Technical Feasibility of Low Carbon Heating in Domestic Buildings

Report for Scottish Government's Directorate for Energy & Climate Change

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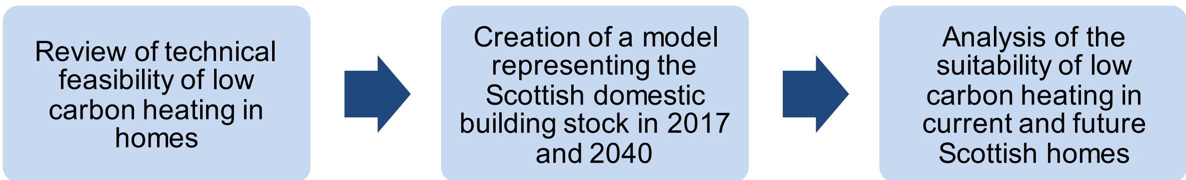
Executive Summary

Motivation and methodology

Scotland's Climate Change Plan set an ambition for emissions from buildings to be near zero by 2050, and targets 35% of domestic and 70% of non-domestic buildings' heat to be supplied using low carbon technologies by 2032. The Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 set a new target for emissions to be net zero by 2045, with interim targets of 75% by 2030 and 90% by 2040. The update to the Climate Change Plan will be published at the end of 2020 to reflect these new targets. The Energy Efficient Scotland programme, launched in May 2018, sets out a wide range of measures to promote low carbon heating alongside energy efficiency improvements in Scotland's buildings. Meeting these targets will require almost all households in Scotland to change the way they heat their homes. It is therefore imperative to advance our understanding of the suitability of the available low carbon heating options across Scotland's building stock.

The aim of this work is to assess the suitability of low carbon heating technologies in residential buildings in Scotland. The outputs generated through this work will form a key part of the evidence base on low carbon heat which the Scottish Government will use to further develop and strengthen Scotland's low carbon heat policy, in line with the increased level of ambition of achieving Net Zero by 2045.

The study was carried out around three key stages, represented in the diagram below.



The first stage focussed on the **review of technical feasibility of low carbon heating in homes**. A comprehensive literature review of the factors influencing suitability and of the barriers to deployment of low carbon heating in domestic buildings was performed, including any features that could be relevant in the Scottish context. The information thus collected was utilised for the identification of the most relevant attributes that should be considered in the following stage for the creation of a stock model.

The second stage aimed at the creation of a **model representing the Scottish domestic building stock**. A set of useful attributes influencing the suitability of low-carbon heating technologies in Scottish homes was identified, based on the available information on the buildings stock offered by Home Analytics. The existing domestic building stock in 2017 was then mapped to the produced list of archetypes. Finally, a scenario for the deployment of energy efficiency measures was developed according to the targets of the Energy Efficient Scotland Route Map[1], in order to identify the characteristics of the likely building stock in 2040.

In the last stage an **analysis of the suitability** of each of the archetypes representing the Scottish domestic building stock for a set of 26 low-carbon heating systems was performed. The suitability of the current and future Scottish domestic building stock for low-carbon heating could therefore be tested and the characteristics and number of homes that are

[1] Scottish Government 2018 Energy Efficient Scotland: route map

suitable only for a restricted range of low-carbon heating technologies was more closely examined.

Creation of a model representative of Scotland’s domestic building stock

The archetypes utilised in the stock model are determined by a list of attributes that can assume a range of values. While the set of attributes is fixed for all archetypes, each archetype is uniquely identified by a different combination of attribute values.

The choice of attributes to be included in the archetype definition was based on relevant attributes influencing the suitability of low-carbon heating and on information provided by Home Analytics on the characteristics of the Scottish housing stock.

Attributes selected for the creation of dwelling archetypes

Attributes	Values
Age	• Pre-1919 • 1919-1991 • Post-1991
Property type	• Detached • Semi-detached • Terraced • Flat (block) • Flat (other)
Size	• Small (< 66 m^2) • Medium (66 – 108 m^2) • Large (> 108 m^2)
Wall insulation	• SWI - Solid wall insulated • SWU - Solid wall uninsulated • CWI - Cavity wall insulated • CWU - Cavity wall uninsulated with low exposure • CWU exposed - Cavity wall uninsulated with high exposure
Roof insulation	• <100 mm • 100-250 mm • >250 mm • Room in roof • No loft
Existing heating system	• Gas boiler • Oil boiler • Electric • Other
Orientation suitable for solar thermal	• Yes • No
Location	• Urban • Rural
Coastal location	• Yes • No
Gas network location	• On gas grid • Off gas grid
District heating potential	• Yes • No

