Feasibility of Low Carbon Heating in Domestic Buildings report for Scottish Government's Directorate for Energy and Climate Change.

Heating types

The baseline heating types are combi boilers, system boilers (gas or oil) and storage radiators. The heat pump solutions for upgraded cases are air source heat pumps and air to air heat pumps. Storage radiators and electric radiant heaters are also all-electric solutions, although they are not heat pumps. The alternative electric heating options in the model are:

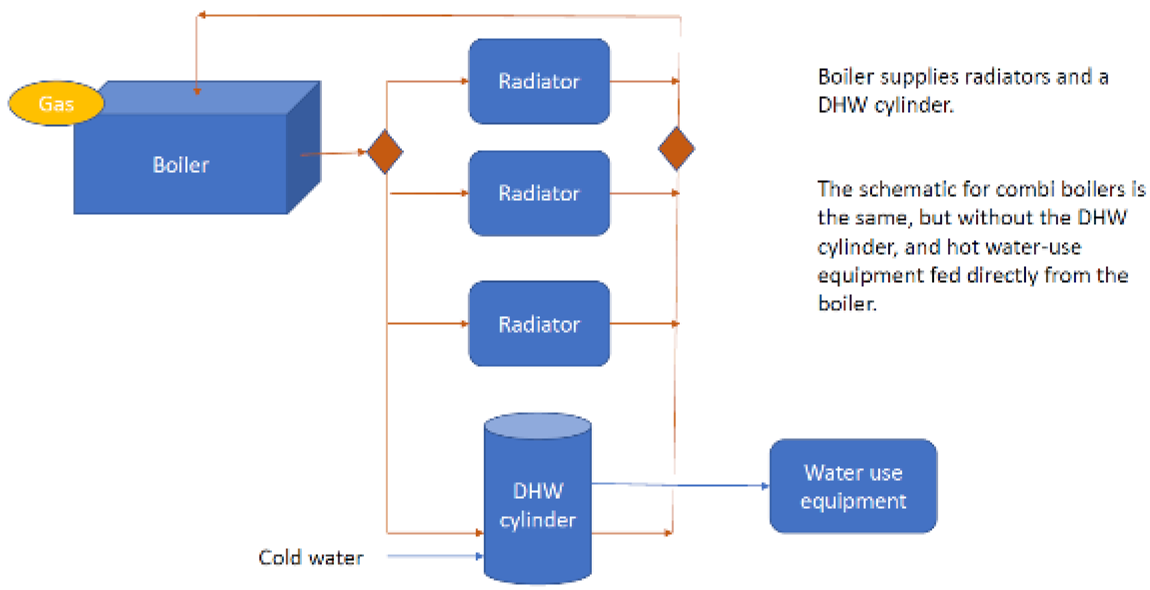
- Air source heat pump (low and high temperature)
- Air to air heat pump
- Electric storage radiator - all electrically heated homes in the base case have storage radiators but these are replaced in modelling, with modern units that provide better performance and comfort than older models.
- Radiant electric heating – controlled using air temperature, like other heating types.

Ground-source heat pumps were modelled, but they were never cost-optimal over 15 years because capital costs are far higher than heat pumps using air as the heat source. Readers should note that efficiencies are higher, so running costs are lower, with ground-source heat pumps (because the ground temperature stays warmer than outdoor air in winter). This means that where the budget and site allows, they may be preferred in the real world.

Boilers

There are two kinds of boiler in unimproved homes: system boilers and combi boilers. The significant difference – reflected in modelling – is that with the system boiler hot water is supplied from a domestic hot water (DHW) cylinder, which in turn is heated from the boiler, see Figure 6 below. In both cases, modelling assumes all DHW is supplied at 50°C at the taps, with tempering by cold water as necessary.

Figure 6. System boilers are modelled as a boiler with radiators and a DHW cylinder



Key features of the model:

Boiler

- Boiler capacity is sized for the demand of both space heating and hot water.
- Efficiency is 85% for gas boilers, 2% less for oil boilers.
- Water is heated to supply the radiators at 65°C.

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 except where otherwise indicated for the archetype.
- 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 depends on size, equivalent to 2.5 W/K for the medium size – cylinder has 50mm of insulation.

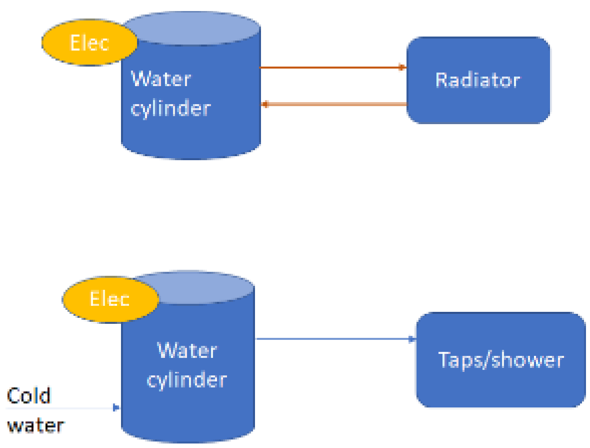
Storage heaters

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 7 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 7: Storage heaters are modelled as a radiator and water cylinder



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The storage is charged overnight, during the heating period:

- November through to March: full charge.
- April through to mid-June: reduced charge (75%).
- Mid-June through to mid-August: no charge.
- Mid-August through to October: reduced charge (75%).

Figure 8 below shows how the storage temperature varies through each day in the heating season. The overall trends are driven by external temperatures, with storage-heater temperatures falling faster on colder days. Key features of this model are:

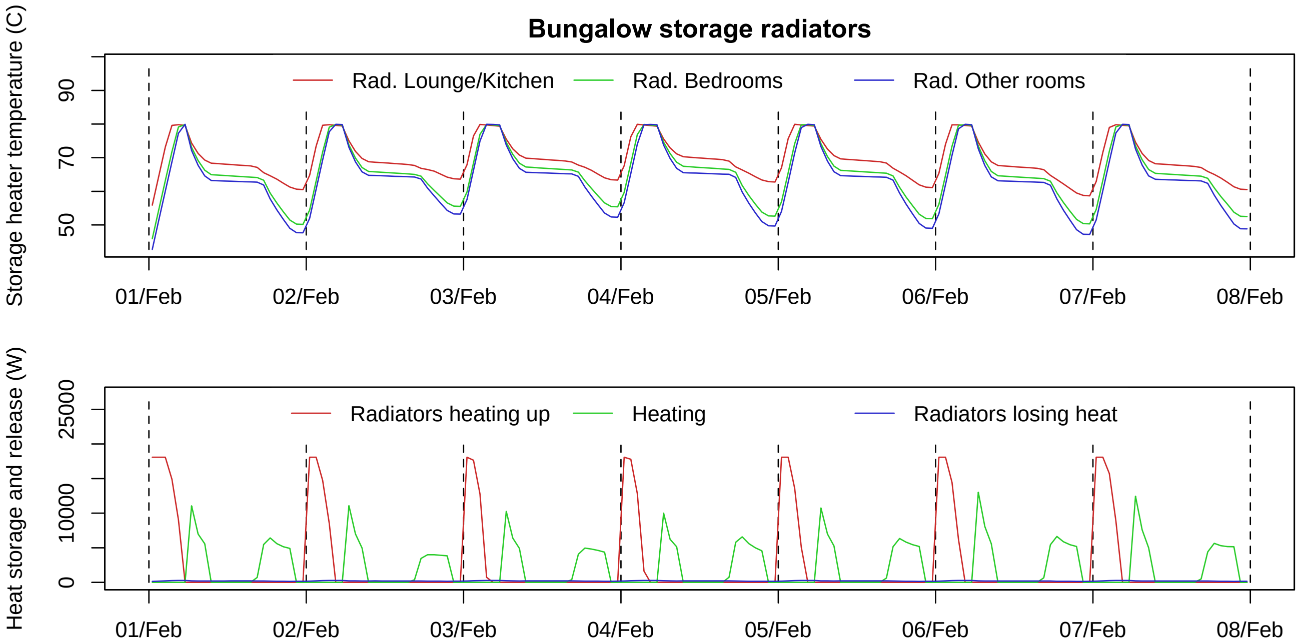
Heat emitter

- 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 – and has 50mm of insulation.
- 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 8. Storage heater temperatures and energy use vary through the day and night, according to how much they charge and discharge heat



Air source heat pumps

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. There also needs to be an expansion vessel for the heating water to expand.

The flow temperature of water from the heat pump to radiators is selected to match the heat loss of each dwelling and its emitter (radiator) sizing. The flow temperatures are set as low as possible, so the heat pumps run efficiently, but also so they achieve the comfort requirements (20°C in the living room and 19°C elsewhere).

Each ASHP is modelled as two: one for hot water and one for space heating. This is because EnergyPlus does not support multiple supply circuits from a single HP running at different temperatures. However, the overall energy use is the same as it would be with a single HP, so running costs are not affected. Weather compensation is used on the space heating circuit, reducing the flow temperature when it is mild outside. The weather compensation results in a flow temperature between the nominal temperature and 20°C lower.

For the standard ASHP, the hot water circuit is supplied at 55°C. For high temperature cases where the nominal flow temperature is higher, then hot water (to heat the cylinder) is supplied at the same temperature as the radiators. 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

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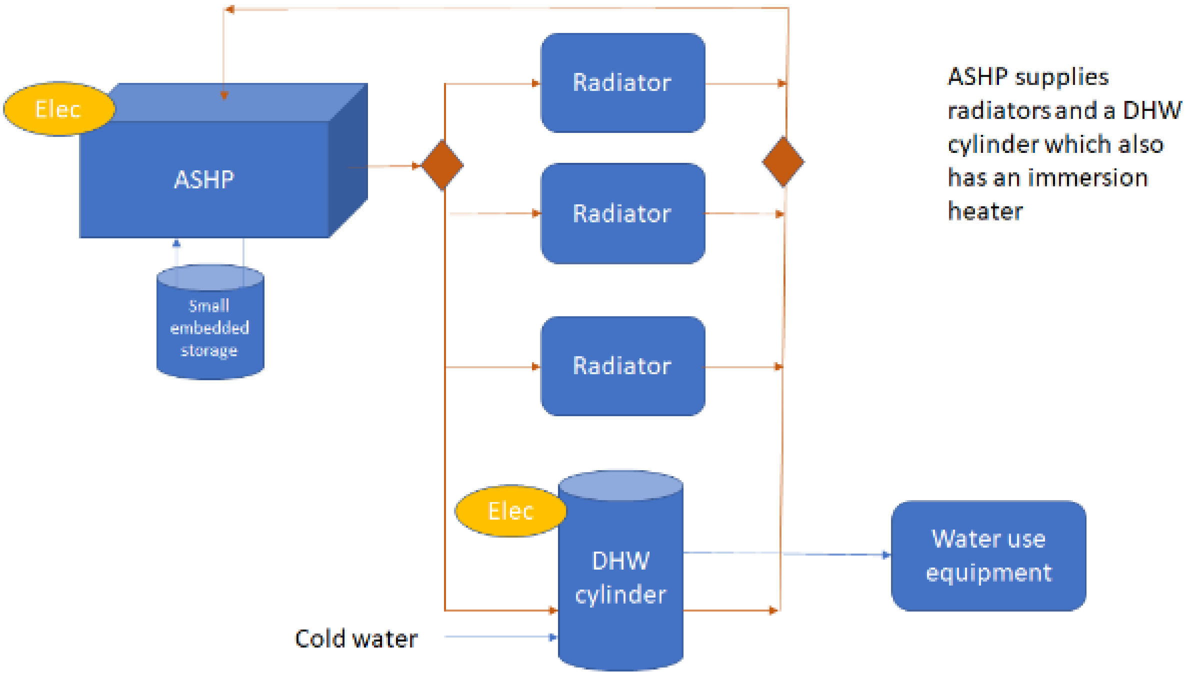
even when the required hot water temperature is higher than the heat pump can deliver on its own.

Figure 9. 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



Key features of the model:

Heat pump

Heat pump capacity is based on heating demand at the design winter conditions (based on the climate for the location the temperature and wind speed are -4.5°C and 3.2 m/s for Glasgow, 0°C and 10 m/s for Aberdeen). 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 fixed base cost and a variable per kW cost, with the latter based on the calculated heating demand.

Nominal COP is 5.0 at 3.5/40°C. (External temperature and supply temperature) Full performance curves are given in the 'ASHP Performance Curves' section below, and Figure 10.

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.

Embedded storage is included depending on the heat pump capacity; for a 10 kW heat pump this would be 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.

The loss rate for embedded storage is 1.5 W/K, based on losses from a reasonably insulated, small DHW cylinder. This is not the same as losses from the hot water cylinder mentioned above, as it does not represent a real cylinder.

Radiators

- Flow temperatures: 45°C, 48°C, 50°C, 55°C (low temperature radiators), 60°C or 65°C (high temperature radiators).
- Baseline radiators are the same as for the baseline boiler case.
- Radiators can be enlarged by 20%, 50% or 100%,

Radiator enlargement adds to the capital cost. 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.

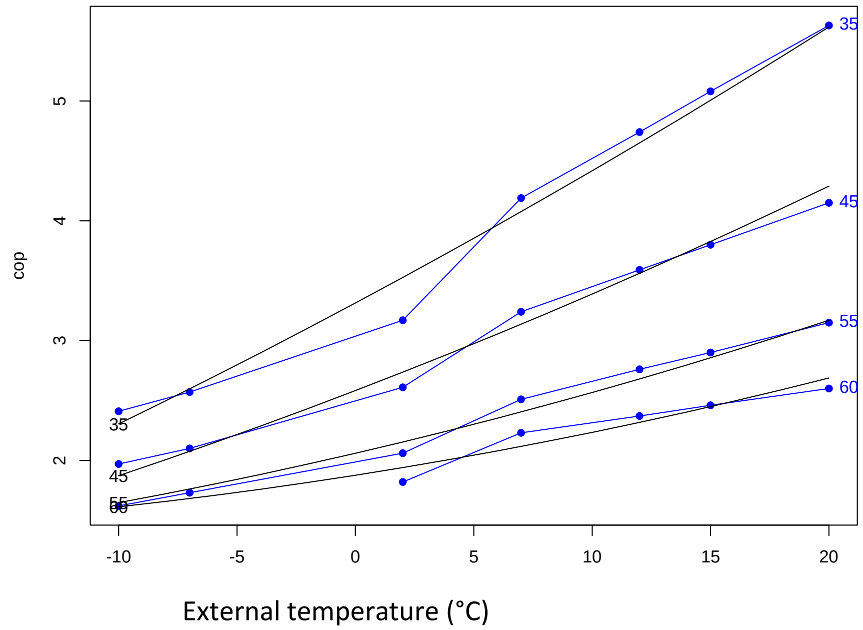
The required radiator size is calculated based on the design heating demand (dependent on insulation, air tightness and glazing measures applied) and the oversize factor recommended by MCS based on the flow temperature. This is compared with the baseline size, and the enlargement factor is selected as the smallest that would be satisfactory. If the 100% factor is insufficient then this combination of efficiency measures and heat pump is rejected.

DHW cylinder

- The DHW cylinder has heat from the heat pump and also an immersion heater for top-up heat and a Legionella cycle.
- Cylinder size depends on the dwelling/family size – 110,140 or 210 litres – and has 50mm of insulation (as for the boiler case).
- Cylinder heat loss depending on size, the same as for the boiler case.
- DHW thermostat is set to 50°C except during the Legionella cycle: 60°C for 2 hours each Sunday

The performance curve implemented in the model is based on an 11kW Mitsubishi Ecodan air-source heat pump. Figure 10 below shows what this looks like. The performance below 5°C external temperature is affected by the defrost function.

Figure 10. ASHP performance curves are based on COPs of a Mitsubishi Ecodan heat pump



Air to air heat pumps

This is similar to air conditioning and widely used in commercial environments such as hotels, although in this model only heating is provided. 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 ScotCODE, but now it is possible to link a single external unit to, say, five internal compressors – although this is uncommon, and we have not modelled this arrangement. (This arrangement would reduce the number of external units required – and potentially reduce equipment costs – although it would require more complex internal refrigerant pipe runs, which would increase installation costs.)

Air to air heat pumps do 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 homes that did not previously have a cylinder, and in the space constrained scenario, instantaneous water heaters are included instead. Each home will need from one to three water heaters, depending on dwelling size and the number of bathrooms.

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.

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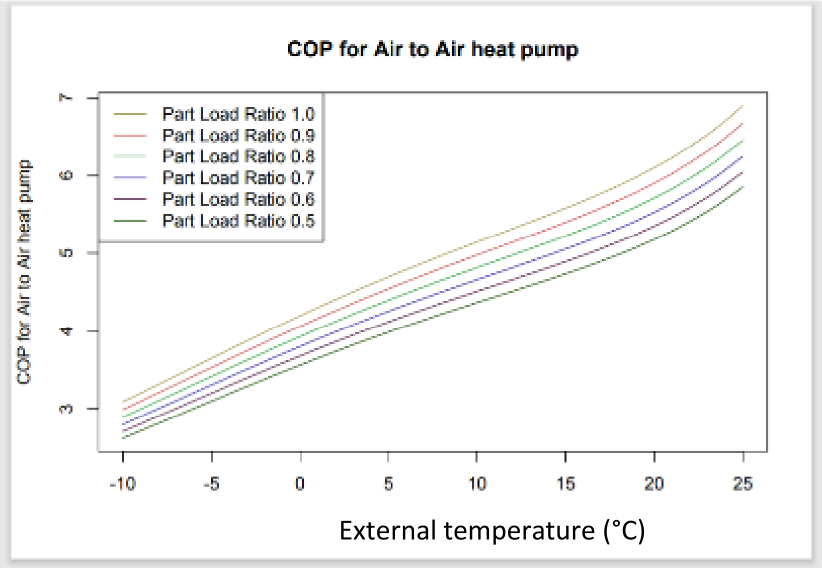
- Capacity as required for the zone.
- Defrost cycle is reverse-cycle, using heat from the dwelling to prevent ice building up. This cycle operates when it is below 5°C outside, based on demand, and it depends on both internal temperature and humidity. This is included in the modelling.

DHW supply

- Where there is a cylinder this is the same as for the storage heater case, except the maximum heating rate is 2kW.
- Where there is an instant water heater, water is heated on demand, maximum 10kW. This type of system would show little difference in use compared to a conventional combi or system boiler for running taps in sinks, but it would have a lower flow rate for showers and baths may take longer to run, compared to a pressurised hot water system. There is usually no 'capacity' as such – the water heater heats as much water as is needed.

As you would expect, COPs for air-to-air heat pumps vary with the external temperature, and at part load. Figure 11 below shows the COP performance curves, using a nominal COP for the air-to-air heat pumps of 5.0.

Figure 11. External temperature and COPs 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).[14] 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.

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

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These are broadly consistent with the COP curves.

Fuse limits

We have assumed that fuses are restricted to 100A (i.e. 24 kW) and we allow 6 kW for other simultaneous appliances. This means that the overall limit to energy demand is 18 kW, except overnight, when it can reach 24kW. This mainly affects storage radiators as they have to load enough heat during the night to last the whole of the next day. (Note that heat pumps sizes are quoted as heat output, not electricity consumption, which is normally only half or one third of the heat output.)

PV and Batteries

Early modelling work and optimisation selected solar PV for all house types, as high electricity prices meant that savings from PV offset upfront capital costs (which are lower than in the past because PV has become more economical). Conversely, the early optimisation work found that batteries were never economically viable over 15 years (partly because they need to be replaced after 10 years, so there are further capital costs downstream). Ultimately both batteries and PV were removed from the project because most households would in practice struggle to afford additional capital costs on top of fabric and heating system upgrades, and also to maintain the project's focus on heating.

Calibrating baseline energy use against Energy Statistics

We have estimated total energy use for Scottish homes based on the archetypes and the number of homes they represent, and compared this against the total energy use reported for Scotland.

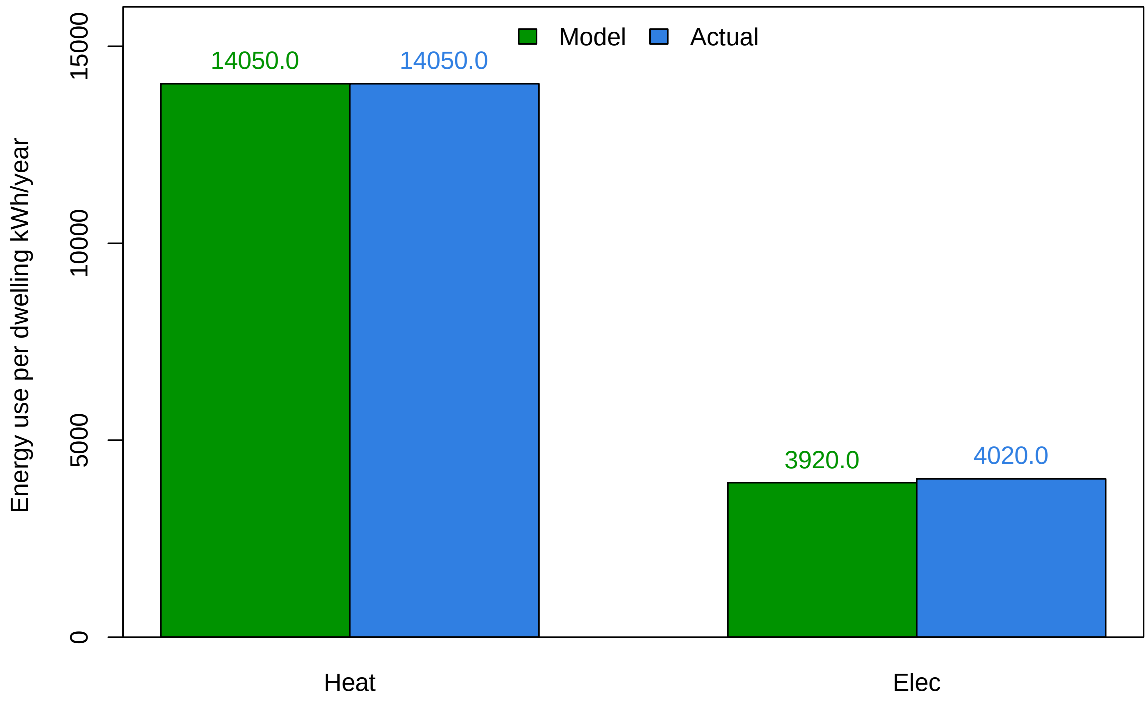
For most of our analysis we used typical weather for Glasgow. However, this is not typical of all of Scotland. We also modelled energy use for the archetypes in Aberdeen and found that they require on average 12% more heating (using a weighted mean of gas and oil use). We also compared the total heat demand against the domestic energy consumption reported in Scottish Energy statistics[15]. This reports heat and electricity use separately. We found that to align these totals we needed to increase the Glasgow results by 6.5% - effectively an average between Glasgow and Aberdeen. In all our analysis we used Glasgow weather and increased the heating energy use by 6.5%.