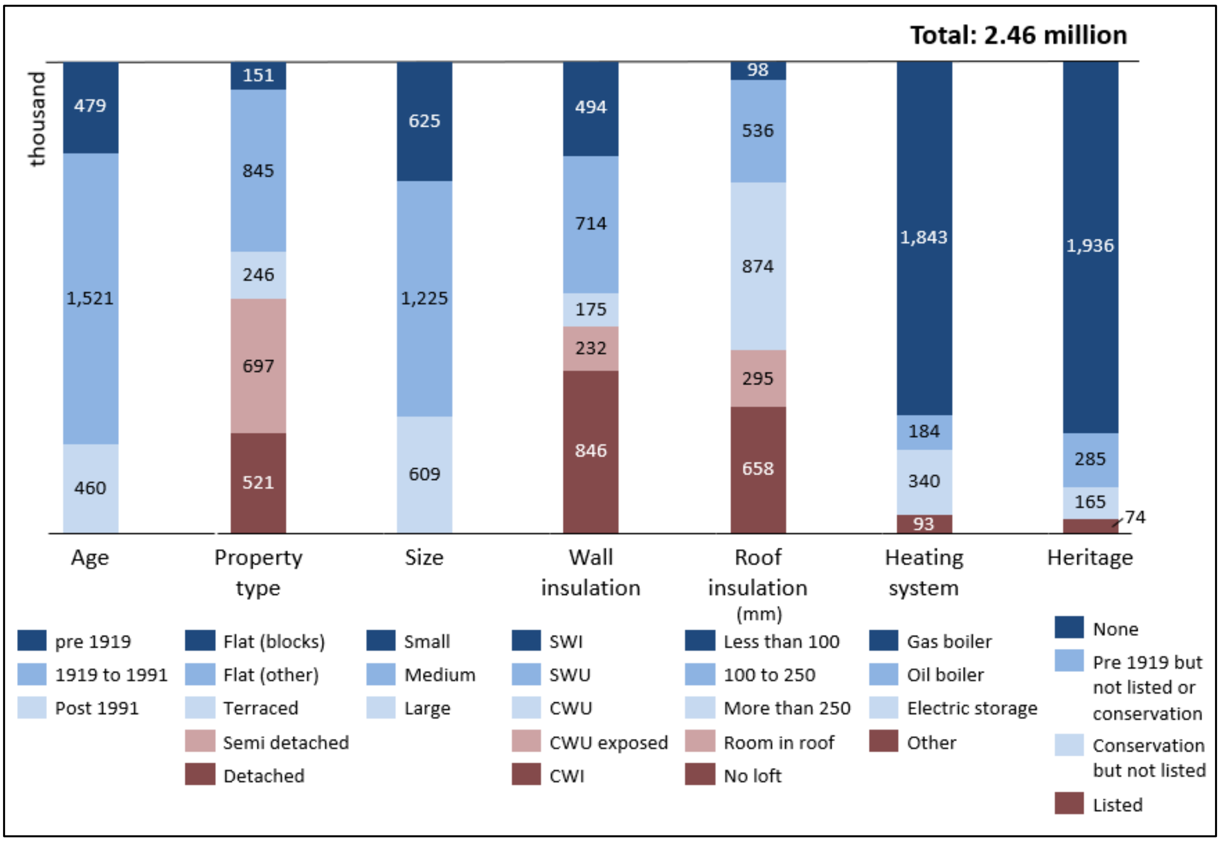
From this list, a set of ~140,000 different **dwelling archetypes** was produced, each representing a unique combination of all chosen attribute values. Each archetype constitutes therefore a simplified representation of a dwelling, equipped with a unique set of physical and geographical characteristics that are useful in the assessment of low-carbon heating suitability.

In order to calculate the stock of each dwelling archetype in the Scottish landscape, all existing homes in Scotland entered in the Energy Saving Trust (EST) Home Analytics database were aggregated based on the chosen attributes. The number of existing homes represented by each archetype was therefore included in the model, providing information on the number of real homes that may be associated with the same suitability constraints of a particular archetype.

Scotland's housing stock in 2017 and 2040

An initial useful output of the stock model is a representation of the characteristics of the current Scottish housing stock, based on a set of interesting attributes. The assessment of the current state of the Scottish housing stock is based on information available for the year 2017.

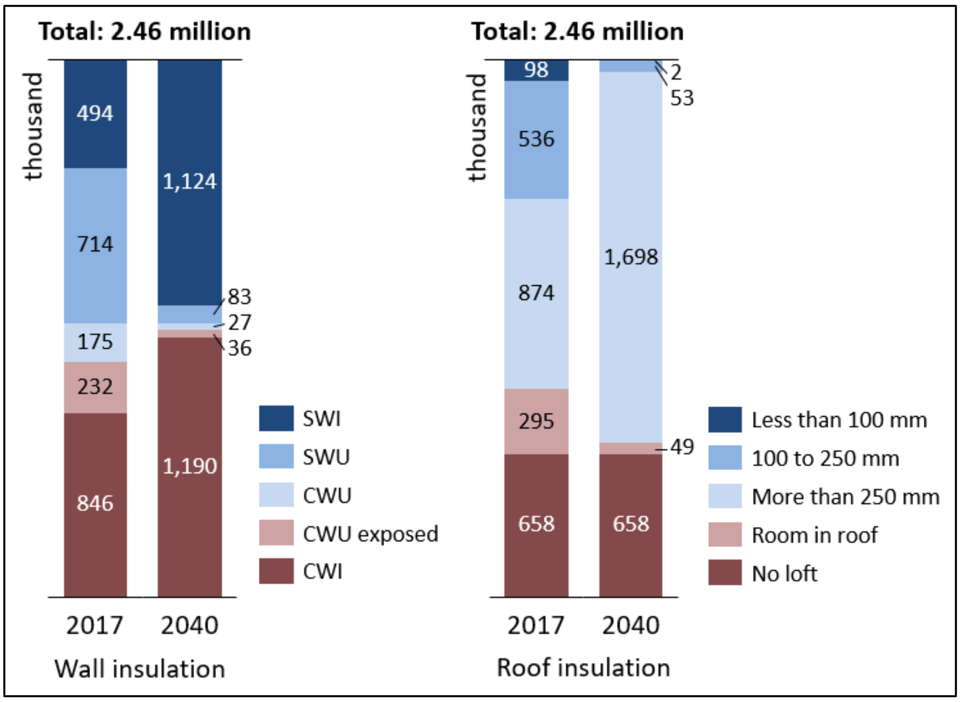
Breakdown of Scotland's housing stock in 2017 depending on various attributes



Energy efficiency measures will need to be implemented between 2017 and 2040 to comply with the requirements imposed by the Energy Efficient Scotland Route Map, including fabric measures influencing the type of insulation and annual space heating demand.

In order to assess the influence of the implementation of expected energy upgrade measures on the characteristics of the existing building stock in 2040, EST's Portfolio Energy Assessment Tool (PEAT) was used to forecast future changes. The influence of the implementation of energy efficiency measures considered by PEAT on the characterisation of the housing stock primarily affect two of the modelled attributes: wall insulation and roof insulation, the modification of which is reported in the figure below.

Modification of Scotland's housing stock after the implementation of energy efficiency upgrades



The number of homes with wall insulation (Solid Wall Insulated or Cavity Wall Insulated) is expected to increase from 54% of the stock in 2017 to 94% in 2040, with nearly two thirds of wall insulation upgrade interventions performed on solid wall homes.

While 27% of dwellings in Scotland are not connected with their building's roof and therefore require no roof insulation (value "no loft"), the number of homes with roof insulation of less than 250 mm thickness or with poorly insulated room-in-roof is expected to reduce from 38% of the stock in 2017 to 4% in 2040.

Barriers to technical suitability of selected low-carbon heating technologies

Low-carbon heating options investigated in this study include a comprehensive selection of 26 technologies reported in the table below.

Heat pumps	
1	Air Source Heat Pump (ASHP)
2	Ground Source Heat Pump (GSHP)
3	High-temperature ASHP
4	High-temperature GSHP
5	Communal ASHP
Electric resistive heating	
6	Electric storage heating
7	Direct electric heating
8	Electric boiler
Bioenergy boilers	
9	Solid biomass boiler
10	BioLPG boiler
11	Bioliquid boiler (B100)
Low carbon gas	
12	Hydrogen boiler
13	Biomethane grid injection
Hybrid heat pumps	
14	Hybrid ASHP + gas boiler (no hot water cylinder)
15	Hybrid ASHP + gas boiler (with hot water cylinder)
16	Hybrid ASHP + bio-liquid boiler (no hot water cylinder)
17	Hybrid ASHP + bio-liquid boiler (with hot water cylinder)
18	Hybrid ASHP + hydrogen boiler (no hot water cylinder)
19	Hybrid ASHP + hydrogen boiler (with hot water cylinder)
20	Hybrid ASHP + direct electric heating (no hot water cylinder)
21	Hybrid ASHP + direct electric heating (with hot water cylinder)
Heat networks	
22	District heating
Combinations with solar thermal	
23	ASHP + solar thermal
24	Electric storage heating + solar thermal
25	Direct electric heating + solar thermal
26	Electric boiler + solar thermal

Key barriers to suitability considered in this study include the following constraints.