Figure 12 below shows the adjusted heat demand (oil and gas) and electricity demand from the baseline stock versus the reported value for 2019 in Scottish Energy Statistics. The adjusted figures are a perfect match for heat (by far the largest portion of Scottish energy use in homes), and 2.5% low for electricity.

This demonstrates that the modelling, scaled up to all homes, is a good match against total heating energy and electricity use in Scotland.

[15] https://www.gov.scot/publications/annual-compendium-of-scottish-energy-statistics/

Figure 12. Baseline energy use calibration



Upgrade measures & costs

Each of the house types described in the previous sections 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 ground-floor or mid-floor flats, and floor insulation only applies to dwellings with suspended timber floors. Most of the fabric upgrades in ScotCODE have costs separated into fixed and variable costs, with variable costs related to floor, wall, roof and window area, see Table 8 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 8. Fabric upgrades included in ScotCODE

Measure	Fixed cost	Variable cost
External wall insulation	£4,780	£42/m^2 (net wall area)[16]
Internal wall insulation	£1,910	£95/m^2 (net wall area)[17]
Top-up loft insulation (150mm to 300mm)	£190	£6/m^2 (roof area)[23]
Floor insulation (For suspended (ground) floors, lift floorboards, fit insulation between joists, make good)	£4,080[14]	- [but costs adjusted -20% to +40% based on floor area]
Draught-stripping to achieve 0.8 ac/h (sealing around doors, windows, service penetrations and blocking chimneys)	£52[18]	£16/m^2 (window and door area)
Triple glazing	-	£345/m^2 (window area)[19]
Flat roof insulation (Install EPS insulation over old roof, replace felt and barge-boards above)	-	£85/m^2 (roof area)[20]
Double glazing (where not present in base case)	£7,460 for all windows, or £620 per window	£345/m^2 (window area) [21]
Cavity wall insulation (where not present in base case)	£770[22]	-

[16] J Palmer et al. (2017) WHAT DOES IT COST TO RETROFIT HOMES? Updating the Cost Assumptions for BEIS's Energy Efficiency Modelling. London: BEIS.
[17] 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).
[18] Scottish Government's Fuel Poverty Strategy Analytical Annex (2021).
[19] 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.
[20] https://www.insulation-info.co.uk/roof-insulation#flatroof
[21] J Palmer et al. (2017) WHAT DOES IT COST TO RETROFIT HOMES? Updating the Cost Assumptions for BEIS's Energy Efficiency Modelling. London: BEIS.
[22] J Palmer et al. (2017) WHAT DOES IT COST TO RETROFIT HOMES? Updating the Cost Assumptions for BEIS's Energy Efficiency Modelling. London: BEIS.

Similarly, most of the heating system costs have fixed and variable components, with the variable components determined either by the size of the heat pump or other heating system installed, or by the number of rooms. (See Table 9 below.) As described above, the sizes of heat pumps are determined based on the heat loss/heat demand of the dwelling, and a comfort test to ensure it is large enough to meet the set-point temperature. In all cases, the heat pump costs include buffer tank, controls and labour, but not a water cylinder or distribution system.

Readers should note that unlike simple like-for-like replacement of a boiler, there are additional plumbing and equipment costs when a heat pump is installed for the first time. The full cost of these ancillary measures, including controls, buffer tanks and pipework, and in some cases new, larger radiators are all included here and detailed in the tables below. However, these additional costs would be far less when the heat pump comes to be replaced – say, in 15 to 20 years. New pipework and radiators should not be needed for the second and subsequent heat pump installations, and labour costs for installing should also be lower.

Table 9. Heating system upgrades included in ScotCODE

Measure	Fixed cost	Variable cost
Air-source heat pump	£5,940	£550/kW[23]
High-temperature ASHP	£6,530	£600[24]
Air-to-air heat pump*	£1,390 per room	£240/kW[25]
Ground-source heat pump	£10,420	£890/kW[26]

[23] Microgeneration Certification Scheme cost data for Scotland, 2019-2021, inflated to £2022. Based on a sample of 10,145 heat pumps installed from 2019-2021. Unpublished. These costs include replacement radiators but exclude major energy efficiency renovations. (We also compared this against quotes for heat pumps in Scotland, which were somewhat lower, but we could not be sure they included all costs.)

[24] High-temperature heat pumps are available in fewer sizes than low-temperature heat pumps, and there are currently only a small number of models available Installers are more likely to round up to next largest capacity available, so we assume simplistically this raises costs by 10%.

[25] Based on multiple quotes from Strathair Air Conditioning supplier in 2022, checked against comparable costs from www.checkatrade.com.

[26] Microgeneration Certification Scheme cost data for Scotland, 2019-2021, inflated to £2022. Unpublished. (We also compared this against quotes for heat pumps in Scotland, which were somewhat lower, but we could not be sure they included all costs.)

Storage heaters	£325 per room	£450/kW[27]
Annual maintenance costs	ASHP/A2A: £110 a year Gas/oil base case: £100 a year Storage heaters: £0 a year.	-

*For air-to-air heat pumps the modelled number and cost of the external compressor units rises in relation to the number of internal heat distributors.

According to the heating system under scrutiny, costs vary according to floor area and the number of rooms. All costs are adjusted from the year evidence was collected to 2022, using the Retail Price Index.

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

Table 10. Ancillary heating upgrades included in ScotCODE

Measure	Fixed cost
Hot-water cylinder (for homes where this is not already present, including a buffer tank)	£2190
Wet heating system (for houses or flats where this is not already present)	Houses: £4380 Flats: £2190
Removal of radiators (where an air to air heat pump is installed, with different internal units).	£210
Larger radiators (where radiators are already present)*	£270 per radiator
Instantaneous electric water heaters (for flats which do not have a hot water cylinder already).	£350

* Radiator upgrades assume that existing pipework is of sufficient size to function with lower flow temperatures. In some cases (e.g. microbore) small diameter pipework could need replacing, which would increase costs above this.

[27] https://www.alertelectrical.com/dimplex-quantum-1250w-high-heat-retention-storage-heater-with-iq-controls-qm125rf.html?

To make it easier for readers to relate the heat pump costs to specific sizes of system, Tables 11 and 12 below show the equipment and labour costs of three different sizes of heat pump, as used in the modelling.

Table 11. Air source heat pump costs in ScotCODE, for specific sizes of heat pump

Technology	Cost for 8 kW	Cost for 12 kW	Cost for 16 kW
Air source heat pump - EQUIPMENT	£5,160.00	£6,840.00	£8,520.00
Air source heat pump - LABOUR & SUPPLY COSTS	£4,730.00	£5,130.00	£5,530.00
	£9,890.00	**£11,970.00**	**£14,050.00**

Table 12. Ground source heat pump costs in ScotCODE, for specific sizes of heat pump

Technology	Cost for 8 kW	Cost for 12 kW	Cost for 16 kW
Ground source heat pump - EQUIPMENT	£7,000.00	£9,160.00	£11,320.00
Ground source heat pump - LABOUR & SUPPLY COSTS	£6,870.00	£7,390.00	£7,910.00
	£13,870.00	**£16,550.00**	**£19,230.00**

Comparing costs against past work

This report and modelling work for Scotland uses the best-available cost data in all cases. Readers should note that the costs of heat pumps and efficiency measures are higher than previous work[28,29]. A number of factors influence this, including inflation. Installation costs for completed air and ground source heat pump installations[29] were used for this study, to reflect current costs in Scotland more accurately. This contrasts to industry estimates/quotes used in past work. Scottish costs also reflect a higher proportion of remote and rural homes in Scotland[30], and these costs may be higher due to homes tending to be larger and older. Readers should also note that the CODE costs came from a source covering the whole of the UK, not just Scotland. Comparisons against past work are shown in Figures 13-14 and Table 13 below.

Figure 13. Costs of air source heat pumps were lower in the UK CODE[29] study for BEIS, published in 2020

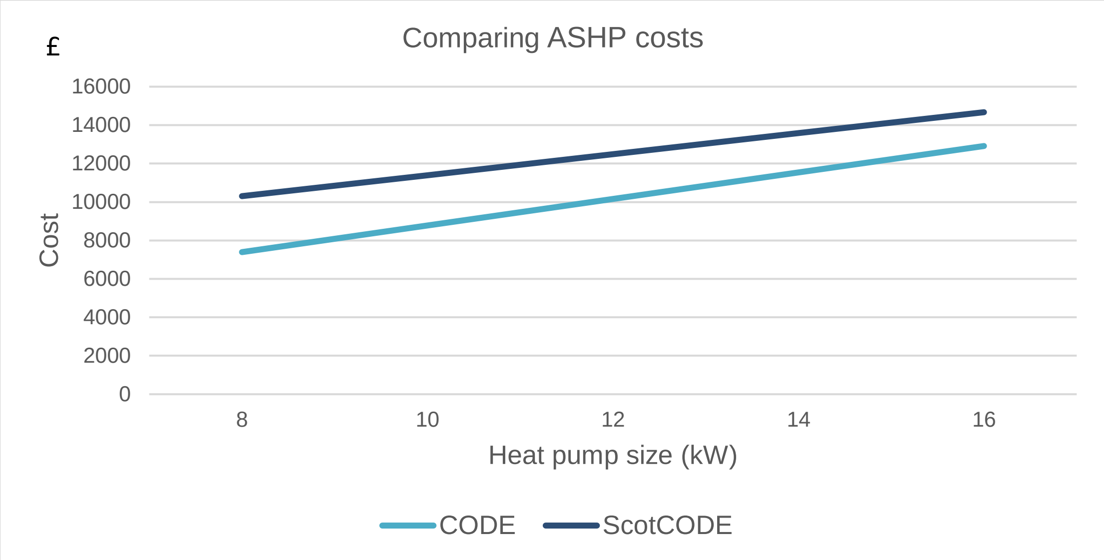


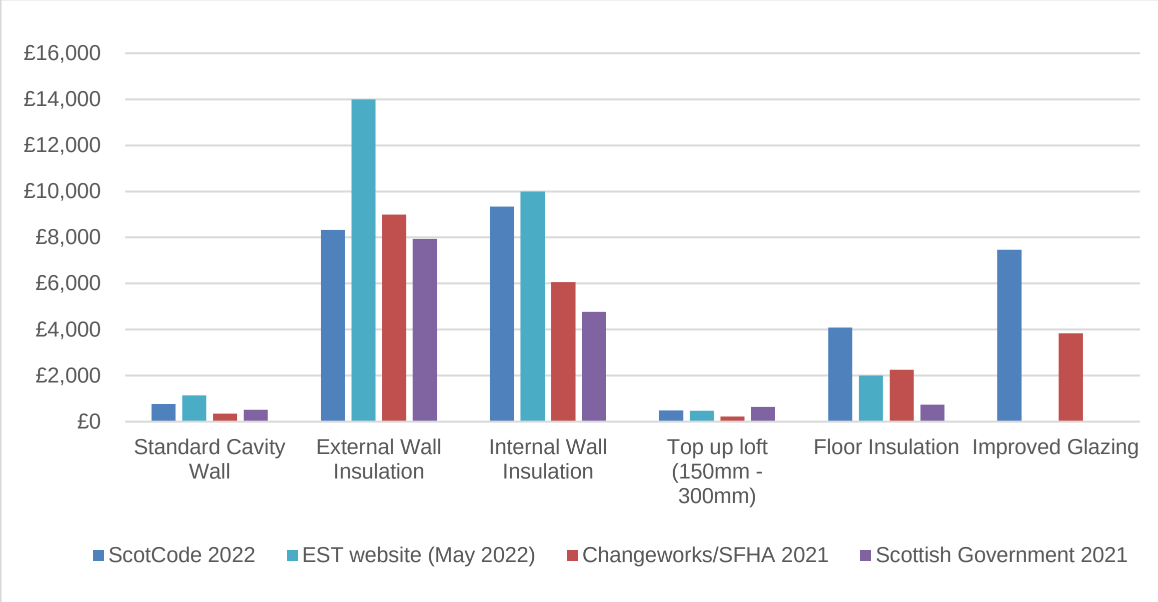
Table 13. ScotCODE costs of energy efficiency improvements compared to previous estimates (for three-bedroom semi-D)

	Standard Cavity Wall	External Wall Insulation	Internal Wall Insulation	Top up loft (150mm - 300mm)	Floor Insulation	Improved Glazing (1)	Flat Roof Insulation (2)
ScotCode 2022	£770	£8,510	£10,290	£480	£4,080	£6,200	£1,260
EST website (May 2022)	£1,134	£14,000	£10,000	£478	£2,000	-	-
Changeworks/SFHA 2021	£345	£8,996	£6,058	£220	£2,250	£3,836	£8,253
Scottish Government 2021	£514	£7,942	£4,768	£646	£739	-	-

(1) Triple glazing assumed by CAR, 'High Efficiency Glazing' by Changeworks/SFHA
(2) Partial roof insulation (e.g. extension) assumed by CAR.

[28] Delta-EE (2020) Cost of Domestic Heating Measures Final Cost Database. BEIS: London.
[29] J Palmer & N Terry (2020) Cost-Optimal Domestic Electrification. London: BEIS.
[30] https://energysavingtrust.org.uk/wp-content/uploads/2021/10/Renewable-heat-in-Scotland-2020-report-version-2.pdf

Figure 14. ScotCODE costs of energy efficiency improvements compared to previous estimates



Notes: Values in the chart and preceding table are average installation costs per home. They have different assumptions and calculation methods but they show the range of cost estimates. ScotCODE 2022[31] and Scottish Government 2021[32] include cost data for measures applied to 12 archetypes; values are an average across the 12. Changeworks/SFHA[33] and the Energy Saving Trust[34] have 'average' costs given for each measure – they do not reflect archetypes.

How will the costs of heat pumps change over time?

It is almost impossible to predict how the installation costs of heat pumps will change over time accurately, because there are so many unknowns, including how many heat pumps will be installed in Scotland, and internationally. However, it seems likely that there will be economies of scale (affecting manufacturing costs and possibly installation costs), and learning effects (primarily affecting speed of installation, and so the cost of installation).

Nesta, the UK's innovation agency for social good, published a report about heat pump costs in 2020.[35] Nesta did not distinguish between economies of scale and learning effects for

[31] Primarily informed by J Palmer et al. (2017) WHAT DOES IT COST TO RETROFIT HOMES? Updating the Cost Assumptions for BEIS's Energy Efficiency Modelling. London: BEIS.
[32] Scottish Government, 2021, Fuel Poverty Strategy - Analytical Annex. Costs drawn from numerous sources.
[33] Changeworks for Scottish Federation of Social Housing Associations (SFHA), 2021, Energy Efficiency Standard for Social Housing 2032 (EESSH2). Modelled for the social housing stock using cost data provided by Energy Saving Trust.
[34] Energy Saving Trust (website) accessed May 2022. Indicative costs for different measures: solid wall insulation costs are for 'a typical 3-bedroom, semi-detached house'; cavity wall insulation is a calculated average across five given house types; floor insulation given as a range of £1,300 to £2,700, middle value presented here; loft top up (120mm to 270mm) is a calculated average across four house types.
[35] Nesta (2020) How to Reduce the Cost of Heat pumps. London: Nesta.

labour compared to equipment costs. Nor did they do any modelling of savings in CapEx (or even include this among their "Other possible cost reductions for a heat pump"). However, Nesta noted that actual install costs *rose* at least 15% from 2018 to 2020.

Overall, in future, Nesta expects the upfront (CapEx) costs of heat pumps to fall by between 4% and 27% by 2030, with a 'Moderate' estimate of 17% lower costs, see Table 14 below. However, Nesta notes that the high ('Optimistic') cost reductions are higher than empirical studies.

Table 14. Nesta forecasts of likely changes to capital costs of heat pumps

Cost reduction from baseline	2025	2030	2035	Basis		
				Experience (or learning) rate	Annual rate	Scenario
Upfront costs	14%	27%	41%	10% (unit) 5% (other)	–	**Optimistic** If the 'optimistic' running costs scenario is applicable, this upfront costs scenario is less likely.
	9%	17%	26%	3% (unit) 5% (other)	–	**Moderate**
	2%	4%	6%	3% (unit)	–	**Conservative** Aligned with CCC's 2019 analysis.[94] Scenario could represent limited innovation in manufacturing and installations or higher electricity rates requiring more efficient systems.

Source: Nesta (2020)

A 17% saving by 2030 translates to a 2.3% compound reduction in costs each year. Readers should note that the savings depend on the balance of supply and demand for heat pumps in Scotland, and the 17% saving is by no means guaranteed. There could be no savings at all – for example, if demand rises more steeply than supply, so manufacturers and installers increase profits from heat pumps – or alternatively there could be larger savings than the 17% used here.

The costs quoted for 2022 are the best estimate of current costs using evidence that is currently available. Moving beyond 2022 the uncertainty about costs increases, and the further into the future these projections are carried, the greater the uncertainty about costs. This applies to energy prices at least as much as it does to capital costs.

Energy prices

Ordinarily we would use current energy prices in the cost optimisation process. However, not only are prices rising rapidly, but it seems likely that prices will be reduced by 2025, the year proposed Scottish Government regulations start to mandate energy efficiency and heat pumps in some homes. Prices will be reduced by shifting 'policy costs' (such as the costs of Feed in Tariffs, the Energy Company Obligation and the Warm Homes Discount) away from energy bills[36]. Since these subsidies mainly fall on electricity bills, this will reduce the price of electricity relative to gas. Readers should also note that the large differential between gas and electricity prices could be further reduced in future by proposed reforms to the

[36] See commitment by UK Government: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf

electricity market, which would remove the impact of high gas prices on wholesale electricity market prices[37].

We have estimated the effect of removing policy costs in the energy prices used in modelling. We have also tested the impact of the full energy prices on the cost-optimal solutions. Energy prices are held constant throughout the 15-year optimisation.

The energy prices for oil and gas are derived starting with the April 2022 Ofgem price caps for Scotland, then removing policy costs. For oil we have used typical values from the period April-June 2022.[38]

The Ofgem price caps are specified as a 'nil bill' and a standard bill (maximum). We have assumed that the nil bill is the fixed daily charge. The standard bill is for 3,100 kWh/year for electricity or 12,000 kWh/year for gas. Table 15 below shows the prices for Southern Scotland. Northern Scotland is so similar as to make no difference – the electricity price is just 0.06p/kWh more.

Table 15. Ofgem price caps (April 2022) for Southern Scotland

	Fixed charge/year	Unit charge p/kWh
Gas	£111.35	7.36
Electricity	£193.61	27.93

Fixed charges are omitted because these need to be paid anyway. Homes will continue to pay the standing charge for electricity.

We have used ClimateXchange's estimate of policy costs from 2021.[39] This is 5.2p/kWh for electricity and 0.2p/kWh for gas. This reduces the price of standard-rate electricity from 27.93 to 22.73p and for gas from 7.36 to 7.16p.

For homes using storage radiators, we assume Economy 7 prices. We have applied the same ratio between this and the standard price as is seen in SAP 2012.

The final electricity prices used are shown in Table 16 below.

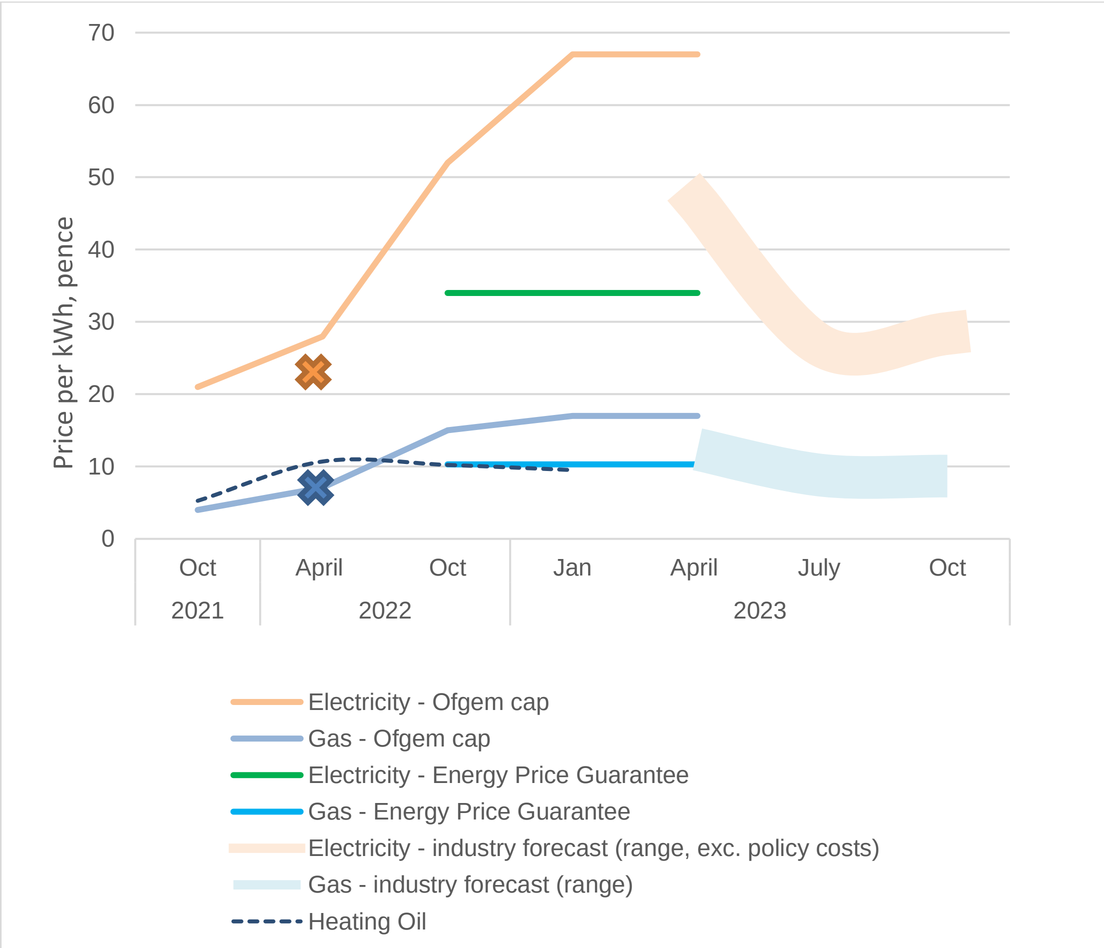
Table 16. Energy tariffs used in this report

Fuel	Daytime	Off-peak
Gas	7.16	7.16
Oil	10.7	10.7
Electricity – standard	22.73	22.73
Electricity – Economy 7	27.00	12.91

[37] https://www.gov.uk/government/consultations/review-of-electricity-market-arrangements
[38] From https://www.boilerjuice.com/heating-oil-prices-scotland/
[39] Boorman, A., Lowrey, C., and Goswell, T. (2021) Review of gas and electricity levies and their impact on low carbon heating uptake. Edinburgh: ClimateXchange.

Since the analysis was run in April 2022 energy prices have risen considerably, driven by increased global demand for gas, and very significant reductions in European imports of gas from Russia following its war on Ukraine. The UK Government has intervened to protect consumers from high prices and in October 2022 introduced the Energy Price Guarantee (EPG), which will maintain prices at a fixed level until April 2023, with electricity and gas prices 50% and 45% higher than assumed in this study. The UK Government's commitment to remove policy costs from energy bills has also been implemented though the EPG[40]. Figure 15 below charts Ofgem's price cap levels and prices assumed in this study, alongside EPG prices to April 2023 and market forecasts to the end of 2023.

Figure 15. Energy prices in 2021 to 2023



Orange and blue crosses show electricity and gas prices used in this study.

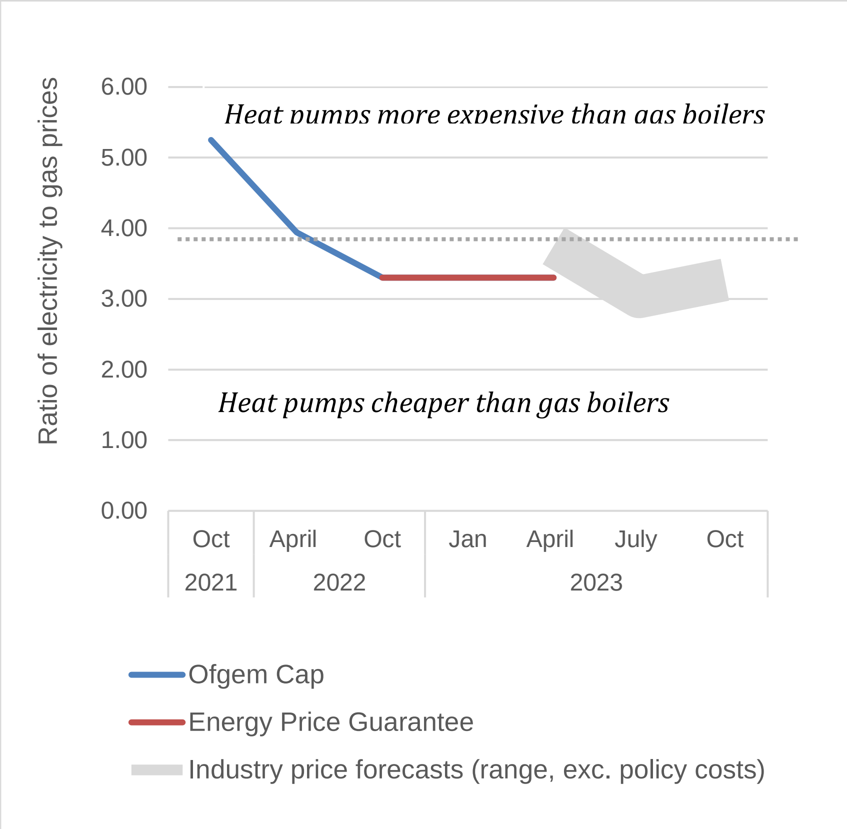
The ratio of electricity to gas prices (a key factor determining heat pump running costs vs. gas) under the EPG is less favourable than that assumed in this analysis. This means increased heat pump running costs in comparison to gas. However, energy prices are forecast to fall in 2023[41] and with the continued removal of policy costs from electricity bills, the ratio of electricity to gas price should return to the level assumed in this study, or below, as illustrated in Figure 16 below. It shows that over time the ratio has become more

[40] https://www.gov.uk/government/publications/energy-bills-support/energy-bills-support-factsheet-8-september-2022

[41] https://www.cornwall-insight.com/predicted-fall-in-the-april-2023-price-cap-but-prices-remain-significantly-above-the-epg/

favourable to heat pumps versus gas boilers, thanks to the removal of policy costs and rising gas prices.

Figure 16. Ratio of electricity to gas prices



These forecasts also indicate that without further UK Government support to help households manage high energy prices, prices will remain at nearly double the levels assumed in this study. This will make heating efficiency even more important and it will increase the savings that households can make from adopting energy efficiency measures.

Low-carbon heating systems

This part of the report concentrates on heating systems – mainly electric heat pumps. The next part of the report deals with energy-efficiency (insulation and air tightness upgrades).

Optimisation

The following sections of the report outline the results of the optimisation used to determine the lowest overall cost solution to provide homes with all electric heating. The optimisation considered both energy efficiency and heating system upgrades together (there are a total of 7,200 combinations in the model), given the interactions between both.

The modelling selects cost-optimal solutions which allow for all-electric heating (in almost all cases using a heat pump) with the lowest overall cost 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 CO2 emissions. All modelling work includes checks on achieved thermal comfort – so that energy and carbon savings do not come as a result of under-heating or discomfort.

Total costs were evaluated over a 15-year time horizon as this is consistent with assumptions about heat pump service life made by the Climate Change Committee[42].

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) 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 lasting up to 30 years.

The optimisation used April 2022 Ofgem price caps for electricity in Scotland, without policy costs. These were 26% lower than the current (temporary) price guarantee for gas, and 33% lower than the price guarantee for electricity, which runs to April 2023.

Possible constraints on low-carbon heating

The cost-optimal solutions for low-carbon heating are slightly different depending on the fuel used for heating in the base case. This is because installing a wet heating system in a home which previously had electric heating is expensive. Some other combinations of base case and upgraded heating system can involve adding a hot water cylinder, or even removing radiators, which may also be expensive.

Heritage constraints (including planning requirements) do not affect the choice of low-carbon heating, since there is usually somewhere to put the external unit of a heat pump that is hidden from the street. However, space constraints may make adding a hot water cylinder difficult. Also the internal units of ASHPs are physically much larger than boilers, so finding space can be difficult.

Homes near the coast have additional costs to ensure heat pumps are corrosion-resistant. This is not enough to affect the choice of heating system, but it does change the capital costs of installing a heat pump.

We have allowed ASHP solutions in flats and tenements, although there are practical difficulties – the outdoor units of ASHPs are typically mounted on the ground, and while it is possible to connect flats on upper floors, this will be technically challenging, as could co-locating multiple units. Another solution could be to mount ASHP units to outside walls – this is more common with air to air heat pumps. This is quite normal for air conditioning abroad, but there is limited experience in Scotland. For small heat pumps it is also possible to install them inside, with just external ducts for air on the outside.

Where these solutions are not practical, storage radiators are a possible low-carbon alternative.

[42] Committee on Climate Change (2019) Net Zero Technical Report. London: CCC

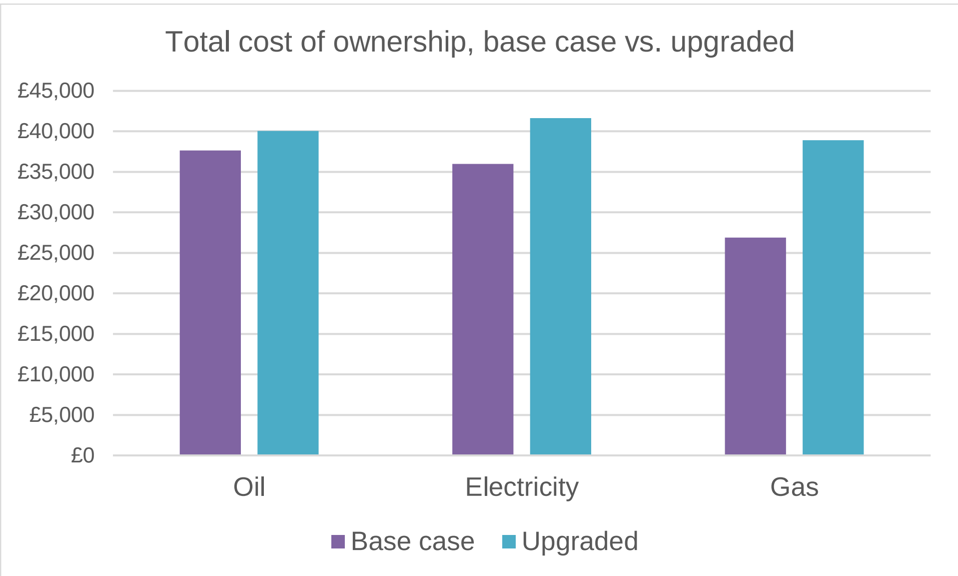
Typical homes with gas, oil heating or electric heating

The least-cost solution for all dwellings with wet heating systems and no constraints is an ASHP, except for the Pre-1919 tenement – and in this case it is marginal (discussed below). Figure 17 below shows solutions and total costs for homes starting with gas heating, over 15 years, discounting at 3.5%, disaggregated into energy costs, maintenance and replacement costs, capital costs of efficiency measures, and capital costs of heating systems. For replacement costs, the baseline heating systems need to be replaced within the 15 years. In all cases, the energy costs (blue) dominate.

Note that we included ground-source heat pumps and high-temperature ASHPs in the optimisation, but neither of these ever came out as cost optimal over 15 years. Ground-source heat pumps were rejected because of high capital costs, while high-temperature ASHPs were rejected because of lower coefficients of performance and so higher running costs. The potential advantage of high temperature heat pumps is avoiding expensive insulation upgrades and replacing radiators, but for the two houses with solid walls, external wall insulation (EWI) and a normal ASHP were more cost-effective (and had lower energy use and carbon emissions) than a high-temperature ASHP without EWI, over 15 years.

Compared to the baseline, total costs of ownership over 15 years are higher for almost all house types with present energy prices and costs for fabric upgrades and heat pumps (noting that discounting future costs places more emphasis on up-front capital costs, and less emphasis on running costs). As Figure 17 below shows, the smallest increases in total life costs are for oil heated homes (on average £2,400 more), followed by electrically heated homes[43] (£5,650 more) and efficient gas boilers (£12,000 more). This gap is what Government financial support needs to close in order to make converting to heat pumps more attractive to households.

Figure 17. Average total costs of ownership over 15 years, base case vs upgraded

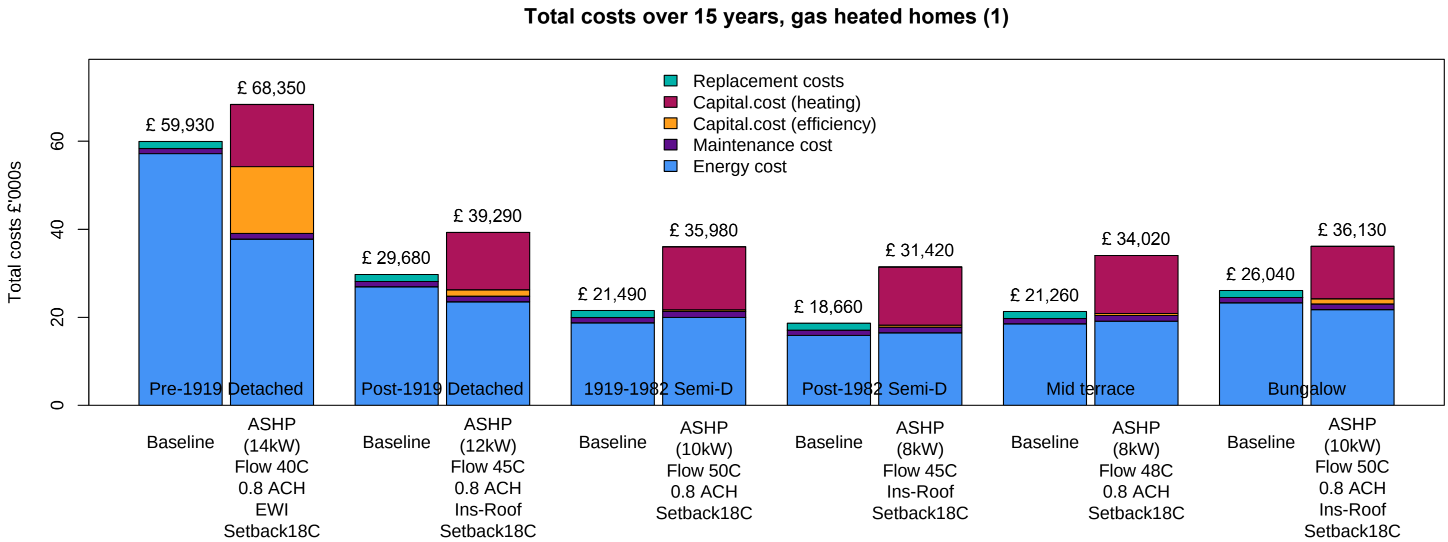


[43] Note that unlike homes with other fuels, base case figures for electric homes do not include the cost of replacing the existing heating system (in this case storage heaters) because these have a much longer operating life than oil or gas boilers.

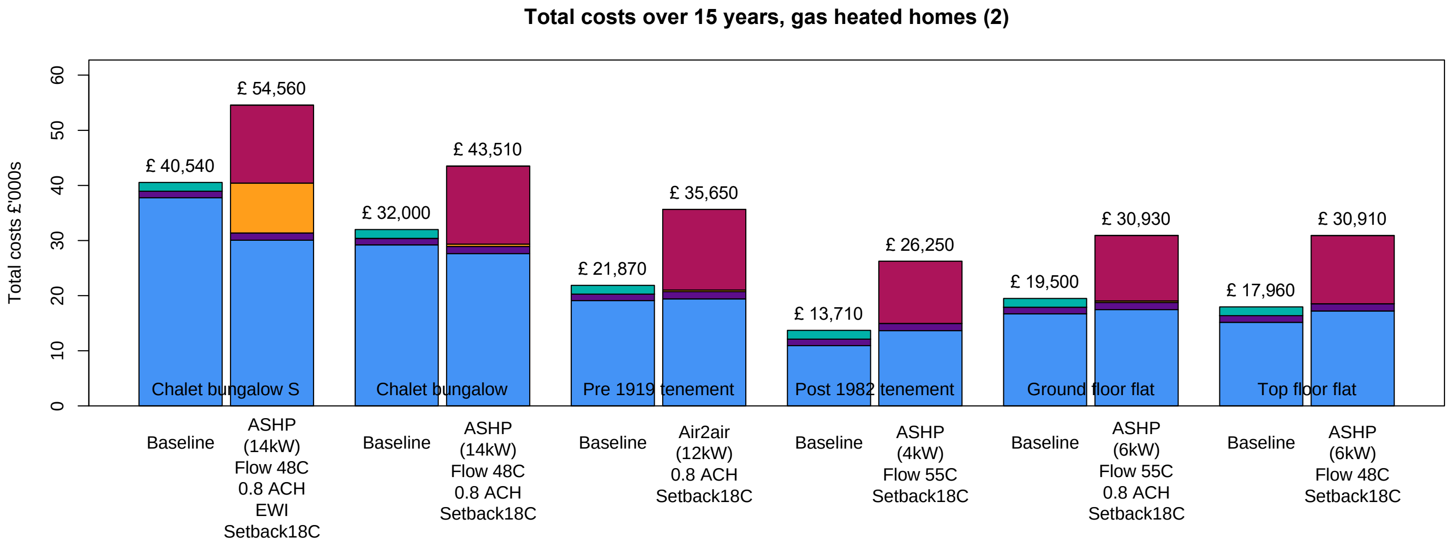
Readers should note that this is not a comparison between net-zero compatible solutions – heating in the gas base case is not penalised for the carbon emissions that are produced. A more valid long-term comparison would be between heat pumps and boilers running on low-carbon hydrogen (which some commentators view as an alternative to heat pumps for mass deployment). However, costs are not available for the latter as the solution is yet to be commercialised anywhere in the world.

The average increase (across archetypes) in lifetime costs versus baseline is 47% higher[44] for gas or oil-heated flats and tenements than houses. The modern tenement and top floor 4 in a block have the biggest overall cost increases, because they are already quite efficient in base case (meaning that bills are quite low), and none of the fabric upgrades are cost effective for them. Both have relatively high flow temperatures (48C and 55C) and a high ratio of hot water to space heating demand. Further, the modern tenement flat has small radiators which it is not cost effective to upgrade (i.e. total costs of ownership over 15 years are still higher).

Figure 18. Total costs for gas heated homes baseline and with efficiency measures



[44] The average increase in total life costs versus base case for gas and oil houses is £7,294. The average increase for gas and oil flats is £10,756.



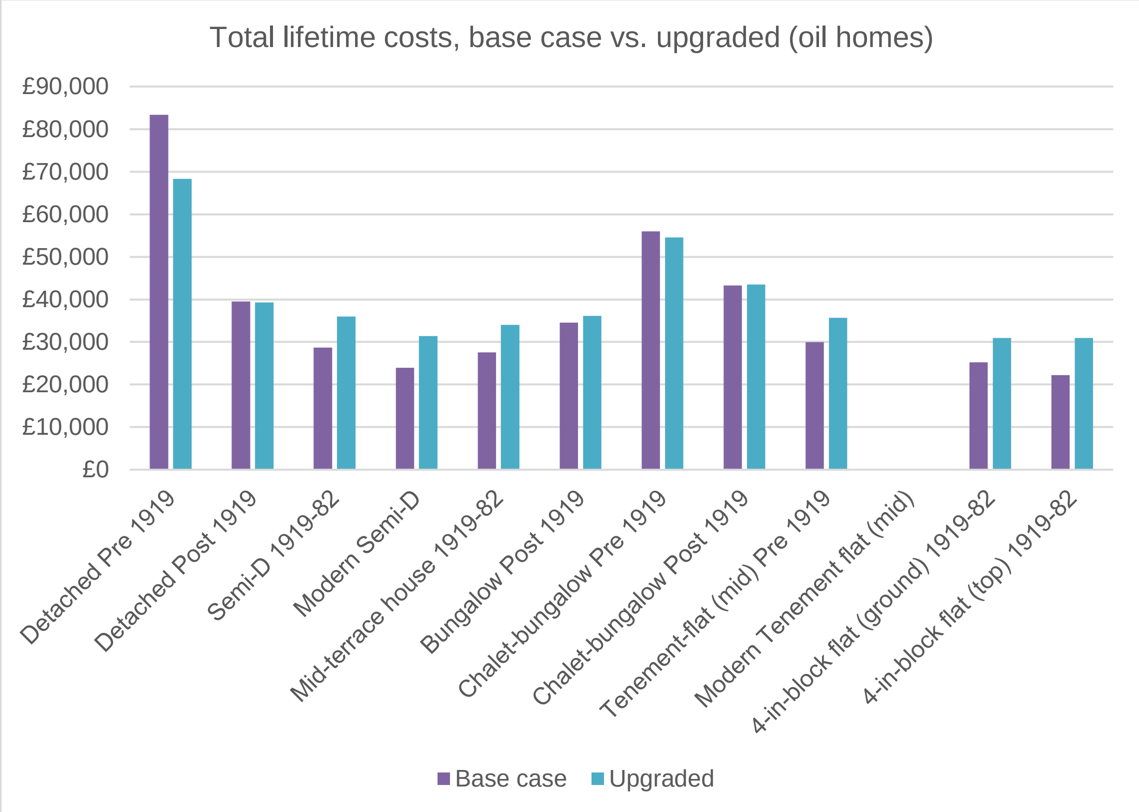
Energy bills are lower with heat pumps for five of the gas heated homes (15% less on average). A further five incur marginally higher running costs (5% on average), while two flats see significantly higher costs (an average of 18% higher). Running costs are listed in Table 17 below, and options to further reduce running costs for these homes are explored in 'Efficiency upgrades and fabric standards', p68 below.

For almost every house type, the up-front capital costs are what pushes the total cost of heat pumps over the baseline costs using a gas boiler. For the most common gas and oil-heated homes, heating systems range from £11,290 to £14,150 and total upgrade costs (including energy efficiency) are £11,290 to £29,280 (capital costs are listed in Table 18 below).