Heat demand (specific heat loss): Homes with specific peak heat loss rate above 150 W/m^2 were considered unsuitable for the use of conventional heat pumps, as the heat delivered even by large emitters would unlikely meet the heating demand, due to the low flow temperature delivered.

Heat demand (fuse limit): The installation of electric resistive heating or heat pumps was considered unsuitable in homes with large heat demand, if resulting in peak electrical power consumption exceeding the maximum fuse limit of 100A. A sensitivity analysis was performed for fuse limit values of 60A, 80A and 100A. Homes with use rating smaller than 60A are expected to be uncommon.

Dwelling type: Communal ASHP were assumed to be unsuitable for detached, semi-detached and end-terrace homes. All other types of dwellings were considered suitable, due to the reduced length of pipes needed for the connections and thus higher cost-effectiveness. The dwelling type was also utilised to estimate the overall suitability of homes for the installation of GSHP and high-temperature GSHP, as detached homes are more likely than other dwelling types to have the available outdoor space for the installation of a horizontal ground loop.

Space constraint: In order to identify dwellings in which space is constrained, total dwelling floor area per habitable room was calculated. Homes with total dwelling floor area per habitable room smaller than $18m^2$ were classified as space constrained. These dwellings were assumed to be unsuitable for the installation of conventional, high-temperature and hybrid heat pumps, due to their additional requirement of a large hot water cylinder for the production of hot water.

District heating: The potential availability of district heating for Scottish homes was assessed on the basis of local heating demand, assuming that district heating networks will be put in place if not already existing in areas where demand for heat is sufficiently high and concentrated. District heating potential was attributed to all homes located in areas in which current annual heat demand density is above a threshold of $40kWh/m^2$/year. Finally, 80% of homes for which a connection to district heating is possible were assumed to be suitable for district heating, based on expected connection rates and prospective deployment of heat networks in areas with high heat density.

Roof orientation: The suitability of a dwelling for solar thermal was based on the orientation of its roof, and suitability was assigned to homes with roofs facing South, South-West or South-East.

Coastal location: The relative distance from the coast was calculated for each home based on its geographical location. Homes located less than 5 km from the coastline were assigned ‘Coastal location’ value ‘yes’. While the coastal location of a home alone was not considered a sufficient barrier to the suitability of any technology, additional costs were assumed for the use of air-source heat pumps, due to the necessary measures required to prevent accelerated corrosion of the heat exchanger.

Gas Network location: Homes located outside of areas supplied by the gas grid were considered unsuitable for the adoption of hydrogen boilers, biomethane grid injection, and any of their combinations with heat pumps in a hybrid heating system, as these technologies rely on the fuel being delivered by the gas grid. On the other hand, homes located in areas supplied by the gas grid were assumed to be incompatible with bioLPG and bioliquid boilers. In fact, given the similarities in technology and operations of both bioLPG and bioliquid boilers with hydrogen boilers, in a scenario with limited bioenergy resources it is expected that hydrogen boilers would be preferred to bioLPG or bioliquid boilers in homes where both grid and bioenergy options are available. Additionally, the adoption of bioLPG and bioliquid boilers is associated with a higher level of disruption, due to the necessity to store the fuel onsite.

Considerations around heritage homes

Listed buildings and homes in conservation areas are respectively buildings and areas categorised to be of architectural or historic interest. Planning permission may be required to make changes to the external appearance of these homes. Additionally, listed building consent may be required to make changes to both external appearance and internal fixtures of listed homes. Additionally, old dwellings may often present similar issues to those of heritage buildings, according to our consultation with Historic Environment Scotland.