These capital costs may fall over time, as the market for installing heat pumps matures. NESTA's 'moderate' scenario for anticipated cost reduction from learning and scaling effects implies savings of around a fifth by 2030: upfront costs for unconstrained gas homes fitting a heat pump could fall by £2,250 on average, with average costs of £11,000. Heat pumps may also continue to get more efficient, which will also help to reduce overall costs of ownership. Continued rebalancing of energy prices so that electricity is favoured in place of (higher-emission) gas would also reduce total costs for heat pumps.

Some homes that currently have oil heating would see savings in total costs compared to their existing costs – because their current energy use costs more per kWh – see Figure 19 below (note that the fabric and heating system upgrades are the same as for the gas homes, outlined in Figure 18 above). When total costs are higher for these homes than at present, the gap is also much smaller than for homes with gas heating, and in all cases energy bills are lower. These are the homes to target first, ahead of the gas homes discussed above.

Figure 19. Total costs of ownership for homes that currently have oil heating, over 15 years



* Modern Tenement flat is blank as there are none of this archetype with oil heating in the model.

Homes that currently have electric storage heaters also compare more favourably than gas homes regarding total costs of ownership (see Figure 20 below).

Non-condensing boilers

A proportion of existing gas and oil boilers in Scotland are older, non-condensing boilers. These are less efficient than condensing boilers, so consequently baseline energy use and emissions would be higher for homes with non-condensing boilers. According to SAP, non-condensing boilers are 20% less efficient than condensing ones (84% efficiency for condensing boilers; 70% non-condensing).

This means that strictly the baseline energy use for homes with non-condensing boilers is around 20% higher than shown in Figure 18 above. Consequently, the energy costs for homes with older, non-condensing boilers are lower with the cost-optimal heat pumps and efficiency measures. After adjusting for lower boiler efficiency, all gas heated houses have similar or lower running costs to the base case, with annual costs on average 14% lower, although some flats still see cost increases (on average 8% higher). All but one of the oil heated homes already have lower running costs when moving from efficient oil boilers, and average savings increase from 25% to 31% if starting with a non-condensing boiler. This makes a very strong argument for upgrading homes with older non-condensing boilers first, because the savings in running costs are clear cut.

Pre-1919 tenements

All the cost-optimal packages of measures use an ASHP, except for the Pre-1919 tenement, where the solution is a 12kW air to air heat pump, see Figure 20 below. However, the difference between this and the 8kW ASHP solution is marginal – only £880. In fact the air to air heat pump would be more disruptive to install because work would be needed in every heated room of the house, and the radiators would need to be removed – this means that many households would probably choose an ASHP in preference. Unlike the other solid wall homes, wall insulation is not cost-effective, as the area of external walls is not large, providing a lower energy saving relative to the fixed costs of this measure[45].

Figure 20. Pre-1919 tenement with solid walls, alternative packages

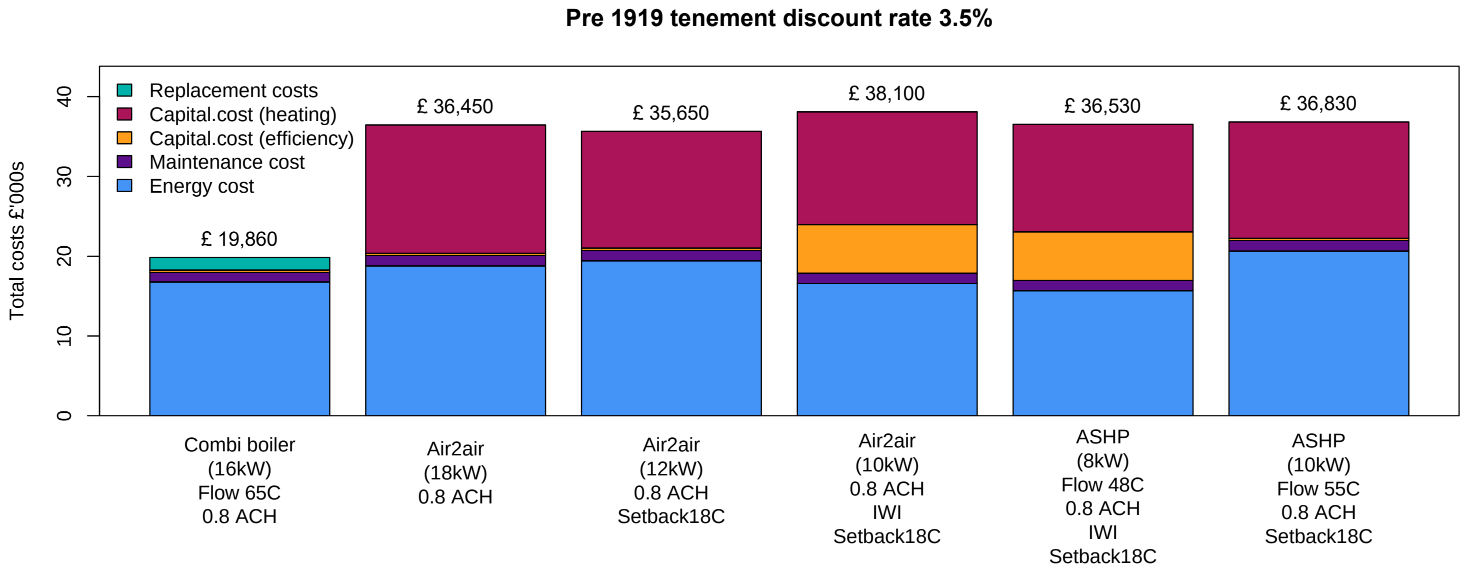


Table 17 below shows the upgrades and running costs for the gas/oil cases compared with the baseline.

Table 17. Energy costs for gas/oil homes

				Baseline		Upgraded
	Archetype	**Efficiency measures**	**Heating system***	**Annual cost Gas homes (£)**	**Annual cost Oil homes (£)**	**Annual cost (£)**
1	Detached with solid walls	AT; EWI	ASHP 14 kW 40 °C	4,890	6,820	3,280 (-33% vs gas, -52% vs oil)
2	Detached with cavity walls	AT; Roof ins	ASHP 12 kW 45 °C	2,360	3,140	2,080 (-12%, -34%)

[45] Potential cost savings from upgrading a multiple units/a whole building at the same time are not included

3	Inter-war Semi-D with timber frame	AT; Roof ins	ASHP 10 kW 50 °C	1,670	2,230	1,790 (+7%, -20%)
4	Modern Semi-D	Roof ins	ASHP 8 kW 45 °C	1,430	1,830	1,490 (+4%, -19%)
5	Mid-terrace house with timber frame	AT	ASHP 8 kW 48 °C	1,650	2,130	1,710 (+4%, -20%)
6	Bungalow with cavity walls	AT; Roof ins	ASHP 10 kW 50 °C	2,050	2,720	1,930 (-6%, -29%)
7	Chalet-bungalow with solid walls	AT; EWI	ASHP 14 kW 48 °C	3,270	4,520	2,630 (-20%, -42%)
8	Chalet-bungalow with cavity walls	AT	ASHP 14 kW 50 °C	2,550	3,450	2,460 (-4%, -29%)
9	Tenement-flat with solid walls	AT	Air to air HP 12 kW	1,700	2,330	1,740 (+2%, -25%)
10	Modern Tenement flat	none	ASHP 4kW 55°C	1,020	1,240	1,250 (+23%, -1%)
11	Ground-floor 4-in-block flat with timber frame	AT	ASHP 6 kW 45°C	1,500	1,940	1,570 (+5%, -19%)
12	Top-floor 4-in-block flat	Roof ins	ASHP 6 kW 48°C	1,370	1,680	1,550 (+13%, -8%)

*Modelling also optimises the flow temperature according to the energy efficiency and emitter area (radiator sizing) of each house type, so dwellings with better efficiency and/or larger radiators have lower flow temperatures. This improves the coefficient of performance of the heat pumps, so saves energy and reduces emissions. The size of heat pumps is also matched against the size of each dwelling and its level of insulation.

Table 18 below shows the capital costs, broken down into energy-efficiency measures and installing the heat pump.

Table 18. Capital costs for gas/oil homes

	Archetype	Heating system*	Heating installation (£)	Efficiency measures (£)	Total (£)
1	Detached with solid walls	ASHP 14 kW 40 °C	14,150	15,130	29,280
2	Detached with cavity walls	ASHP 12 kW 45 °C	13,060	1,420	14,480

3	Inter-war Semi-D with timber frame	ASHP 10 kW 50 °C	14,300	380	14,680
4	Modern Semi-D	ASHP 8 kW 45 °C	13,210	470	13,680
5	Mid-terrace house with timber frame	ASHP 8 kW 48 °C	13,210	370	13,580
6	Bungalow with cavity walls	ASHP 10 kW 50 °C	11,970	1,150	15,260
7	Chalet-bungalow with solid walls	ASHP 14 kW 48 °C	14,150	9,040	23,190
8	Chalet-bungalow with cavity walls	ASHP 14 kW 50 °C	14,150	430	14,580
9	Tenement-flat with solid walls	Air to air HP 12 kW	14,630	290	14,920
10	Modern Tenement flat	ASHP 4kW 55°C	11,290	0	11,290
11	Ground-floor 4-in-block flat with timber frame	ASHP 6 kW 45 °C	11,890	270	12,160
12	Top-floor 4-in-block flat	ASHP 6 kW 48°C	12,390	0	12,390

Cost optimal heat pumps

All the ASHP solutions have a setback temperature (overnight and 'heating-off' thermostat setting) of 18°C. We modelled setback temperatures of 16°C and 18°C for heat pumps. The higher setback increased heat demand overall, but the lower temperature needs a higher-capacity heat pump in order to heat the dwelling quickly in the morning. There is not necessarily a trade-off between capital costs and running costs because the higher setback temperature can also bring lower running costs, as well as capital costs. This is because it usually means the heat pumps run at a lower flow temperature (they operate for longer, and the average indoor temperature stays more constant, so radiators can be cooler and still bring rooms up to temperature) and are therefore more efficient.

The choice of flow temperature depends on both the heating capacity required and the size of radiators. This modelling initially sets the flow temperature at the lowest that is compatible with the existing radiators. If this is higher than 45°C then a lower temperature will also be tested, with radiator upgrades as required. However, the 45°C option (requiring radiator upgrades in most homes) is not as cost effective as leaving the radiators alone and paying higher energy costs.

Several of the archetypes can use a flow temperature of 45°C without radiators upgrades, with the recommended efficiency measures. This includes the detached home with solid walls, after air tightness measures and external wall insulation. The others can use 50°C or lower except for the ground floor flat and the modern tenement, which need 55°C. The optimal flow temperature is sensitive to the initial radiator sizes. We have modelled 180 W/m2 for most homes, on the basis that heating installers go by floor area rather than doing a detailed calculation. It is lower for the mid floor flats and especially the modern tenement, where it is just 90 W/m2, reflecting the higher standard of efficiency as built. It is higher for the solid wall homes, reflecting their higher heat loss to start with.

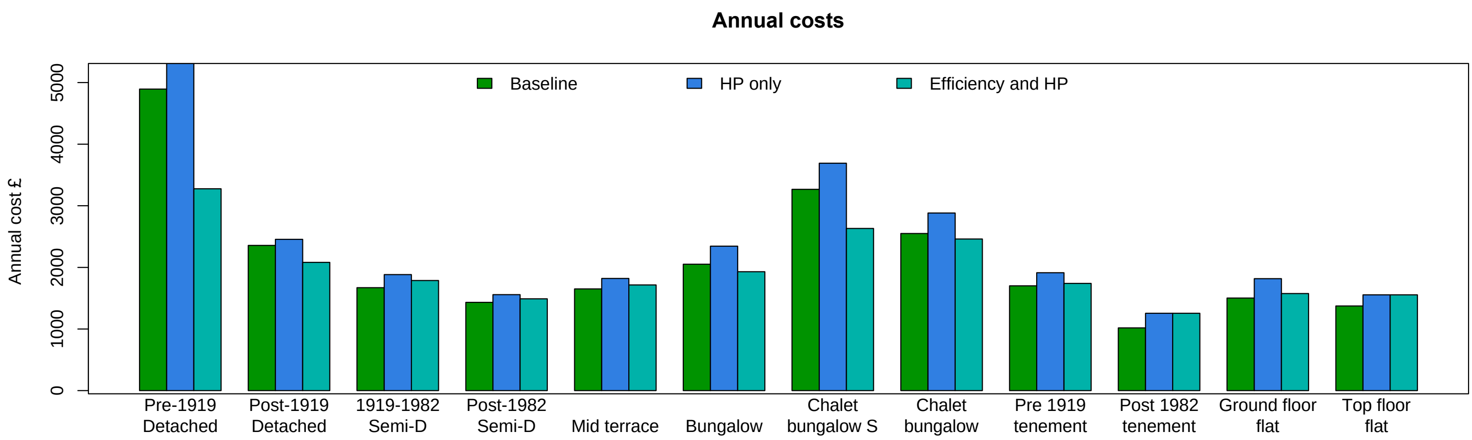
Focusing purely on energy costs (blue in the charts above), the solid-wall homes that are upgraded with EWI see major savings in running costs compared to the baseline costs using gas heating. However, most of the other house types witness very small changes in running costs, and some have a small increase. This is because even though heat pumps run around three times more efficiently than gas boilers, the price of electricity used in modelling is still 3.2 higher than gas per kWh. Even with energy efficiency measures, savings are not sufficient to completely offset this large difference in energy prices.

There is also a second factor at play here which alters the balance of gas versus electric heat pump running costs. The higher setback temperatures chosen for heat pumps in every house type through the optimisation (selected because they reduce total costs, including capital costs over 15 years) have a knock-on effect on heating demand. Effectively these homes are heated for longer, with heating running at a low level overnight and when homes are not occupied. This inevitably raises electricity use and energy costs. This is complicated, and it means that it is not sufficient to focus on running costs alone. Capital costs also affect the overall cost of ownership, and OpEx and CapEx themselves inter-relate with setback temperatures, flow temperatures and the operating efficiency of heat pumps.

Fabric upgrades

The baseline house types already had relatively good energy, with insulated cavities, all double glazing, and usually 150mm of loft insulation. After these measures are in place, apart from the two houses with solid walls, the only additional efficiency measures emerging as cost-effective are draught proofing and top-up loft insulation. The costs for these are low, but the impacts on running costs are considerable. Figure 21 below shows the running costs only for each archetype, comparing gas baseline cost, upgraded with a heat pump but no efficiency measures, and upgraded with both. Note that these results are sensitive to the underlying gas/electric energy prices – a more favourable ratio between the two would reduce heat pump running costs, but this also shows the benefit of energy efficiency in protecting households against future energy price changes. It would be possible to lower heat pump running costs further (e.g. with larger radiators and lower flow rates, and/or more insulation) but the modelling found this not to be cost effective over the 15-year analysis. Further reducing the differential between gas and electricity prices would also lower heat pump running costs in relation to gas.

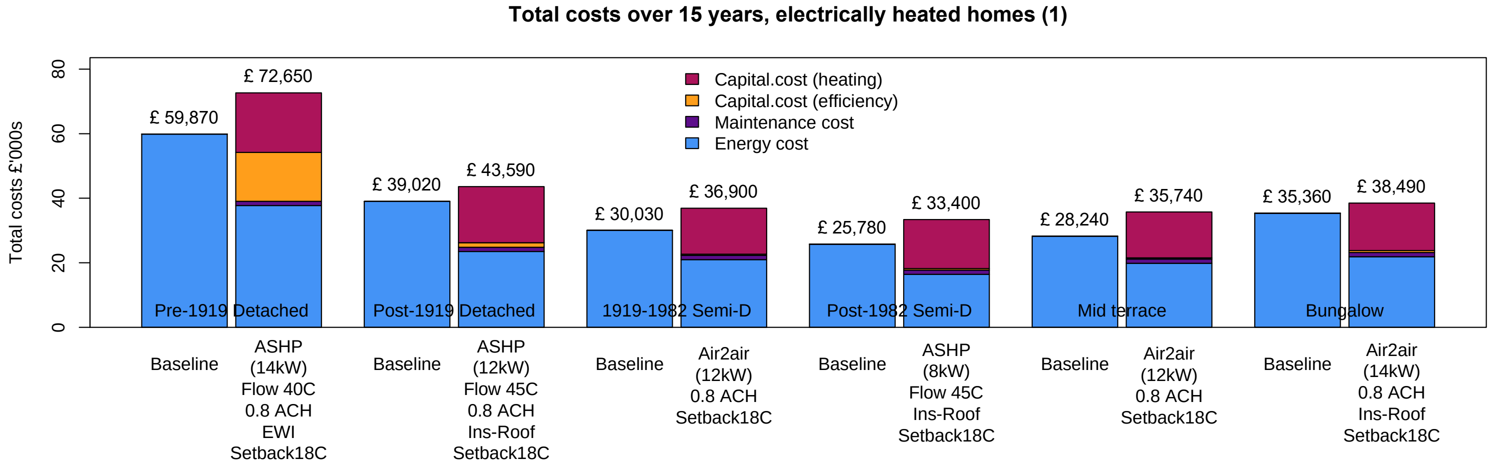
Figure 21. Annual running costs for all archetypes showing benefits of efficiency measures

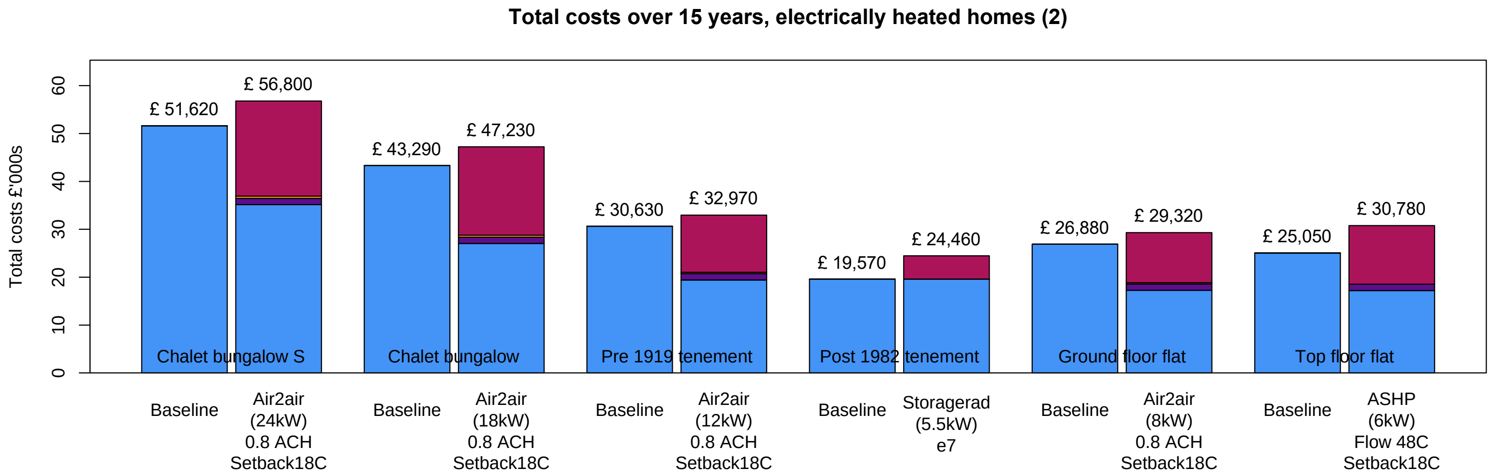


No constraints/electricity

Strictly speaking, converting a home that is already electric is not necessary given that all types of electric heating will decarbonise as the carbon intensity of the grid falls further. However, the efficiency of a heat pump reduces energy bills for our archetypes by at least 25%, and for homes that are using direct electric heating rather than storage radiators the savings will be much greater. Heat pumps also cut annual carbon emissions in half compared to storage heaters. Figure 22 below shows overall baseline costs compared to upgraded cost for the electrically heated homes, assuming they start with storage radiators. Overall costs are usually a little higher (on average £5,587 higher than the base case) but energy costs are lower in all cases.

Figure 22. Total costs for electrically heated homes





Air to air heat pumps (with no water pipework or radiators) are selected for most of the electrically-heated homes - converting from electric heating to a wet system costs more and is more disruptive than if you already have radiators and the associated pipework. All these homes have a hot water tank with electric immersion heater, and retain these.

ASHPs have the lowest costs in some cases, as above, but the difference is marginal – at most 4% greater cost over 15 years for three of the four archetypes selecting ASHP (the difference is larger for the pre-1919 detached home due to the lower flow rates and larger number of rooms, which increase air to air heat pump costs). The modern tenement adopts new storage radiators, with an air to air heat pump costing more overall (10%) and ASHP marginally more expensive again – small radiators, good initial fabric efficiency and high hot water to space heating ratio increase the costs of this solution.

The results suggest that where a home is well insulated or very large, an air source heat pump may have a cost advantage. Air to air heat pump costs increase in proportion to the number of rooms to be heated, and so this option is more cost effective in smaller homes.

Regarding efficiency measures, the most economical solutions for all houses are the same as for the gas/oil cases, except that with an air to air heat pump, external wall insulation is not required for the Chalet bungalow with solid walls. However, the difference is marginal.

Figure 23 below compares the best ASHP and air to air solutions for each archetype, starting with electric heating. Again, the difference is small and in practice, households may find it less disruptive to move from storage radiators to air to air rather than air to water heat pumps, avoiding the need to fit radiators and run pipework below floors.

Figure 23. Comparing ASHPs with air to air heat pumps for electric heating

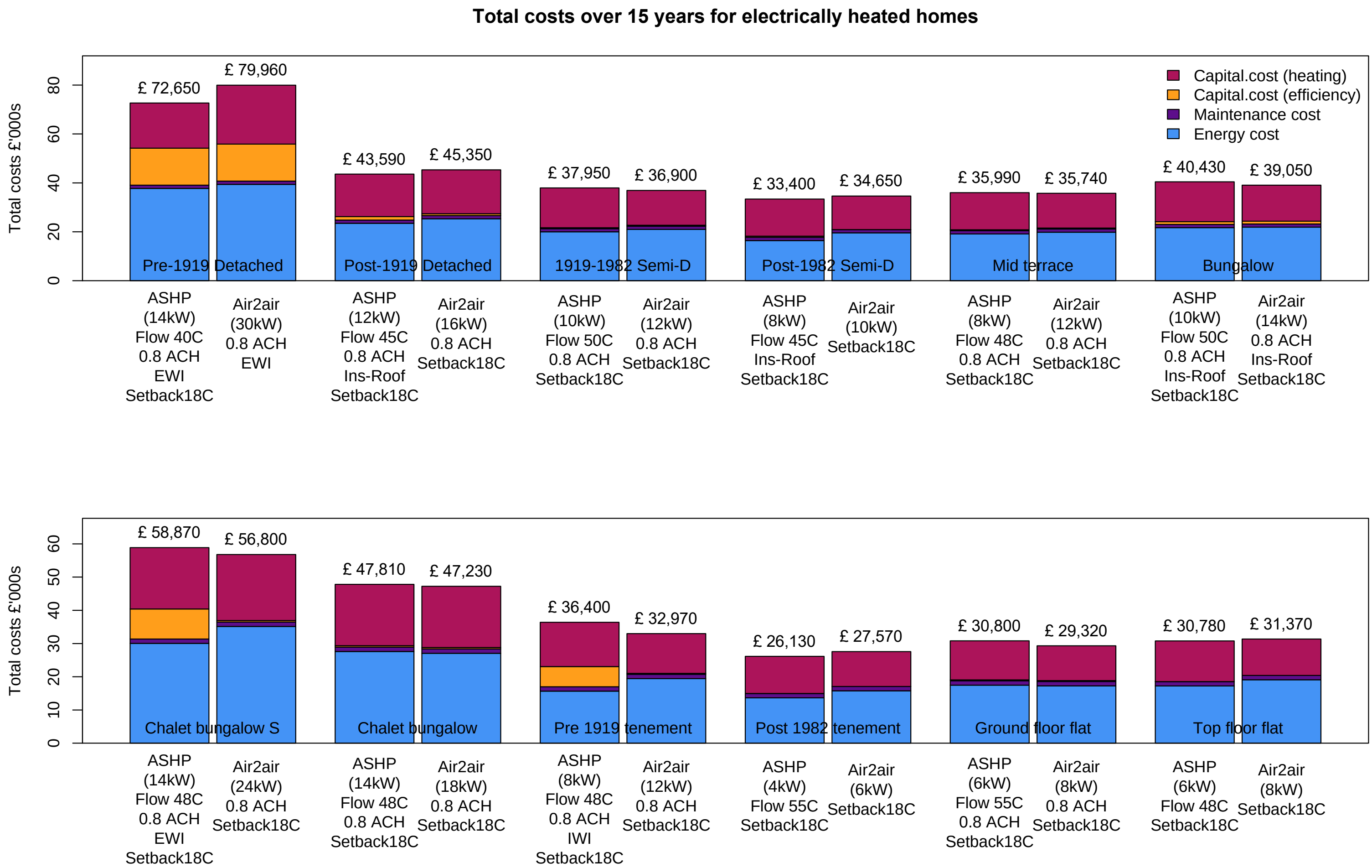


Table 19 below compares before and after running costs for the homes starting with electric heating (storage radiators). All energy costs fall considerably, even though the storage heaters originally used off-peak electricity, moving to standard electricity prices after the upgrade.

Table 19. Annual costs for electric homes

				Before	After
	Archetype	**Efficiency measures**	**New heating system***	**Annual cost baseline (£)**	**Annual cost upgraded (£)**
1	Detached with solid walls	AT; EWI	ASHP 14 kW 40 C	5,020	3,280 (-35%)
2	Detached with cavity walls	AT; Roof Ins	ASHP 12 kW 40 C	3,270	2,080 (-36%)
3	Inter-war Semi-D with timber frame	AT; Roof Ins	Air2air 12 kW	2,520	1,870 (-26%)
4	Modern Semi-D	Roof Ins	ASHP 8 kW 45 C	2,160	1,490 (-31%)
5	Mid-terrace house with timber frame	AT	Air2air 12 kW	2,370	1,770 (-25%)
6	Bungalow with cavity walls	AT; Roof Ins	Air2air 14 kW	2,970	1,950 (-34%)
7	Chalet-bungalow with solid walls	AT	Air2air 24 kW	4,330	3,060 (-29%)
8	Chalet-bungalow with cavity walls	AT	Air2air 18 kW	3,630	2,380 (-34%)
9	Tenement-flat with solid walls	AT	Air2air 12 kW	2,570	1,740 (-32%)
10	Modern Tenement flat	none	Storage radiators 5.5 kW	1,640	1,640
11	Ground-floor 4-in-block flat with timber frame	AT	Air2air 8 kW	2,260	1,560 (-31%)
12	Top-floor 4-in-block flat	Roof ins	ASHP 6 kW 48°C	2,100	1,550 (-26%)

*As before, the flow temperature is optimised according to the energy efficiency and emitter area of each house type, so dwellings with better efficiency and/or larger radiators have lower flow temperatures. Air to air heat pumps have no hot water circuit, so there is no conventional 'flow temperature'.

Table 20 below shows the capital costs, broken down into energy efficiency measures and installing the heating system, as before. The efficiency measures are the same as the gas/oil cases above (except for Chalet Bungalow with solid walls, which drops EWI), but the heating installation costs are different, because they include the cost of new radiators and pipework, or give a different heating system altogether. Capital costs for air to air heating systems are around 7% lower than ASHPs. In general, heating system capital costs are higher for these homes that start with storage radiators than those starting out with gas/oil heating - on average 15% more for homes adopting a heat pump.

Table 20. Capital costs for electric homes

	Archetype	Heating system*	Heating installation (£)	Efficiency measures (£)	Total cost (£)
1	Detached with solid walls	ASHP 14 kW 40 C	18,460	15,130	33,590
2	Detached with cavity walls	ASHP 12 kW 45 C	17,370	1,420	18,790
3	Inter-war Semi-D with timber frame	Air2air 12 kW	14,220	380	14,600
4	Modern Semi-D	ASHP 8 kW 45 C	15,180	470	15,650
5	Mid-terrace house with timber frame	Air2air 12 kW	14,220	370	14,590
6	Bungalow with cavity walls	Air2air 14 kW	14,700	590	15,850
7	Chalet-bungalow with solid walls	Air2air 24 kW	19,880	1,150	20,030
8	Chalet-bungalow with cavity walls	Air2air 18 kW	18,440	430	18,870
9	Tenement-flat with solid walls	Air2air 12 kW	11,940	290	12,230
10	Modern Tenement flat	Storagerad 5.5 kW	0	0	4,860
11	Ground-floor 4-in-block flat with timber frame	Air2air 8 kW	10,480	270	10,750
12	Top-floor 4-in-block flat	ASHP 6 kW 48 C	12,260	0	12,260

These results suggest that air to air heat pumps could be a cost effective and less disruptive solution to reduce carbon emissions and running costs for electrically heated homes. Moving from storage radiators to an air to air heat pump cuts annual carbon emissions by an average of 54% per year across the archetypes (similar to ASHP, which reduces emissions by 52% on average). However, these have the disadvantage that the heat pump does not heat hot water, so that an immersion heater is required and that increases annual costs compared to a wet heating system. Also, to date, air to air heat pumps have never been included in any grant schemes. This could be a cost disadvantage.

Changing to a heat pump can also reduce peak demand on the local grid, compared to either direct electric heating or storage heaters. Storage heaters draw power at off-peak times, but they need to store enough heat for the whole day in a few hours of off-peak tariff time. This means their maximum power draw is higher than a direct electric system would be, and much higher than that of a heat pump.

Heritage homes

Approximately half of all solid-wall properties are classified as 'heritage', because they are listed or located in a conservation area[46] and planning requirements may therefore preclude the installation of insulation on external walls, requiring this to be done from the inside. For the Pre-1919 detached house, the area of walls makes internal wall insulation (IWI) much more expensive than external wall insulation (EWI) - more rooms means it takes longer to install IWI, increasing labour costs, and more materials are needed. It is possible that costs could be reduced by using a mixture of IWI and EWI depending on planning requirements. However, in any case this affects a small number of homes – this archetype accounts for less than 1% of homes.

The Chalet bungalow with solid walls (which is twice as common as Pre-1919 detached houses), has fewer rooms, which means that IWI has similar cost to EWI. Running costs are also very similar.

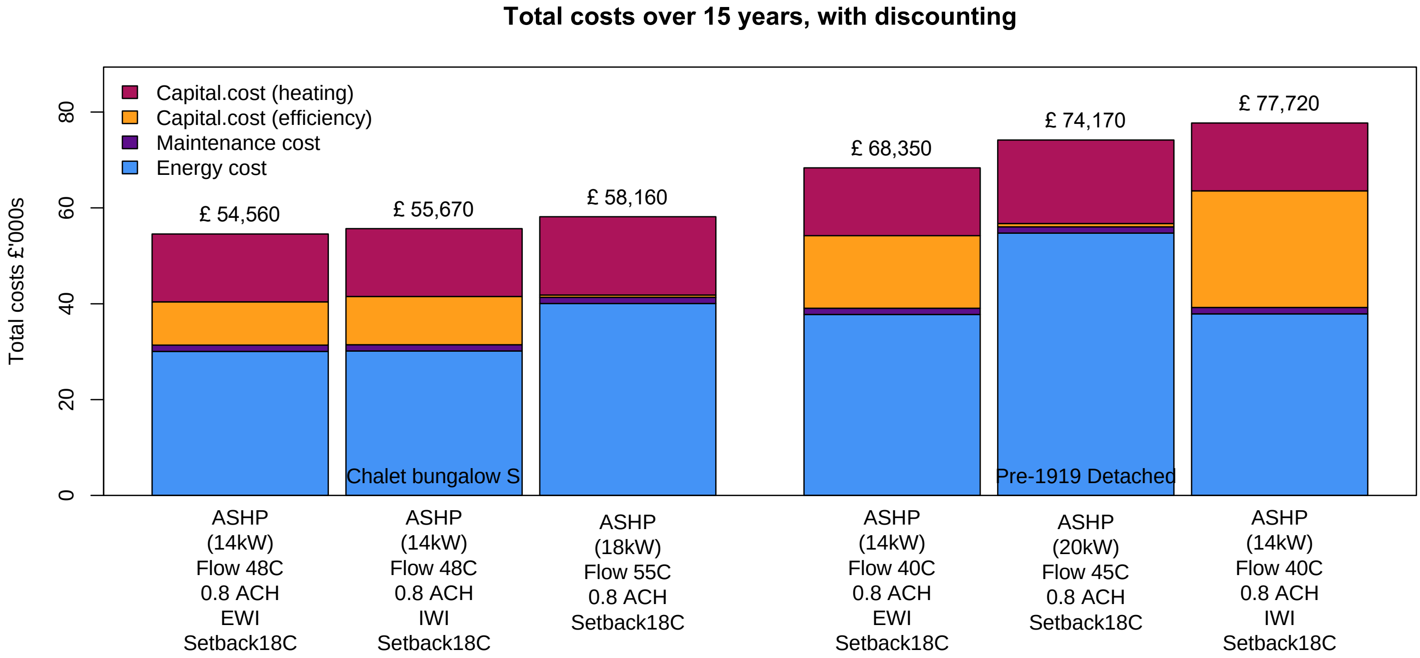
Figure 24 below shows the impact of EWI and IWI on the costs for the two Pre-1919 houses, when costs are considered over 15 years. There is very little difference in the Chalet bungalow case, but for the Detached home the increased costs of IWI compared to EWI (60% higher capital cost) almost offset the annual savings. As before, the discount rate is 3.5%.

The figure illustrates that in the most common house types, heritage status alone does not lead to a significant increase in cost; for larger, more complex homes with more rooms, heritage status likely leads to higher cost, but for average-sized dwellings there is only a small difference. The costs for large, solid-wall homes suggest that not installing wall insulation is more cost effective than IWI. However, reducing energy use and bills (which are 4% lower per year with wall insulation), and carbon emissions (which are 45% higher per year without any wall insulation) are still good reasons for requiring such homes to install IWI.

In both cases, a high temperature ASHP without any wall insulation has significantly higher overall costs than the low temperature ASHP without internal/external wall insulation. This is because the homes have enough energy efficiency (the baseline with added draught proofing) and large enough radiators to operate low temperature heat pumps at efficient flow temperatures. Fitting heat pumps into these homes with lower than baseline energy efficiency (e.g. without adequate loft insulation and/or double-glazing), where high temperature heat pumps are often required, was also modelled when we looked specifically at dwellings below-baseline efficiency, but this was not cost-effective.

[46] Element Energy (2020) Technical Feasibility of Low Carbon Heating in Domestic Buildings. Edinburgh: Scottish Government.

Figure 24. Costs for internal and external wall insulation, and no wall insulation



Space-constrained homes

Whether space constraints act as a barrier to installing heat pumps in smaller dwellings is a controversial question. Some past studies (including the Energy Systems Catapult[47]) do not cite size as a barrier, whereas others (like Element Energy[48]) do view this as an important impediment. We considered this carefully and explored different options for modelling heat pumps in smaller dwellings. Ultimately we decided that space constraints may be limiting for some house types – the terraces, single-storey bungalow, and the semi-detached houses – a total of 344,000 homes (13.8% of the stock, 65% of which are houses).

For these homes with space constraints (those with average habitable rooms below 18m^2) heat pumps are presumed to be too large except for air to air heat pumps – because there is not sufficient space for the internal unit of an air-source heat pump. (This threshold is consistent with Element Energy's work.)

Upgrades are the same for all archetypes whether they have gas/oil and electric in the base case. The majority of homes move to air to air heat pumps, which have small wall-mounted internal units internally (rather than a large single internal unit for ASHP, which is likely to be bigger than the boiler it replaces). Further, in house types where there was a combi boiler in the base case, space constraints preclude a hot water cylinder, so an instant hot-water system is installed[49]. These typically have lower flow rates than combi or system boilers, so it may take longer to run a bath, and shower pressure may be more limited, but otherwise the difference would scarcely be noticeable, and there is no cylinder, so they do not 'run out' of hot water. The number of hot-water systems depends on the size of the home, typically one

[47] https://es.catapult.org.uk/news/electrification-of-heat-trial-finds-heat-pumps-suitable-for-all-housing-types/

[48] Element Energy (2020) Technical Feasibility of Low Carbon Heating in Domestic Buildings report for Scottish Government's Directorate for Energy and Climate Change.

[49] A 'heat battery' which uses phase-change materials to heat water in more compact form than a traditional cylinder could be an alternative, although it was out of scope for this project.

in the kitchen and one in each bathroom. With space constraints, both the Modern Semi-D and the Modern tenement adopt storage radiators in the modelled cost-optimal solution.

There is little difference between the optimised solutions for constrained and unconstrained electrically heated homes, as most already adopt air to air heat pumps and instant water heaters. In almost all cases, energy efficiency upgrades are the same as for unconstrained homes[50].

Running costs are also similar to dwellings that are not space-constrained. For homes adopting air to air heat pumps, savings are still made in all homes against base case oil (27% lower on average) and electric (31% lower on average). Gas heated homes make fewer running cost savings; three of the eight constrained homes make savings (5% on average) with the rest seeing slightly higher costs (6% more on average).

Capital costs are slightly higher for constrained gas/oil homes than unconstrained ones - on average 9% more for the air to air systems. Costs are higher due to removal of radiators and their replacement with internal A2A units. There is just a marginal difference between constrained/unconstrained capital costs for electric base case homes.

The exceptions are the modern homes (Semi D and Tenement Flat) which adopt storage radiators, with higher running costs (but much lower capital costs). This is so even though these were modelled with storage heaters, which benefit from lower off-peak electricity tariffs. Air to air heat pumps are higher overall cost than storage radiators in these homes due to the high energy efficiency and relatively low energy bills of these homes, which favours low Capex/high Opex solutions. Table 21 below shows the capital costs for both gas/oil and electric baseline cases. Since the energy efficiency measures have mostly not changed (because the same fabric upgrades are cost-optimal), only the heating installation cost is different. (Note that homes 1, 2, 7 and 8 are larger and not space-constrained, so modelling this constraint was not necessary.)

Table 21. Annual costs for space-constrained homes

				Baseline			Upgraded
	Archetype	**Efficiency measures***	**Heating system**	**Annual cost Gas (£)**	**Annual cost Oil (£)**	**Annual cost Elec. (£)**	**Annual cost upgraded (£)**
3	Inter-war Semi-D with timber frame	AT; Roof Ins	Air2air instant 12 kW	1,670	2,230	2,520	1,740 (+4%, -22%, -31%)*
4	Modern Semi-D	none	Storage radiators 12 kW	1,430	1,830	2,160	2,110 (+48%, +15%, -2%)
5	Mid-terrace house with timber frame	AT	Air2air 12 kW	1,650	2,130	2,370	1,770 (+7%, -17%, -25%)
6	Bungalow with cavity walls	AT; Roof Ins	Air2air 14 kW	2,050	2,720	2,970	1,950

[50] There is one change: the Inter-War Semi D adopts top up roof insulation; the higher air to air heat pump running costs make this cost effective.

							(-5%, -28%, -34%)
9	Tenement-flat with solid walls	AT	Air2air-instant 12 kW	1,700	2,330	2,570	1,610 (-5%, -31%, -37%)
10	Modern Tenement flat	none	Storage radiators 5.5 kW	1,020	1,240	1,640	1,640 (+61%, n/a, 0%)
11	Ground-floor 4-in-block flat with timber frame	AT	Air2air-instant 8 kW	1,500	1,940	2,260	1,430 (-5%, -26%, -37%)
12	Top-floor 4-in-block flat	none	Air2air-instant 8 kW	1,370	1,680	2,100	1,620 (+18%, -4%, -23%)

* Efficiency measures have not changed from non-constrained archetypes
** Figures in brackets show percentage difference between baseline and upgraded running costs (gas, oil, electric)

It is possible that these costs are too high, since space constrained homes are likely to be smaller than the archetypes. However, space constraints are not related to size alone, but size relative to the requirements of the residents. The data source for the number of homes that are space constrained[51] used criteria based on size and number of habitable rooms.

Table 22. Installation costs for space-constrained homes

		Gas/oil heating baseline		Electric heating baseline	
	Archetype	**Total CapEx (£)**	**Heating only (£)**	**Total CapEx (£)**	**Heating only (£)**
3	Inter-war Semi-D with timber frame	16,730	15,870	15,080	14,220
4	Modern Semi-D	12,030	11,560	9,110	0
5	Mid-terrace house with timber frame	17,510	17,140	14,590	14,220
6	Bungalow with cavity walls	16,440	15,290	15,850	14,700
9	Tenement-flat with solid walls*	13,350	13,060	12,230	11,940
10	Modern Tenement flat	7,550	7,550	4,860	0
11	Ground-floor 4-in-block flat with timber frame	11,870	11,600	10,750	10,480
12	Top-floor 4-in-block flat	12,100	12,100	10,980	10,980

*Flats and tenements have lower costs for air to air heat pumps because they have fewer rooms, which lends itself to air to air, since these need an internal unit in every room. For the electric base case, no work is required to the wet heating system, and often in flats only one instant water heater is needed.

[51] Element Energy (2020) Technical Feasibility of Low Carbon Heating in Domestic Buildings report for Scottish Government's Directorate for Energy and Climate Change.

Homes on the coast

For coastal locations, heat pumps can still be installed but they need to be corrosion resistant, and this means higher capital costs. Modelling assumes that installing heat pumps near the coast costs £1,000 more – both ASHPs and air to air. The solutions are the same as for typical homes with no constraints.

Current energy prices

We also analysed the lowest cost solutions (over 15 years) with current energy prices (i.e. *without* removing policy costs), based on OFGEM price caps from April 2022. The higher prices make heating efficiency more important. However only a few cases change. The higher energy prices are shown in Table 23, and the outcomes of these higher prices are shown in Table 24 below.

Table 23. Energy tariffs without removing Policy Costs

Fuel	Daytime	Change	Off-peak	Change
Gas	7.36	+3%	7.36	+3%
Oil	10.7	0%	10.7	0%
Electricity – standard	27.93	+23%	27.93	0 +23%
Electricity – Economy 7	33.2	+23%	15.87	+23%

Naturally, increasing energy prices means that running cost are higher in all cases. But how does this affect the cost-optimal solutions? In fact, only four of the 12 house types witness a change in the cost-optimal solutions, see table. For the space-constrained modern semi-D house, where lower energy prices meant that storage heaters were cost-effective, air to air heat pumps replaces them when energy costs are higher. For heritage detached homes with solid walls (where external wall insulation is not allowed), internal wall insulation becomes viable with higher energy costs. This demonstrates the risk of fitting storage radiators and heat pumps without insulation to solid walls, which expose households to increased risk of excessive running costs if energy prices rise.

For the detached house with cavity walls, and the inter-war semi-D, top-up loft insulation is justified more often, and air to air heat pumps become more attractive in space-constrained cases.