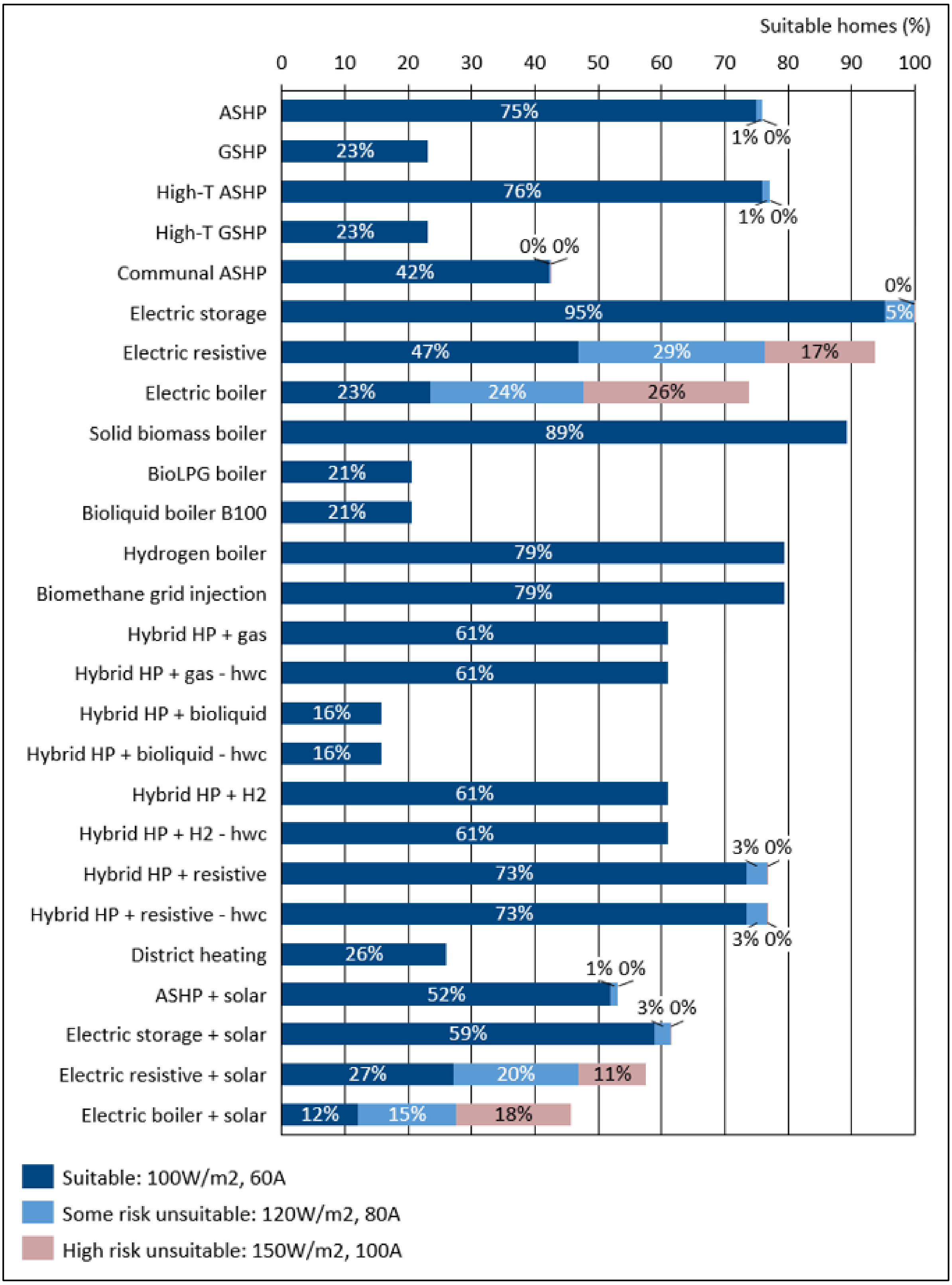
The impact of the peculiar characteristics and restrictions of heritage and old homes on the suitability and costs for the implementation of low-carbon heating was not assessed, due to the complexity and case-by-case nature of the barriers to retrofit.

Listed homes account for 3% of Scotland's housing stock and homes in conservation areas but not listed account for an additional 7% of the stock. Older homes that are neither listed nor located in conservation areas amount to 12% of the total housing stock. Given the large portion of homes that may be affected by additional requirements and restriction in the implementation of low-carbon heating and given the uncertainty about the impact of these restrictions on suitability and costs, it is advisable that these parameters are further investigated.

Suitability of Scotland's housing stock for low-carbon heating technologies

The expected suitability of each home for the considered low-carbon heating technologies in 2040 is reported in the figure below, for various combinations of peak specific heat demand and fuse limit.

Percentage of homes compatible with each technology in 2040; the sensitivity of suitability was tested against three combinations of peak specific heat demand and fuse rating



ASHP and high-temperature ASHP: While thermal comfort is at risk of not being met without appropriate energy efficiency fabric measures being carried out in some of the suitable homes with the installation of an ASHP in 2017, the installation of a high-temperature ASHP would ensure thermal comfort in homes where energy fabric measures or an upgrade to low-temperature wet system may not be feasible. While overall suitability of both technologies does not vary significantly in 2040 (the year by which it is assumed by this work that energy efficiency fabric measures will have been carried out), the advantage of high-temperature ASHP over conventional ASHP is lost, as the reduced space heating demand allows for both technologies to meet thermal comfort equally.

GSHP and high-temperature GSHP: The suitability of GSHP and high-temperature GSHP is much lower than that of ASHP due to the additional requirements for the installation of a ground loop in a sufficiently large, accessible and geologically suitable plot.

Communal ASHP: The suitability for communal ASHP is lower than that of individual ASHP due to additional constraint posed on the suitable dwelling type.