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Table 24. Outcomes of higher energy prices

Archetype	Conditions	Original Assumptions (removing policy costs)	Higher Price Scenario (with Policy Costs)	Notes
Modern Semi-D	All fuels, space constrained	Storage radiators and top-up roof insulation	Air to air heat pump and no top-up insulation	The air to air heat pump is more efficient than storage radiators.
Detached with solid walls	All fuels, heritage	No wall insulation	Internal wall insulation	Internal wall insulation is more expensive, but it is worthwhile when the energy price is high.
Detached with cavity walls	All fuels	Top-up roof insulation with air to air heating	Top-up roof insulation in all cases	The air to air heat pump is used in space-constrained cases.
Interwar Semi-D	All fuels	Top-up roof – with air to air-instant heating	Top-up roof insulation in all cases	Air to air heating is used in space-constrained cases.

Reducing running costs

Some of the archetypes have higher running costs after upgrading with new heating systems and efficiency measures, but others have lower running costs. Savings are achieved either by reducing heat loss or by improving heating efficiency. The biggest savings come in those homes which add solid wall insulation. In other cases, heat-loss savings are relatively minor and efficiency is more important.

Improving heating efficiency

ASHPs are more efficient when supplying low temperatures so a low radiator temperature (50°C or less) is good. This may mean radiator upgrades in order to achieve comfort. However, since hot water heating requires higher temperatures, low temperatures for space heating are less important when hot water demand is a large fraction of overall heating demand. For example, the cost-optimal temperature is 45°C for both the detached house with cavity walls and the modern semi-D. The SCOP (Seasonal coefficient of performance) for the detached case, where only 10% of the heat demand is for hot water, is 3.1. For the modern semi-D, with 25% of the heat demand for hot water (with a family of four, as opposed to three for the detached), the SCOP is 2.9. (Readers should note that all SCOP figures quoted here are lower than equivalent figures for England because Scotland generally has lower external temperatures than England, which means there is less thermal energy available in outdoor air for the heat pump to use. Gas and oil boilers do not suffer this efficiency penalty resulting from lower temperatures.)

Figures 25 and 26 below show how heating efficiency in the best solutions varies with the hot water ratio and with radiator temperature. Broadly, a higher proportion of heating energy used for hot water means a lower SCOP, and a higher flow temperature to radiators also means a lower SCOP.

Figure 25. Heating efficiency varies according to the fraction of heating used for hot water

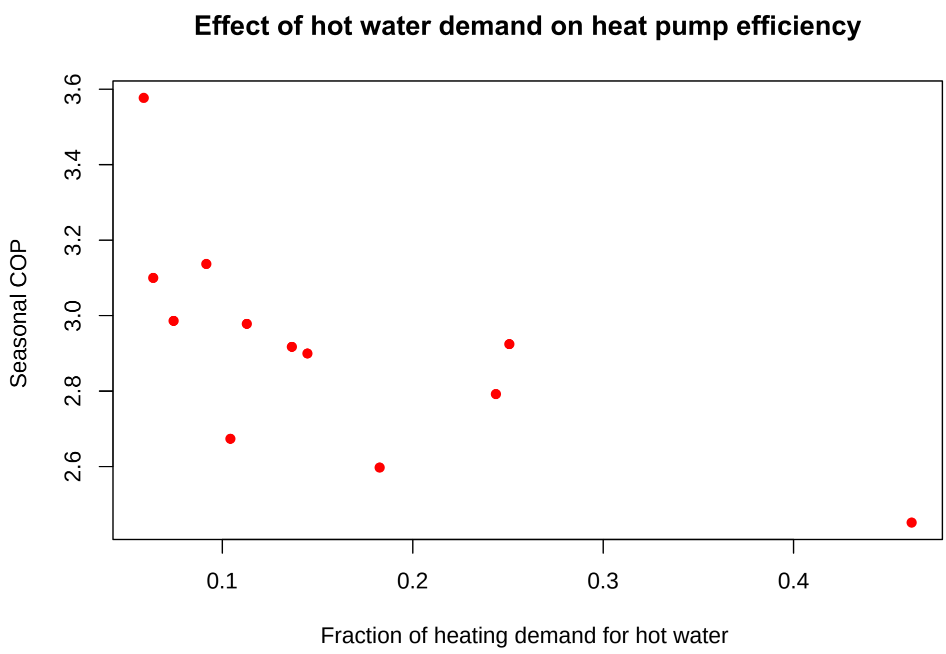
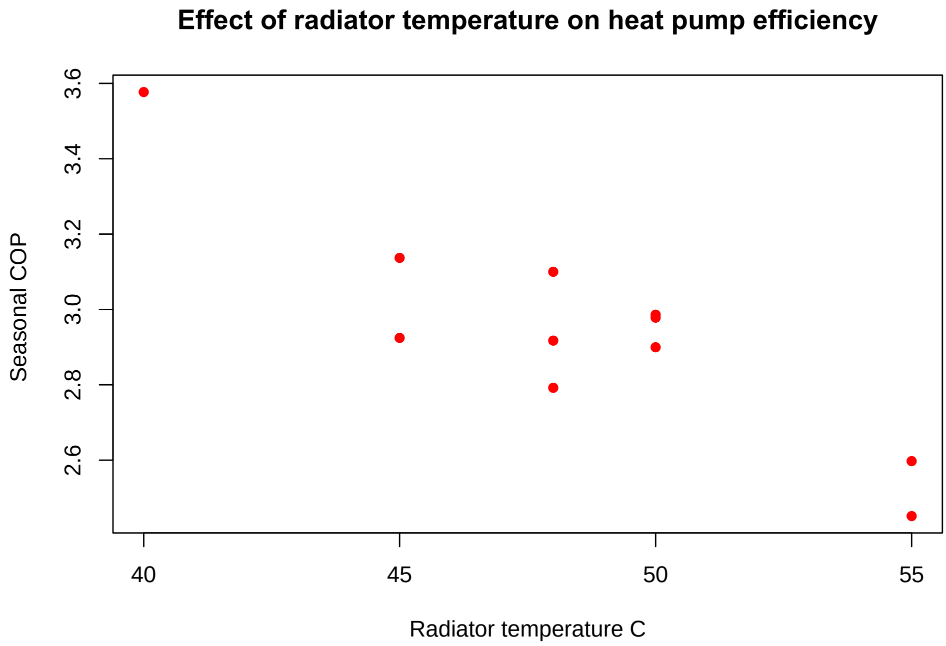


Figure 26 Heating efficiency also varies according to flow temperature to radiators



Lower running cost solutions

In most cases it is possible to achieve lower running costs than the gas baseline with some additional capital cost. Table 25 below shows the lowest cost measures to do so for the homes (with no constraints) that fail to achieve lower running costs against the base case. In most cases this can be achieved with small efficiency measures and/or radiator upgrades which allow a lower temperature. For the modern tenement and the modern semi-D cases, running costs cannot be reduced below the baseline, with the efficiency measures we have modelled. This is because space heating demand in these homes is low and hot water consumptions is a high proportion of the heat demand. In these cases, a solar thermal heating system could be beneficial (although modelling this is beyond the limits of this study).

The tenement with solid walls is the only case that uses an air to air heat pump instead of an ASHP. In this case it is possible to reduce running costs by using a lower setback temperature, but this would necessitate a larger heat pump, large enough to heat the flat up to comfort temperature quickly in the morning.

Table 25. What additional measures would reduce running costs (against the gas base case) further than the optimised solutions?

	Archetype	Running costs increase (£/year)	Measures	New running cost increase (£/year)	Capital cost of measures (£)
3	1919-1982 Semi-D	117	Rad+50%; top-up roof insulation	-2	2,350
4	Modern Semi-D	56	Triple glazing; floor insulation	36	9,000
5	Mid Terrace	65	EWI*	-36	7,090
9	Tenement with solid walls	38	Reduce setback temperature to 16°C; increase air to air heat pump size to 18kW	-16	1,440
10	Modern tenement	238	Rad+100%	148	1,750
11	Ground floor flat	72	Rad+50%	-43	1,400
12	Top floor flat	181	Rad+20%; top-up roof insulation	110	1,750

**External wall insulation is still the lowest-cost way to reduce running costs below baseline, even though this house type has insulated cavity walls to begin with. (Insulating externally normally allows thicker insulation than the cavity width alone, which is normally 50mm.)*

Other strategies for reducing running costs

Early optimisation runs which included solar PV selected it as an upgrade measure, with high electricity prices resulting in the savings from PV offsetting its capital costs and reducing overall running costs. The initial results suggested that solar PV is currently economically viable for households that can afford it, and it could also be a strategy to ensure lower running costs in fuel poor homes – provided they are supported to meet capital costs.

Time of Use Tariffs reward consumers for using electricity at periods of low demand, and avoiding use at periods of high demand. This can help to lessen the strain on the grid, ensure maximum usage of clean renewable electricity, and reduce bills. Prior to the spikes in energy prices in 2021/22 these tariffs could be used in conjunction with a heat pump to reduce overall running costs. In well insulated homes the heat pump can be turned up before, and lowered during, peak pricing periods (typically 4 -7pm). At present, few Time of Use Tariffs are available, as many energy suppliers have temporarily removed them from the market in response to the current volatility of energy prices. Those that remain are currently unattractive compared to standard tariffs.

However, Time of Use (TOU) Tariffs could well become more common as more homes are converted to cleaner electric heating, and the energy suppliers are likely to make them more attractive to help address periods of very high demand without huge investments in electricity networks. It remains uncertain how the conventional and TOU tariffs will evolve, but it is possible that the running costs of heat pumps will fall in future, provided they are able to make use of cheaper low-demand electricity prices.

Efficiency upgrades and fabric standards

This part of the report focuses on energy-efficiency measures that may accompany heat pumps to make heat pumps run more efficiently. These measures include loft, wall and floor insulation, double glazing and draught-stripping.

Towards a fabric efficiency standard for Scotland

There are many ways to measure the energy efficiency of a house, depending on what is allowed for. Starting with the simplest, the main ways are:

1. The heat-loss, or heat-transfer coefficient (HTC, W/K – Watts per degree of temperature difference). This can be normalised by the floor area as the heat-loss parameter (HLP, in W/K m^2). This is based on heat loss from the fabric only – by conduction through walls and through air leakage.
2. The space heating demand (kWh/year/m^2) is the total space heating demand over a typical year. This takes into account the heating regime (thermostat settings and timings) and also heat gains from the sun through windows and from the occupants of the house: their use of lighting and appliances, and even their presence in the house. It also takes into account typical weather for the location.
3. The energy consumption (kWh/year) describes how much energy is needed to supply that demand and other energy needs of the household. It depends on the efficiency of the heating system and also includes the energy demand for other services: lights, appliances and hot water.
4. Cost of energy (£/year) – which depends on the amount of energy used and energy prices.

The current definition of EPC grade is based on the cost of energy bills (4). However, the practicalities of the transition to heat pumps depend mainly on heat loss (1) and space heating demand (2). This is because of key issues such as:

- Heat pumps are more efficient when supplying lower temperatures than boilers. Can the space heating demand be supplied by existing or possibly upgraded radiators, at a flow temperature that a heat pump can deliver efficiently?
- Radiators running at lower flow temperatures are less responsive (i.e. they take longer to heat a dwelling) and heat pumps work more effectively at constant or nearly constant thermostat temperatures. Will this lead to excessive heat loss when high temperatures are not needed – for example, overnight?

Upgrades for typical homes

Table 26 below shows the heat loss, normalised for floor area (HLP) and the space heating demand for the cost-optimal improvement levels. The results are the same for all the archetypes, regardless of the baseline heating system: gas, oil or electric[52]. Costs are moderate except for external wall insulation (EWI) – this would be expensive for any dwelling, and it is particularly expensive for the detached house with solid walls, as it is so large. Fortunately, this only affects a small proportion of the stock, no more than 1.4%.

Readers should note that all archetypes in the base case are relatively well insulated, with at least 100mm of loft insulation, double glazing, and insulated cavities for homes with cavity walls. Although representative of the average Scottish home (and therefore a suitable baseline for the archetypes) some homes do not have all of these measures already installed. The number and cost of these 'below baseline' measures are discussed in the 'Baseline insulation cases' section which follows.

Table 26. Cost-optimal measures and the resulting heat loss and space heating demand

	Archetype	Baseline measures	Additional measures	Capital cost per home (£)	Space heating demand (kWh/year /m²)	Heat Loss (HLP) (W/K/m²)
1	Detached with solid walls	100mm roof insulation, double glazing	air tightness measures; EWI (3/4)	15,130	75	1.8
2	Detached with cavity walls Post 1919	Cavity wall insulation; double glazing, floor insulation; air tightness	air tightness measures; top-up roof insulation (5/5)	1,420	65	1.5
3	Inter-war semi-D with timber frame	Cavity wall insulation; 50 mm roof insulation; double glazing;	air tightness measures (3/5)	380	83	2.1
4	Modern semi-D	Cavity wall insulation; floor insulation; air tightness	top-up roof insulation (5/5)	470	50	1.5
5	Mid-terrace house with timber frame	Cavity wall insulation; double glazing	air tightness measures (3/5)	370	74	1.9
6	Bungalow with cavity walls	Cavity wall insulation; double glazing	air tightness measures; top-up roof insulation (4/5)	1,150	84	2.2
7	Chalet-bungalow with solid walls	100mm roof insulation; double glazing	air tightness measures; EWI (3/4)	9,040	100	2.0

[52] When upgrading from electric storage heaters the chalet bungalow with solid walls has lowest costs without external wall insulation (and an air to air heat pump), but the difference is very marginal compared with ASHP and EWI.

8	Chalet-bungalow with cavity walls	Cavity wall insulation; 100mm roof insulation; double glazing	air tightness measures (3/4)	430	99	2.1
9	Tenement-flat with solid walls (mid floor)	Double glazing	air tightness measures (2/4)	290	117	2.3
10	Modern tenement flat (mid floor)	Cavity wall; floor insulation; double glazing; air tightness	None (4/4)	0	36	1.1
11	Ground-floor 4-in-block flat with timber frame	Cavity wall insulation; double glazing	air tightness measures (3/4)	270	77	2.0
12	Top-floor 4-in-block flat	Cavity wall insulation; double glazing	None (2/4)	0	59	1.6

*All archetypes have 150mm loft insulation at baseline unless other value stated
**Brackets indicate the total number of fabric upgrade measures applied from those available – note that top-up roof insulation is not available for the detached house with solid walls (because it has a room-in-roof), chalet bungalows or ground/mid-floor flats.

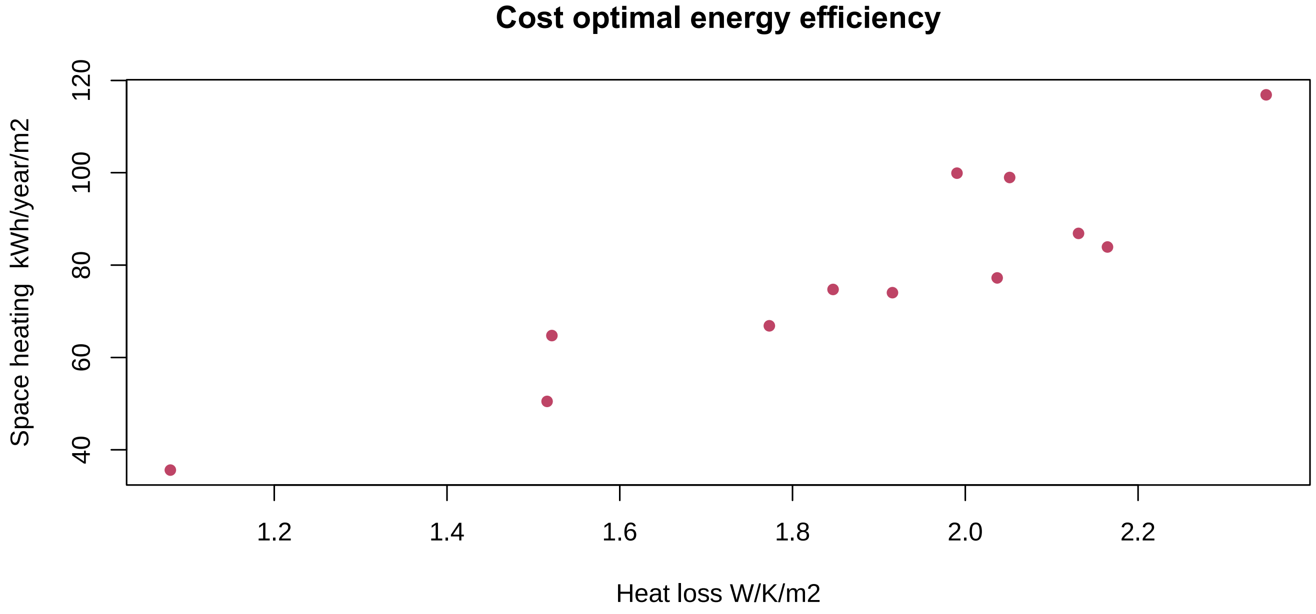
Table 27 below shows how much gas would be saved with the cost-optimal packages of fabric measures. The percentage energy savings shown would be the same for oil and electric heating, although cost savings would be higher for oil and much higher for electricity.

Table 27. Cost savings from energy efficiency measures

		Baseline Gas Use (kWh)	Gas Use with Energy Efficiency Measures (kWh)	Gas Saved (kWh)	Cost Saving	Percentage Gas Saved
1	Detached with solid walls	51,171	28,081	23,090	£1653	45%
2	Detached with cavity walls	20,774	16,002	4,772	£342	23%
3	Inter-war Semi-D with timber frame	14,938	13,653	1,285	£92	9%
4	Modern Semi-D	10,654	10,137	517	£37	5%
5	Mid-terrace house with timber frame	12,816	11,694	1,123	£80	9%
6	Bungalow with cavity walls	17,884	14,098	3,786	£271	21%
7	Chalet-bungalow with solid walls	33,370	23,306	10,164	£728	30%
8	Chalet-bungalow with cavity walls	24,005	20,367	3,638	£260	15%
9	Tenement-flat with solid walls	16,866	14,182	2,684	£192	16%
10	Modern Tenement flat	5,895	5,895	-	-	0%
11	Ground-floor 4-in-block flat with timber frame	11,566	8,688	2,877	£206	25%
12	Top-floor 4-in-block flat	8,268	8,268	-	-	0%

Figure 27 below displays the same data, showing the relationship between heat loss and space heating demand. There is some correlation, but there are other factors. For example, the bungalow and the tenement with solid walls both have high HLPs, but the occupants of the bungalow use more appliances (they are in during the day), which means there are more heat gains to offset the losses and space heating demand is less. Homes with a combi boiler have higher space heating demand than homes with a hot water cylinder, because losses from the cylinder contribute additional gains – and there are also differences due to window orientation and solar gains, number of occupants, and so on.

Figure 27. Fabric energy efficiency for the cost-optimised heating cases



Three energy efficiency upgrades are adopted in the model: air tightness, loft top-up and external wall insulation, with five of the 12 archetypes adopting extra insulation. This rises to ten once homes adopting draught proofing are included. This level of draught proofing implies a higher proportion of homes requiring energy efficiency upgrades than other studies (that have typically looked at bringing all homes to EPC C). This is likely due to a higher standard of draught proofing upgrade being assumed here (to 0.8 air changes/hour). It also reflects the available, albeit limited, evidence which suggests that there is still significant potential to improve the majority of homes to this level of air tightness[53].

All the archetypes benefit from air-tightness measures except post 1982 homes and the Top-floor flat, which all start from a very good standard of air tightness. Air tightness is usually low cost and very effective. With timber suspended floors, sealing between the floorboards is very important as well as the usual windows and doors, skirting boards, loft hatch and any penetrations for services. It is important to retain some ventilation however. We have used an air tightness target of 0.8 air changes per hour, which normally gives sufficient fresh air and should be achievable without extreme measures requiring airtightness membranes taped around windows, doors and other penetrations through the building envelope.

Top-up roof insulation is recommended in cases where there is a significant area of roof, and it is not already insulated to a depth of 300mm. It is selected in three of six cases where it could be installed. It could not be installed in homes with attic roofs – that is the Detached house with solid walls or the Chalet-bungalows. These homes have loft rooms with insulated sloping roofs and it would not normally be possible to install top-up loft insulation because this would lower the ceilings and there would be insufficient head room in these rooms after

[53] For relevant literature see: Milner et al (2014) Home energy efficiency and radon related risk of lung cancer: modelling study; Johnston, D and Miles-Shenton, D (2009) Airtightness of UK dwellings. In: Proceedings of the Construction and Building Research Conference. UNSPECIFIED, London, 271 – 280; J Love et al (2017) 'Hitting the target and missing the point': Analysis of air permeability data for new UK dwellings and what it reveals about the testing procedure. Energy and Buildings Volume 155, 15 November 2017, Pages 88-97.

insulating. It is not selected for small homes such as the mid terrace house and the top floor flat, because the fixed costs of installing roof insulation are not worthwhile for the marginal savings in heating. Loft insulation is only selected in homes that have a large roof area to insulate.

All archetypes also have insulated cavity walls to start with. Where cavity walls are unfilled it would be cost-effective to install this (see next section). Solid-wall archetypes benefit from insulating the walls, except for the tenement (mid floor). For this dwelling the area of external walls is not large, providing a lower energy saving relative to the fixed costs of this measure (though there are quite a lot of walls to communal stairwells which, although they are not heated, are much less exposed to the weather). In practice, EWI would normally be applied to a whole building rather than a single flat within it, which would improve the economics of this measure by pooling the fixed costs (e.g. scaffolding) between multiple homes.

For homes with solid walls that have a large area of external wall, like the Pre-1919 detached houses and chalet bungalows, solid-wall insulation is usually beneficial. This can be internal or external but, for most homes, external wall insulation costs less than internal, and is also much less disruptive. Until recently, it was usual to install external wall insulation only to just above the damp course, but this leaves a cold bridge which can lead to condensation. Under current rules in PAS 2035[54], insulation would need to be continued below the damp course and floor insulation may also be required. However, careful detailing of the junction between the insulation, the damp course and the joists may make this unnecessary. There are similar issues for internal wall insulation.

It is technically possible to install larger heat pumps without SWI in homes with solid walls, but this increases the total costs of ownership because of higher energy bills, see Table 28 below.

Table 28. Costs for solid wall houses with and without external wall insulation (gas baseline)

Archetype	Baseline	With EWI			Without EWI		
	Annual Energy bill	Capex	Annual Energy bill	Total Cost of Ownership	Capex	Annual Energy bill	Total Cost of Ownership
Detached with solid walls	£4,890	£29,280	£3,280	£68,350	£18,110	£4,700	£74,170
Chalet bungalow (solid walls)	£3,270	£23,190	£2,630	£54,560	£16,800	£3,470	£58,160

Not fitting solid wall insulation to these properties saves them up to £11,170 in upfront capital costs, but running costs are higher than with EWI - £1,420 more per year for the large, detached home and £840 more for the smaller chalet bungalow (although running costs without EWI are similar or lower than baseline running costs for gas or oil). Total

[54] BSI (2019) PAS [Publicly Available Specification] 2035: 2019 Retrofitting Dwellings for Improved Energy Efficiency – Specification and Guidance. London: BSI.

lifetime costs over 15 years (discounted) for these archetypes without external wall insulation are on average £4,700 more than with a heat pump and external wall insulation. Omitting EWI also increases carbon emissions and puts a greater burden on the electricity grid because more electricity is required to operate the heat pumps.

All of the archetypes already have full double glazing. Adding triple glazing reduces heat losses, but also solar gains. Overall, triple glazing is not cost effective: discounted bills savings do not repay the capital costs over 15 years. If there was no double glazing in a dwelling to start with, typical costs would be £7,460 for installing 100% double glazing; in many cases it would be cost effective over 15 years to install (and where it is not, there are comfort and condensation benefits to a household of installing it).

Note that none of the house types select floor insulation through optimisation. The two post-1982 homes and the detached house with cavity walls already have insulated floors, but it is not cost-effective for any of the older homes because it is high cost (typical costs of £4,080). Floor insulation is sometimes recommended for use with heat pumps[55], but ScotCODE modelling indicates that it is not necessary. Floor insulation would be needed for most house types to go below 65-85 kWh/m^2 for space heating (depending which house type), but this would bring substantial extra costs.

Upgrades for heritage and space-constrained homes

For each house type we modelled other situations that affect what upgrades are feasible: heritage status (either being listed, or in a conservation area, which affect a proportion of older homes) and space constraints (where there is insufficient space for the internal unit of a heat pump and/or a hot-water cylinder, or internal wall insulation, which affect a proportion of the smaller homes).

For listed homes or those in conservation areas, external wall insulation (EWI) is not normally allowed under planning rules, so the two archetypes that adopt EWI in the unconstrained case are modelled without EWI. Internal wall insulation (IWI) is allowed and selected for the bungalow, but it is 60% more expensive than EWI for the very large detached house: EWI has high fixed costs but relatively low variable costs, dependent on wall area. IWI has low fixed costs but high variable costs, dependent on the number of rooms (with more rooms making installation more fiddly and time-consuming). The cost difference is moderate for the chalet bungalow with solid walls. However, for the detached house with solid walls, IWI costs more and this cost outweighs the benefits. In practice it may be possible to apply EWI on part of the house (often the rear), even in a heritage area.

Space-constrained homes are modelled without the option of IWI, given that internal space is presumed to be at a premium. In practice, IWI is not selected for any upgraded homes, EWI being lower cost. The only space constrained *and* solid walled archetype (pre-1919 tenement) which could be affected by this constraint does not select wall insulation of any kind. In any case, there are a small number of these homes - less than 0.8% of the stock.

Minimum standard

Most of the houses end up with a space heating demand of 65-85kWh/m^2/y, which is suitable for installing a heat pump: enough for the houses to meet the desired level of

[55] It is required where underfloor heating is used.

heating on cold days, without very high flow temperatures (i.e above 50°C) that would make the heat pumps operate less efficiently.

The Modern semi-D is exceptional with very low space heating demand (50 kWh/m^2/year) – it has low heat loss even without the top-up roof insulation, but this is an inexpensive measure and is worthwhile at current electricity prices. The chalet bungalows have higher heating demand (c.100 kWh/m^2/year) driven by their large roof area and attic rooms that are expensive and disruptive to insulate. Floor insulation would be an alternative but is relatively expensive and not found to be cost effective.

These findings suggest that 65-85kWh/m^2 is a reasonable maximum heating-demand target for houses to aim for, with some flexibility for difficult cases, for example the Chalet-bungalows with rooms in the roof, which make roof insulation more difficult and bring problems with insulating sloping ceilings. A lower figure could be set for more modern (e.g. post 1982) homes, which have a better starting point for energy efficiency but still benefit from improvements to lower heat pump running costs.

Space heating demand per m^2 in the upgraded flats is on average lower than for the houses, partly reflecting the lower ratio of external walls to floor area. This suggests that minimum standards could be set lower these types of dwelling. The exception is the Pre-1919 tenement flat, where further flexibility could be needed as external wall insulation is not justified on purely cost grounds over 15 years.

Proposed standards in the Netherlands give an example of the approach that could be taken in Scotland. There, a net heating demand target for dwellings varies both with the age of a dwelling and the ratio of floor to wall area, with very similar thresholds to the 'cost effective' fabric upgrades in our work).[56] This is currently a voluntary standard for landlords and building owners, but it could become mandatory in the future. The Dutch standards for four house types are shown in Table 29 below.

Table 29: Dutch voluntary standard for minimum fabric efficiency (targets)

Example/reference house	Proposed standard	
	Floor area and compactness	Net heat demand (kWh/m^2)
Mid terrace, built 1920	103.6m^2 1.8*	144
Detached house, built 1988	225.4m^2 2.1*	87
Apartment built, 1925	47.4m^2 1.3*	116
Apartment built, 1968	92.1m2 0.9*	45

* Sum of external surfaces of the building divided by total floorspace

Source: RAP, 2022

[56] Regulatory Assistance Project, RAP (2022) How much insulation is needed? A low-consumption, smart comfort standard for existing buildings. Brussels: RAP. https://www.raponline.org/wp-content/uploads/2022/05/rap-sunderland-insulation-standard-2022-may-4.pdf

Scotland could introduce similar targets, possibly using the 12 house types here that are representative of Scottish homes.

However, lower heating demand would be better still, if it can be achieved at a reasonable cost. With heat pumps, energy use reduces faster than heat demand (in general), as lower heat demand allows lower flow temperatures and higher efficiencies. Often it also reduces the size of the heat pump that is needed, which reduces capital costs, and it always reduces running costs.

The Scottish Government has previously committed to bringing all homes to at least an Energy Performance Certificate (EPC) C rating[57]. The cost optimal efficiency measures (i.e. improvements in building fabric: insulation and air tightness) achieve at least EPC grade C in all cases. [58] (For the modern tenement apartment, the EPC grade was B even in the unimproved base case, and we did not add any further measures).

Table 30 below compares the EPC cost ratings for different house types in the baseline state and in the improved state.

Table 30. Cost-optimal upgrade EPC ratings

	Archetype	Measures	EPC rating (improved)
1	Detached with solid walls	air tightness measures; EWI	71 (C)
2	Detached with cavity walls	air tightness measures; top-up roof insulation	77 (C)
3	Inter-war Semi-D with timber frame	air tightness measures	72 (C)
4	Modern Semi-D	top-up roof insulation	77 (C)
5	Mid-terrace house with timber frame	air tightness measures	74 (C)
6	Bungalow with cavity walls	air tightness measures; top-up roof insulation	73 (C)
7	Chalet-bungalow with solid walls	air tightness measures; EWI	72 (C)
8	Chalet-bungalow with cavity walls	air tightness measures	72 (C)
9	Tenement-flat with solid walls	air tightness measures	71 (C)
10	Modern Tenement flat	none	81 (B)
11	Ground-floor 4-in-block flat with timber frame	air tightness measures	73 (C)
12	Top-floor 4-in-block flat	none	77 (C)

[57] Scottish Government, 2021, Heat in Buildings Strategy. Glasgow: SG.
[58] We used the Cambridge Housing Model to evaluate EPC grades, with slight adaptions. The CHM is based on SAP 2012, which includes the latest version of RdSAP, used for EPC ratings. The heating regime is the same as SAP, and we used the default occupancy – based on the floor area – instead of the actual occupancy, matching the method for an EPC.

Baseline insulation cases and cost of upgrading

The baseline for each archetype includes energy efficiency measures that are currently typical for the stock. However, there are still some homes below this standard. Conversely, there are also homes that are above it, for example with more loft insulation, more modern and better performance glazing than we have assumed, or solid wall insulation (18% of homes with non-cavity walls have already been insulated).[59] This section of the report considers the number and cost of bringing less efficient houses up to the base-case standards.

Unless otherwise stated, all costs are derived from J Palmer et al (2017) What does it Cost to Retrofit Homes? Updating the Cost Assumptions for BEIS's Energy Efficiency Modelling.[60] (Inflated to £2022.)

Sloping roof insulation – less than baseline insulation

Some 23% of the total stock has a pitched roof with less than the baseline insulation which is 150mm, or 100mm if there is a room in the roof. We have calculated the cost of upgrading homes excluding homes with no roof and chalet bungalows, where most of the roof is inaccessible.

Flat roofs – less than baseline insulation

Most homes (and all of the archetypes) have at most only a small area of flat roof. Our baseline assumes that these roofs have 50mm of insulation, but some homes with flat roofs have less than this. (Equally, some homes already have more.) There is data about flat-roof insulation in the Scottish House Condition Survey (SHCS), but it is not in the public domain. We estimate that currently 10 to 30% of homes with flat roofs have less than 50mm of insulation – and these are likely to be small sections of roof covering recent extensions rather than a whole roof. Again, assuming that the cost of achieving baseline insulation is the same as we allowed for top-up insulation on flat roofs, the average cost of this per dwelling is £1,340 per dwelling. Since the roof areas are modest, and a small proportion of the total roof area, savings from insulating small areas of flat roof would be minimal – in most cases not sufficient to warrant the investment on cost grounds.

No floor insulation

There is no floor insulation in the baseline except in the modern homes, where Building Regulations required it when the homes were built. (From the SHCS, less than 1% of homes have retrofitted floor insulation, and more than 80% of homes built before 1982 have suspended floors, which bears out the assumed floor constructions.) Therefore, there is nothing to do to bring the homes up to standard. (For homes with poor air tightness, air tightness measures include draught proofing the skirting boards, and these costs are already included.)

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[59] https://www.gov.scot/publications/scottish-house-condition-survey-2019-key-findings/
[60] https://www.gov.uk/government/publications/domestic-cost-assumptions-what-does-it-cost-to-retrofit-homes

Double glazing throughout

The model house types are all defined as having double glazing, which is true for typical homes in Scotland. However, there are some homes that still have single glazing, and the fabric upgrade costs do not include the cost of replacing single-glazing with double.

According to the SHCS data, 8% of homes are not fully double glazed, and for these cases typically half the windows are still single glazed. Pre-1919 tenements are worse: on average they are 86% single glazed, if not fully double glazed.

Fitting double glazing to tenements (and some other homes) may be difficult because of planning barriers in conservation areas and for listed buildings, and even when double glazing is permitted it is often a requirement for conservation buildings to use more expensive traditional designs and materials, sometimes with inferior thermal performance. However, secondary glazing could be fitted instead. The performance of secondary glazing is very similar to double glazing of the type we have used in the baseline, although the best double glazing now is considerably better.

Cavity wall insulation

According to the Scottish House Condition Survey, 27% of cavity walls are not insulated (20% of all homes), but this may be an overestimate as it is becoming increasingly difficult for surveyors to verify the installation. (The injection holes are obscured over time and contractors are getting better at concealing their work.) There is also a barrier to installing cavity-wall insulation in areas that are prone to wind-driven rain (predominantly on the west coast), where CWI can cause damp problems and special measures are recommended to prevent damp ingress. The SHCS considers 14% of the total housing stock have uninsulated cavity walls that can be handled with standard measures. The remainder have 'hard to treat' uninsulated cavity walls which have higher cost. CWI would be cost-effective for the vast majority of homes that currently have uninsulated cavity walls.

Solid wall insulation

According to the SHCS, 25% of homes have solid walls that are not insulated. This is almost all homes with solid walls, and our baseline does not assume any solid wall insulation.

Table 31 below summarises the cost of the upgrades discussed in this section and Table 32 summarises the number of each archetype requiring upgrades.

Other measures

Readers should note also that all baseline archetypes have insulated hot water cylinders (where a cylinder is present) and heating controls: a thermostat to maintain set temperatures and radiator valves to control temperatures within rooms. A small minority (perhaps less than 10%) of current homes may not have these measures already installed[61].

[61] https://www.gov.scot/binaries/content/documents/govscot/publications/progress-report/2016/11/low-carbon-behaviours-framework-key-behaviour-areas-data-scotland/documents/00510259-pdf/00510259-pdf/govscot%3Adocument/00510259.pdf

Table 31. Fabric upgrades for homes that are below the baseline level of insulation

Measure	Fixed cost	Variable cost	Cost for the semi-detached house with cavity walls	Extra energy demand per year for the semi-D with cavity walls (kWh)
Sloping roof insulation (50mm to 300mm)	£180	£8.40/m² (loft floor area)	£600	1,159
Double glazing	-	£414/m² (window area)[62]	£3,730 (for half the windows)	736
Cavity wall insulation (standard)	-	£8.70/m² (net wall area)	£770	3,692
Cavity wall insulation (hard to treat)	-	£26/m² (net wall area)	£2,290	

Table 32. Number of homes of each archetypes requiring upgrades to achieve the baseline level of insulation

	Archetype	Sloping roof insulation	Double glazing	Cavity wall insulation (standard)	Cavity wall insulation (hard to treat)
1	Detached with solid walls	0	3,367	0	0
2	Detached with cavity walls	98,444	19,713	0	0
3	Inter-war Semi-D with timber frame	166,293	33,299	89,865	44,933

[62] 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).

4	Modern Semi-D	0	0	0	0
5	Mid-terrace house with timber frame	93,073	18,637	50,297	25,148
6	Bungalow with cavity walls	117,830	23,595	63,675	31,838
7	Chalet-bungalow with solid walls	0	6,430	0	0
8	Chalet-bungalow with cavity walls	0	14,568	39,316	19,658
9	Tenement-flat with solid walls	0	22,075	0	0
10	Modern Tenement flat	0	0	0	0
11	Ground-floor 4-in-block flat with timber frame	0	19,666	53,073	26,537
12	Top-floor 4-in-block flat	98,211	19,666	53,073	26,537
	Totals	573,850	199,600	349,300	174,650

Total energy efficiency costs

The previous sections have outlined two sets of energy efficiency upgrades in homes: those applied in the optimisation to the base case archetypes, and those required to get homes to that standard. This section brings these two sets of data together to answer the question: 'What will it cost to bring all homes to the optimal level of energy efficiency set out in this report?'

The total capital cost of the 'optimised' and 'below baseline' energy efficiency measures is estimated at £5.5 billion. Split across the whole housing stock this gives an average of £2,210

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per home. However, not all homes will require upgrades – many will already meet or exceed the optimised level of energy efficiency.

How many homes are likely to need upgrades to reach the optimal level of energy efficiency? Energy Performance Certificate rating data in the SHCS for the existing housing stock gives an indication, with 50% of homes already reaching a 'C' rating in 2019. The number of energy efficiency measures added to homes in this study is broadly aligned with this, with 35% of the archetypes[63] adopting extra insulation (loft and solid wall). This rises to 78% when archetypes adopting draught proofing are included. In addition to this, 1.3m measures (loft and cavity wall insulation, and double glazing) must be installed in homes to bring them to the 'baseline' level of energy efficiency. If assigning one measure per home this would equate to 50% of the total stock. In reality, the need for these measures will be concentrated in fewer homes (i.e. some will be missing more than one insulation measure) as indicated by the 360,000 homes with current EPC ratings of E-G.

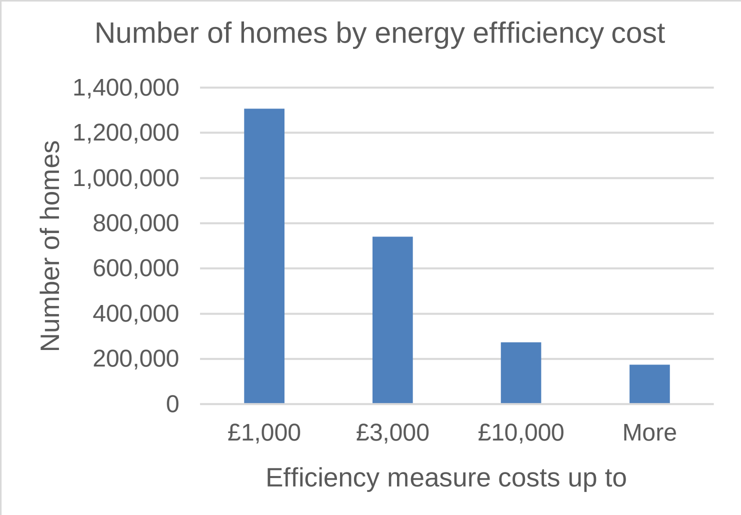
Modelling and optimisation found that 78% of house types will require at least one upgrade to reach the cost optimal level of energy efficiency. This is much higher than those currently below an EPC 'C' rating and reflects the higher rate of draught proofing in this study. The average cost for homes fitting an energy efficiency measure is £2,820.

Readers should note that this figure includes an adjustment to better match the number of uninsulated solid-wall homes (and costs of fitting EWI to most of them) in the housing stock, given the significant share of total capital costs made up by EWI. The initial scaling up of the archetypes (see 'Scaling up' section above) suggested there were 25% fewer homes with uninsulated solid walls than reported in the Scottish House Condition Survey. This was due to simplifications made to keep the number of archetypes manageable. These homes and the costs of fitting EWI to them are included in the total and average capital cost estimates above[64].

Figure 28 below illustrates how these costs may differ between households. The majority of homes will have costs of less than £1,000, which includes roughly 500,000 homes that do not require any upgrade at all, and many that simply require draught proofing. At the upper end of the scale are roughly 175,000 homes with costs of £10,000 or more.

[63] Scaled up to national totals so each is weighted by the number of dwellings it represents.
[64] The 'extra' solid wall homes and EWI costs are all nominally Archetype 7 – Pre 1919 chalet bungalow. In reality, they are a mixture of pre 1919 semi-detached, mid terrace and bungalows.

Figure 28. Number of homes by efficiency costs



The chart above combines the costs of both the optimised energy efficiency measures, and those required to reach the baseline level. The latter are distributed individually to archetypes (i.e. each archetype is missing only one measure) but as discussed above the real-world distribution is likely to be less even, which would slightly increase the number of homes at either end of the cost range.

Table 33 below displays the most common type of energy efficiency upgrade package once both the optimised and below baseline measures are combined. The package affecting the largest number of each archetype is listed.

Table 33. Most common upgrade packages per archetype

	Archetype	Below baseline measures	Optimised measures	Capital cost per home (£)
1	Detached with solid walls		air tightness measures; EWI	15,130
2	Detached with cavity walls Post 1919	Roof insulation	air tightness measures; top-up roof insulation	2,420
3	Inter-war semi-D with timber frame	Roof / cavity wall insulation	air tightness measures	1065
4	Modern semi-D		top-up roof insulation	470
5	Mid-terrace house with timber frame	Roof / cavity wall insulation	air tightness measures	870
6	Bungalow with cavity walls	Roof insulation	air tightness measures; top-up roof insulation	1,330
7	Chalet-bungalow with solid walls		air tightness measures; EWI	9,040
8	Chalet-bungalow with cavity walls		air tightness measures	430

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9	Tenement-flat with solid walls (mid floor)		air tightness measures	290
10	Modern tenement flat (mid floor)		none	0
11	Ground-floor 4-in-block flat with timber frame		air tightness measures	270
12	Top-floor 4-in-block flat	Roof / cavity wall insulation	none	605

Note: 'roof /cavity insulation' indicates that broadly equal numbers of modelled homes require either of these measures. In these cases the capital costs of the more expensive measure appears in the final column (in all cases the cost of the measures is very similar).

Alternative combinations of heating systems

Previous sections of this report focus on just one heating system for each house type. In most cases this is the air-source heat pump, because this works in a similar way to conventional boilers, with a wet heating system, radiators, and a hot-water cylinder. However, we also modelled alternative heating systems installed in each house type, combined with hundreds of different combinations of fabric upgrades. For each possible heating system, the impact of the most cost-effective combination of fabric measures on energy bills is shown in Figure 29 below. Baseline costs (before any upgrades are installed) is shown in grey at the bottom, and the upgraded cases are colour-coded so lighter blue means they are lower, with a square border around the lowest energy costs.

Readers should note that the ASHP is the most cost-effective solution in six out of 12 cases. Air to air heat pumps with instant water heaters ("Air2air instant") are cheapest in the other six cases. This is largely because they have almost no losses from domestic hot water. However, these systems are quite different from what most households are used to, with a separate water heater in each kitchen/bathroom, and fan units (instead of radiators) on the walls. They also mean removing the existing radiators or storage heaters, where these are present. For these reasons most households are likely to reject the Air2air instant option, and opt instead for ASHPs – even if the running costs are a little higher. In most cases the difference in running costs is small, with the highest difference £210 a year (10%) higher, in the case of the Chalet bungalow with cavity walls. Readers should also note that the fabric measures installed alongside the heating systems in the chart may be different – in each case the cost-optimal measures are selected.

Storage heaters are more expensive than the heat-pump options in every case, and the modelling suggests that storage heaters would not provide sufficient heat to provide comfortable heating in the large Pre-1919 Detached house with solid walls.