Electric resistive heating: While very few homes are limited by fuse rating in the implementation of electric storage heating, a large portion is restricted for the installation of direct electric heating by the same constraint. This is due to the larger number of domestic appliances that are consuming electricity while direct electric heating is operating, thus reducing the amount of power that the heating devices can draw before exceeding the fuse limit. This also results in a larger share of suitable homes in 2040, due to a reduced space heating demand. Similar considerations are also valid for electric boilers, which are operating during daytime and at an even lower efficiency than direct electric heating.

Bioenergy boilers: Solid biomass boilers, bioLPG boilers and bioliquid boilers are not suitable in all homes, due to the requirement of space for the volume of their storage/equipment. In addition, bioLPG boilers and bioliquid boilers are overall less suitable, as they were assumed to be only considered for homes that are located off the gas grid.

Low-carbon gas boilers: Hydrogen boilers and biomethane grid injection are assumed to be technically suitable in all buildings that are located on the gas grid.

Hybrid heat pumps: The suitability for hybrid ASHP technologies is based on the combined suitability of its two main components: the ASHP and the additional heating source. The suitability of the ASHP component is evaluated applying the same constraints as for conventional ASHP but considering a lower peak heat demand, compatibly with the reduced load delivered by the ASHP component in a hybrid system.

Solar thermal: The suitability for systems including solar thermal collectors is based on the suitability of the main heating system component, with the additional requirement of the availability and appropriate orientation of a roof on which to secure the collectors.

Dwellings with limited suitability

A significant share of Scottish homes is likely to be suitable only for a limited range of heating technologies. A restriction in the choice of heating system may carry some risks for the decarbonisation of domestic heating. Most relevant risks are associated with following low-carbon heating technologies:

- **Electric resistive heating:** the reliance on electric resistive heating technologies for the decarbonisation of domestic heating might result in high costs. Included technologies are electric storage heating, direct electric heating, electric boilers and their combinations with solar thermal.

- **Bioenergy**: the implementation of low-carbon heating based on bioenergy relies on the future access to sufficient biomass feedstock and might therefore be subject to fuel availability uncertainty. Considered technologies are solid biomass boilers, bioLPG boilers, bioliquid boilers and hybrid heat pumps with bioliquid boilers as secondary source.
- **Decarbonised gas grid**: the availability of technologies that are supported by a decarbonised gas grid is tied to the future delivery of low carbon gas through the grid and might therefore be subject to implementation uncertainty. In fact, a strategic decision on the decarbonisation of the gas network though the supply of hydrogen will likely be based on the outcome of further studies on the technical suitability and safety of the use of hydrogen. Affected technologies are hydrogen boilers and hybrid heat pumps with hydrogen boilers as secondary source. Biomethane grid injection is also included in this category, but it is also affected by the fuel availability uncertainty of the bioenergy category.
- **District heating**: similarly, the availability of district heating will predominantly depend on the scale of the development of heat networks and could therefore be subject to implementation uncertainty.

The portion of the stock resulting unsuitable for heat pump technologies in 2040 is reported in the table below, broken down into 16 categories with various combinations of technology choice restriction. The reported figures on the right refer to the portion of homes that can choose from all groups indicated in the respective row on the left at the same time.

Number of homes with restricted choice of suitable technologies, considering fuse limit of 80A and peak specific heating demand of 120 W/m² in 2040

	Suitable technologies for homes with restricted choice				Homes	% of stock
1	District heating	Decarb. gas	Electric resistive	Bioenergy	20,000	0.8%
2	District heating	Decarb. gas	Electric resistive	–	112,000	4.5%
3	District heating	Decarb. gas	–	Bioenergy	1	0%
4	District heating	Decarb. gas	–	–	40	0%
5	District heating	–	Electric resistive	Bioenergy	22,000	0.9%
6	District heating	–	Electric resistive	–	0	0%
7	District heating	–	–	Bioenergy	70	0%
8	District heating	–	–	–	0	0%
9	–	Decarb. gas	Electric resistive	Bioenergy	136,000	5.5%
10	–	Decarb. gas	Electric resistive	–	90,000	3.6%
11	–	Decarb. gas	–	Bioenergy	60	0%
12	–	Decarb. gas	–	–	60	0%
13	–	–	Electric resistive	Bioenergy	78,000	3.2%
14	–	–	Electric resistive	–	0	0%
15	–	–	–	Bioenergy	1,200	0.05%
16	–	–	–	–	0	0%
TOTAL					**459,000**	**18.7%**

Four combinations in particular are identified as most at risk, due to their restricted selection of suitable technologies and the relatively large number of affected homes:

- **Row 9: 136,000 homes** that must choose among decarbonised gas, electric resistive and bioenergy technology groups only. These homes are potentially at risk of incurring in high costs (electricity) or the uncertain availability of the selected technology (decarbonised gas and bioenergy).
- **Row 10: 90,000 homes** that must choose between decarbonised gas and electric resistive technology groups only. These homes are potentially at risk of incurring in high running costs (electricity) or the uncertain availability of the selected technology (decarbonised gas).
- **Row 13: 78,000 homes** that must choose between electric resistive gas and bioenergy technology groups only. These homes are potentially at risk of incurring in high running costs (electricity) or the uncertain availability of the selected technology (bioenergy).
- **Row 15: 1,200 homes** that can only choose bioenergy technology group only. These homes are potentially at risk of uncertain availability of the selected technology.

Conclusions

The key findings of this study provide interesting learnings on the composition of Scotland's housing stock and on its potential interaction with a wide range of low-carbon heating technologies that will be essential for the decarbonisation of domestic heating in Scotland.

- **The characteristics of the insulation of the existing stock will change over time in order to comply with the requirements set by the Energy Efficient Scotland Route Map**. The most effective fabric energy performance upgrade measures investigated in this study are wall and roof insulation. These result in a reduction of the space heating demand of most dwellings enough for it to have an impact on the suitability of some of the considered heating technologies.
- **The feasibility of the implementation of low-carbon heating in heritage homes will need to be assessed individually**. Listed buildings and homes in conservation areas require planning consent to make changes to the external appearance or to the internal fixtures. Additionally, old dwellings built before 1919 were reported by Historic Environment Scotland to often present similar issues to those of heritage buildings. Heritage and old homes account for ~22% of Scotland's housing stock.
- **The fuse limit constraint affects the implementation of electric resistive heating more than heat pump technologies.** The number of homes that might be constrained by fuse limit in the installation of ASHP is significantly lower than for electric storage heating and direct electric heating, due to the higher efficiency of heat pumps. Furthermore, the number of homes affected by the fuse limit constraint decreases substantially between 2017 and 2040, due to the lower space heating demand enabled by the implementation of energy performance upgrade measures.
- **The installation of heat pumps is not advisable in homes with peak specific heat demand above 150 W/m^2**. The installation of an ASHP results to be advisable for heat loss rates of up to 100 W/m^2, while homes with heat loss rates comprised between 100 W/m^2 and 150 W/m^2 might incur in risk of thermal comfort not being met by the heat pump system.
- **In 2040 ASHP and high-temperature ASHP are expected to be equally suitable in Scottish homes.** The overall suitability of the stock for ASHP and high-temperature

ASHP is similar, as it is almost exclusively determined by the space constraint. However, in 2017 a portion of homes that are suitable for ASHP are still at risk of not meeting thermal comfort. The advantage of high-temperature ASHP over conventional ASHP is lost in 2040, as the reduced space heating demand allows for both technologies to meet thermal comfort equally.

- **Electric storage heating is expected to have a larger suitability than direct electric heating**. While very few homes are limited by fuse rating in the implementation of electric storage heating, a large portion is restricted for the installation of direct electric heating by the same constraint. This is due to the larger number of domestic appliances that are consuming electricity while direct electric heating is operating.
- **Homes with limited choice of suitable low-carbon heating options may be more subject to implementation risk**. Four main groups of dwellings with limited suitability were identified, including homes that are suitable for (a) decarbonised gas, bioenergy and electricity only, (b) decarbonised gas and electric resistive heating only, (c) electric resistive heating and bioenergy only, (d) bioenergy only. These homes may be at risk of incurring in high costs (electricity) or not being able to rely on the availability of the technology (decarbonised gas grid and bioenergy). The number of homes with restricted suitability could amount to up to ~20% of the housing stock.
- **While there are no concerns around sufficient availability of bioenergy to cover heating demand, bioenergy resources may be directed to use in other sectors**. In fact, the Net Zero report by the CCC advises against the use of the available biomass for domestic heating and recommends its use in other sectors, in combination with CCS.

1 Introduction

1.1 Background

In April 2019, the First Minister declared a global climate emergency – calling for action from Scotland and the world – and committed Scotland to net-zero greenhouse gas emissions by 2045, in line with the UK Committee on Climate Change (CCC) recommendations[2].

The Climate Change (Emission Reduction Targets) (Scotland) Act 2019 has been passed by the Scottish Parliament setting in law very ambitious targets to reduce greenhouse gas emissions, requiring Scotland to reach net-zero emissions by 2045, with 75% reductions by 2030 and 90% reductions by 2040.