Figure 29. Annual energy costs of different replacement heating systems, when the homes start out with gas heating

Annual energy cost £/year - for dwellings initially heating with gas

	Pre-1919 Detached	Post-1919 Detached	1919-1982 Semi-D	Post-1982 Semi-D	Mid terrace	Bungalow	Chalet bungalow S	Chalet bungalow	Pre 1919 tenement	Post 1982 tenement	Ground floor flat	Top floor flat
Storagerad	NA	£2,870	£2,350	£2,110	£2,210	£2,580	£3,610	£3,300	£1,970	£1,640	£1,960	£2,030
Air2air instant	£3,190	£1,940	£1,630	£1,570	£1,540	£1,700	£2,820	£2,140	£1,500	£1,250	£1,320	£1,510
Air2air	£3,310	£2,120	£1,760	£1,640	£1,660	£1,840	£2,950	£2,270	£1,630	£1,320	£1,450	£1,600
HT ASHP	£3,630	£2,170	£1,770	£1,550	£1,710	£1,930	£2,720	£2,480	£1,730	£1,140	£1,460	£1,530
ASHP	£3,170	£1,970	£1,680	£1,380	£1,600	£1,820	£2,520	£2,350	£1,310	£1,140	£1,460	£1,440
Baseline	£5,160	£2,470	£1,710	£1,480	£1,720	£2,140	£3,410	£2,670	£1,720	£1,040	£1,560	£1,440

Figure 30 below shows similar figures for the carbon emissions of each house type-heating system combination. Again, the baseline emissions are shown in grey at the bottom, and upgraded cases are colour-coded so that lower emissions appear in lighter green and the lowest-emission combination is shown with a square border. Unsurprisingly (given that all upgraded costs are for electricity), the same cases come out with lowest carbon emissions as lowest energy costs above. This means that six house types would theoretically achieve lower emissions if they used an air to air heat pump with instant electric water heaters instead of ASHPs. However, once again, these would probably be unattractive to most households because this is so different from the central heating they are accustomed to. Readers should note that in all cases there is a very substantial reduction in emissions from the baseline to the cost-optimal package of fabric and heating measures – a saving of more than 90% for the house types with solid walls. (The fabric measures in this chart are the same cost-optimal ones as the previous chart.)

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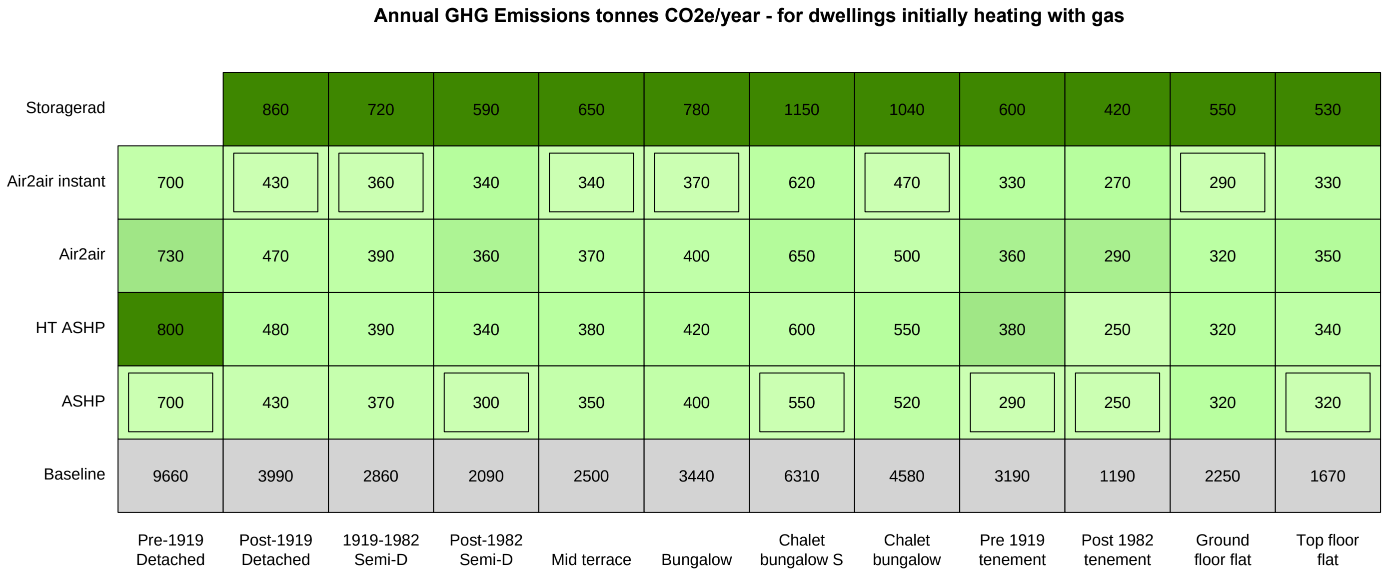
Figure 30. GHG emissions for different replacement heating systems, when the homes start out with gas heating



Stock level carbon emissions savings

The previous section shows carbon savings at the archetype level for particular cases – where the initial heating system is gas and there are no constraints. In this section we discuss the GHG emissions savings at the stock level. Table 34 shows emissions savings by fuel, Table 35 emissions savings by archetype and Table 36 emissions by sector.

Table 34. Emissions for all baseline heating fuels, whole stock

Fuel	Number of homes (1000s)	Baseline emissions (ktCO2)	Upgraded emissions (ktCO2)	Emissions savings (ktCO2)	Reduction (%)
Gas	2,100	6,131	789	5,342	87%
Oil	121	885	61	823	93%
Electricity	274	192	106	87	45%
Total	2,495	7,208	956	6,252	87%

Although homes using oil have greater GHG emissions individually (7.3 tonnes CO_2/year on average, compared to 2.9 tonnes/year for gas-heated homes), there are few of them, so the overall emissions are low. For homes using electricity, there are more of them but the emissions per home are lower, so the overall savings potential from these homes is very low indeed.

From the point of view of emissions savings, there is little need to convert homes that are already heated by electricity to heat pumps. (Because this would bring minimal savings.) However, the *cost* savings for heating with a heat pump versus storage radiators are at least 25%, and even higher for direct heating with standard tariff electricity instead of off-peak.

This saving would be of particular benefit for homes on low incomes. There are 73,000 households using electricity that are on low incomes and recorded as being fuel poor in the 2019 Scottish House Condition Survey. This is 27% of all homes using electricity. The number of homes in fuel poverty today is likely to be considerably higher, because of fuel-price increases since 2019.

How to prioritise homes most effectively comes down to a political decision. If we wish to maximise carbon savings we would convert homes currently using oil-fired heating to heat pumps first and electrically heated homes last, but if we wish to maximise the benefit to households in fuel poverty we would convert homes on oil and electric heating first, and gas heating last. (Oil is 49% more expensive than gas per kWh, so the cash savings are higher for oil-heated homes.)

Table 35. Emissions savings by archetype, whole stock

	Archetype	Number of homes (1000s)	Baseline emissions (ktCO2)	Upgraded emissions (ktCO2)	Emissions savings (ktCO2)	Reduction (%)
1	Detached with solid walls	40	452	34	418	92%
2	Detached with cavity walls	233	938	101	837	89%
3	Inter-war Semi-D with timber frame	393	1,088	144	944	87%
4	Modern Semi-D	131	259	50	209	81%
5	Mid-terrace house with timber frame	258	613	92	522	85%
6	Bungalow with cavity walls	279	931	112	819	88%
7	Chalet-bungalow with solid walls	76	511	43	468	92%
8	Chalet-bungalow with cavity walls	134	619	69	549	89%
9	Tenement-flat with solid walls	261	758	92	666	88%
10	Modern Tenement flat	227	221	72	149	68%
11	Ground-floor 4-in-block flat with timber frame	232	469	74	395	84%
12	Top-floor 4-in-block flat	232	350	74	276	79%
	Total	**2,495**	**7,208**	**956**	**6,252**	**87%**

The modern homes have low savings potential both because there are few of them and because they are already energy efficient – at least, compared to older homes. The highest potential savings are from bungalows – because there are so many of them.

Table 36. Emissions savings by tenure, whole stock

	Number of homes (1000s)	Baseline emissions (ktCO2)	Upgraded emissions (ktCO2)	Emissions savings (ktCO2)	Reduction (%)
Owner-Occupied homes	1,508,394	4,940	610	4,330	88%
Private rented homes	305,774	800	130	673	84%
Social housing	680,832	1,460	310	1,151	79%
Households in fuel poverty (across all three tenures)	611,302	1,090	260	837	76%

Fuel poor homes and social housing have lower reductions potential because they are already at a higher standard of efficiency, on average.

Installation trajectories – how many homes?

We have modelled the impact of rolling out efficiency and heating upgrades to all homes, starting with 5,000 in 2022 and doubling the rate each year, up to 150,000 in 2027. Thereafter installations are maintained at the same rate. We have used these figures because the Microgeneration Certification Scheme recorded 4,655 heat pump installations in Scotland 2021, up from 2991 in 2020. This illustrates two points: first, that there are currently around 5,000 heat pump installations a year in Scotland, and second that the supply of heat pumps in Scotland is growing at a rate of roughly 50% a year.

With these assumptions, by the end of 2030, 760,000 homes will have been converted to low-carbon heating. This is below the Scottish Government's target of 1 million homes. According to our modelling, the target will be met two years later: 2032. Provided Scotland can raise the deployment rate to 150,000 heat pumps a year, we would expect 1.06 million homes to be converted by the end of 2032.

There are currently 1.8 million houses in Scotland, compared to 950,000 apartments and flats. This means it is eminently possible to achieve the Scottish Government's 1 million homes target without converting apartments and flats to heat pumps. Indeed, in the short term there would be larger carbon savings per pound if the Government prioritises houses and leaves flats until later (see below). However, in the medium term – 2030 onwards – once the larger houses and bungalows are upgraded, oil and gas-heated flats begin to offer the best carbon savings per pound. In particular, flats in older tenements with solid walls should be targeted once large houses and bungalows have been upgraded.

We have modelled two strategies for the order in which homes are converted:

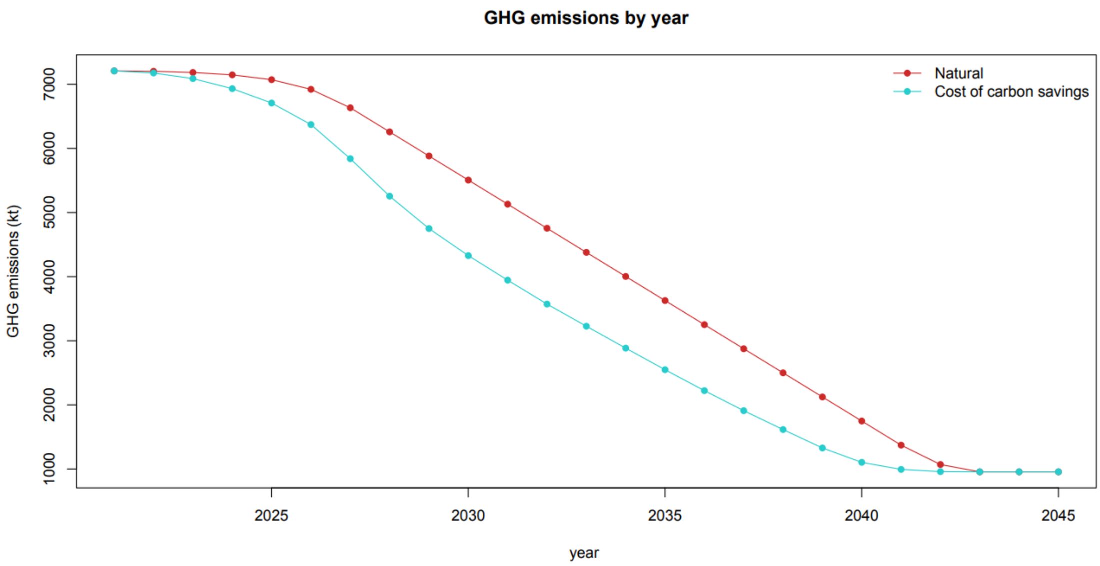
A) An equal proportion of all homes ("Natural") assuming a doubling of heat pump installation rates per year to reach 150,000 by 2027

B) Ordering by to maximise carbon savings per pound (capital cost/GHG emissions savings, “Cost of carbon savings”).

Figure 31 below shows what impact these two strategies for targeting homes would have on greenhouse gas emissions overall. Both strategies suggest that this deployment rate would convert all Scottish homes to low-carbon heating by the early 2040s, with a plateau on emissions at around $1MtCO_{2e}$ a year. These are emissions linked to electricity generation needed to power Scotland’s heat pumps (along with lights and other electrical appliances). It may be possible to decarbonise power generation in parallel with converting homes, but that is outside the scope of this work.

The timing as well as the magnitude of annual emissions is important, and Strategy B (Cost of carbon savings/blue line) saves emissions earlier, with roughly $1MtCO_{2e}$ less emitted in years 2027 to 2035, so this is the best option from the perspective of helping to address climate change.

Figure 31. GHG emissions by year using two strategies for targeting homes



Optimising for carbon savings per pound tends to select oil heated homes first, then gas heated homes. Figure 32 below shows what combination of oil, gas and electrically-heated homes are converted, year by year, from 2022 to 2042 under Strategy C. This shows that homes that start with electric heating do not start to be upgraded until all the rest have been converted in 2040.

Figure 32. Sequence of upgrades each year using Strategy C (maximum carbon savings per pound)

Yearly upgrades by fuel (1000s)

	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
Oil	5.0	4.8	16.5	40.0	43.5	5.0	0.5	3.1	0.3	1.2	0.5	0.1	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Gas	0.0	5.2	3.5	0.0	36.5	145.0	149.5	146.9	149.7	148.8	149.5	149.9	149.9	149.9	150.0	149.9	150.0	150.0	115.8	0.0	0.0
Electricity	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	34.2	150.0	90.0

Figure 33 below shows the year-by-year upgrades under Strategy C presented as house types. The large houses with solid walls are done first, bungalows around the middle because they have large wall areas, and modern dwellings and flats tending to be last.

Figure 33. Which homes converted in successive years, by archetype, under Strategy C

Yearly upgrades by archetype (1000s)

	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042
Pre-1919 Detached	5.0	10.0	13.3	0.0	8.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	0.0
Post-1919 Detached	0.0	0.0	0.0	11.0	0.0	29.4	149.5	39.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	0.0
1919-1982 Semi-D	0.0	0.0	0.0	0.5	0.5	4.5	0.1	0.1	25.6	26.6	25.5	25.5	25.5	49.4	86.2	58.5	6.8	36.0	0.0	21.8	0.0
Post-1982 Semi-D	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	8.4	8.4	8.8	8.4	8.4	8.4	8.4	8.4	8.4	41.8	2.5	0.0	10.5
Mid terrace	0.0	0.0	0.0	0.3	0.3	0.3	0.3	2.6	16.4	16.4	16.4	16.4	16.4	16.5	16.4	16.4	50.7	47.0	5.4	19.6	0.0
Bungalow	0.0	0.0	0.0	13.4	31.7	0.0	0.0	107.9	38.3	3.6	37.8	6.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	39.2	0.0
Chalet bungalow S	0.0	0.0	0.0	10.8	9.4	25.0	0.0	0.0	6.3	18.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	3.9	0.0
Chalet bungalow	0.0	0.0	6.7	3.8	27.8	90.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0
Pre 1919 tenement	0.0	0.0	0.0	0.1	1.5	0.0	0.0	0.0	15.9	37.2	22.4	53.9	60.6	36.6	0.0	0.0	0.0	0.0	32.3	0.0	0.0
Post 1982 tenement	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	11.4	48.8	0.0	63.8
Ground floor flat	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.3	13.8	13.8	13.8	13.8	13.8	13.8	13.8	41.5	58.9	0.0	0.0	34.8	0.0
Top floor flat	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	13.8	59.0	19.1	15.7

Total costs

What are the total capital costs to decarbonise Scotland's homes? Table 37 below gives the total capital costs for fitting the optimal heating systems to homes. Different cost reduction assumptions are applied to deployment 'Trajectory C' outlined above.

Table 37. Total capital costs (£m) to convert Scottish homes to cost-effective decarbonised heating

	Heating capex (£m), under cost reduction scenarios		
	Low	Medium	High
Total	£32,240	£25,750	£21,680

Greenhouse gas emissions

So how much carbon can we save if we switch all of Scotland's heating to zero emission alternatives? Table 38 below shows aggregate GHG emissions for all house types, in kilo-tonnes of CO_2 equivalent ($ktCO_2e$). There would be a huge reduction in emissions if all homes convert to cost-optimal low-carbon heating: an 87% reduction in annual emissions from household energy use. This is more than enough to meet the Scottish Government's target of a 68% reduction in emissions from housing by 2030 – but it would also require a mammoth effort to convert all Scotland's homes.

The 68% target translates into savings of 4,897 $ktCO_2e$ a year on a baseline of total housing stock emissions of 7,208 kt (7,208 x 0.68). Baseline emissions include household use of electricity and gas for domestic appliances and were calibrated against energy demand and carbon emission data for Scotland[65].

If the Scottish Government wishes to do just enough to meet the 2030 target, and assuming that it carries out upgrade work evenly across the archetypes presented here, then it needs to convert 78% of the housing stock to low-carbon heating. This is higher than the 50% figure in the Scottish Heat in Buildings Strategy, and the difference reflects different assumptions about the rate of energy efficiency improvements across the stock, as well as much larger contributions from other low-carbon heat sources, like biogas and hydrogen.

This analysis uses the current Scottish emissions factor for electricity, 50gCO2e/kWh. This is significantly lower than the current UK factor of 230gCO2e/kWh, used previously in CODE to model UK emissions.[66] (In 2017, 2018 and 2019 the Scottish carbon factor was actually

[65] Scottish Government Website, accessed April 2022, 'Scottish Energy Statistics Hub: Total Final Energy Consumption by Sector, 2020' and Scottish Government, 2020, 'Scottish Greenhouse Gas Statistics 1990 to 2019'

[66] https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2019/05 /annual-compendium-of-scottish-energy-statistics/documents/annual-compendium-august-2020/annual-compendium-august-2020/govscot%3Adocument/ACSES%2B2020%2B-%2BAugustFinal.pdf

below this. Also, Scotland has produced more than 98% of its electricity from own generation for several years.)

Table 38: Scaled-up emissions savings if all Scottish homes switch to cost-effective decarbonised heating

	Archetype	All homes: baseline carbon emissions (kt/year)	All homes: upgraded carbon emissions (kt/year)	All homes: carbon savings (kt/year)
1	Detached with solid walls	452	34	418
2	Detached with cavity walls	938	101	837
3	Inter-war Semi-D	1088	144	944
4	Modern Semi-D	259	50	209
5	Mid-terrace house	613	92	522
6	Bungalow with cavity walls	931	112	819
7	Chalet-bungalow with solid walls	511	43	468
8	Chalet-bungalow with cavity walls	619	69	549
9	Tenement-flat with solid walls	758	92	666
10	Modern Tenement flat	221	72	149
11	Ground-floor 4-in-block flat	469	74	395
12	Top-floor 4-in-block flat	350	74	276
		7,208	**956**	**6,252**

Recommendations

This research provides clear evidence about how to deploy heat pumps effectively in Scotland. First, the lowest cost solution over 15 years for the majority of homes to decarbonise is to install air-source heat pumps. In most cases these heat pumps can run with lower flow temperatures than traditional boilers, in the range from 40 to 50°C, and this brings greater efficiency than higher flow temperatures. It usually better to have a relatively high set-back temperature (18°C) over night or when residents are out, in order to meet comfort criteria quickly and efficiently. Our modelling found that with a high set-back temperature, replacing radiators with larger ones is unnecessary in most cases: a lower peak demand for heat when heating comes on means that the existing radiators are sufficient to come up to a comfortable temperature.

Second, energy efficiency is cost effective and is a pre-requisite for heat pumps to operate efficiently in most house types. In a minority of special cases – for example, listed homes or homes in conservation areas – some energy-efficiency measures are not currently economically viable, and for these instances new approaches to improving efficiency are needed.

Third, minimum standards for thermal efficiency for homes would be very useful in supporting deployment of heat pumps in Scottish homes – arguably more useful than current EPC ratings, which are crude and confound thermal efficiency with renewables and lighting efficiencies. The research indicates that 65-85kWh per m^2 per year is a suitable minimum target for thermal efficiency, because this standard or better means that homes can be heated effectively using low flow temperatures.

Some flexibility is needed in minimum thermal standards, and a minority of homes – for example, chalet bungalows with sloping ceilings in the roof, which are hard to insulate – may merit less demanding targets. (Conversely, new homes can in some cases be raised above the minimum standard economically.)

Fourth, the cost and carbon savings from switching to heat pumps are greatest for homes that currently have oil-fired heating. Scotland should start with these homes, because carbon emissions must fall as fast as possible, and because there is a clearer cost-benefit case for oil-heated homes.

Fifth, air to air heat pumps – which are currently absent from policy measures – can be useful and they should get Government support in the same way as air-source heat pumps. Air to air HPs are particularly well suited to electrically-heated homes that do not currently have radiators, where installation is less disruptive and expensive than installing a new wet heating system.

Sixth, many flats still offer opportunities for improving energy efficiency – particularly through improved air tightness, and (for top-floor flats) top-up loft insulation. It is also worth exploring communal heating systems for flats, where demand for space and water heating is usually lower than for houses, and where space constraints (inside and outside the flats) make it more difficult to switch to heat pumps. Shared external units serving multiple flats may work out more cost-effective than separate systems serving individual flats, both for installation and maintenance.

Finally, the biggest impediment to installing heat pumps in Scottish homes now are the high up-front costs of carrying out the work. This is likely to need continued Government support – now, and into the future. The current system of grants from the Scottish Government, with extra money for rural properties, is very positive, and maintaining accompanying funding for energy efficiency alongside heat pumps is also very helpful.