Scotland's Climate Change Plan set an ambition for emissions from buildings to be near zero by 2050, and targets 35% of domestic and 70% of non-domestic buildings' heat to be supplied using low carbon technologies by 2032. This Plan is due to be updated in 2020 to reflect the new emission targets. Scotland's Energy Strategy includes a separate target for 50% of Scotland's energy across heat, transport and power to be supplied using renewable sources by 2030. The Energy Efficient Scotland programme, launched in May 2018, sets out a wide range of measures, including funding, pilot projects and information provision, to promote low carbon heating alongside energy efficiency improvements in Scotland's buildings.

Meeting these targets will require almost all households in Scotland to change the way they heat their homes. There is a wide range of potential low carbon heating options, and as yet there is no clear consensus on the most appropriate technology or mix of technologies. It is therefore imperative to advance our understanding of the suitability of the available low carbon heating options across Scotland's building stock.

1.2 Objectives

The aim of this work is to assess the suitability of low carbon heating technologies in residential buildings in Scotland.

There is large variation across the building stock in Scotland, leading to significant differences in the most suitable and effective low carbon heating options and the additional improvements required to install low carbon heating.

Numerous factors influence the suitability of one or more of the available heating technologies. Concerning the building itself, this includes the building construction type and energy efficiency level, the existing heating technology and heat distribution system, listed or conservation area status, internal and external space constraints and other factors.

However, the factors influencing suitability of low carbon heating options relate not only to the building itself, but also to the location in which the building is situated. For example, the potential for a heat network in the vicinity of the building presents a potential means of decarbonising heat even where deep energy efficiency retrofit could be difficult, as does the presence of a gas network, through which low carbon gas could be delivered. The ease of physical access to the building may have an impact on the cost or technical feasibility of

[2] CCC 2019, Net Zero – The UK's contribution to stopping global warming

applying new, prefabricated insulation approaches, and the exposure of the building to coastal or other more severe environmental conditions might impact the cost of materials.

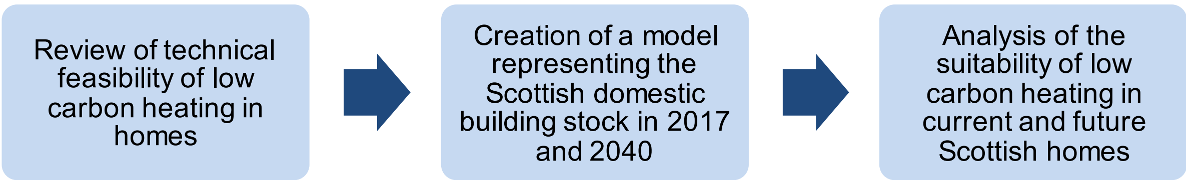
In order to deliver a useful analysis of the suitability of low carbon heating technologies in Scottish homes, this study aims to produce:

- A set of archetypes representative of the Scottish housing stock, segmented according to the most material attributes influencing the suitability of low carbon heating;
- An assessment of the technical feasibility of the considered low carbon heating options within each of the archetypes;
- An overall assessment of the suitability of each low carbon heating option across the Scottish building stock.

The outputs generated through this work will form a key part of the evidence base on low carbon heat which the Scottish Government will use to further develop and strengthen Scotland's low carbon heat policy, in line with the increased level of ambition of achieving Net Zero by 2045.

1.3 Methodology

This research and analysis for this study were carried out in three key stages, illustrated in the following chapters.



The first stage, reported in Chapter 2, focussed on the **review of technical feasibility of low carbon heating in homes**. A comprehensive literature review of the factors influencing suitability and of the barriers to deployment of low carbon heating in domestic buildings was performed, including any features that could be relevant in the Scottish context. The information thus collected was utilised for the identification of the most relevant attributes that should be considered in the following stage for the creation of a stock model. Some of the most relevant sources utilised are the recent work on 'Hard to Decarbonise Homes' for the CCC[3] and the Evidence gathering for electric heating options in off gas grid homes for BEIS[4].

The second stage, described in Chapter 3, aimed at the creation of a **model representing the Scottish domestic building stock**. Initially, a review of the data on Scottish homes found in Home Analytics Scotland Dataset and various other sources was performed. Based on the available information on the buildings stock offered by Home Analytics and on the relevant suitability parameters determined in the previous stage, a set of useful attributes influencing the suitability of low-carbon heating technologies in Scottish homes was identified. The existing domestic building stock in 2017 could therefore be mapped to a list of archetypes, characterised by these selected attributes. Finally, a scenario for the deployment of energy efficiency measures was developed according to the targets of the Energy Efficient Scotland Route Map, allowing for a comparison between of the characteristics of the current building stock in the year 2017 and of the likely building stock in 2040.

[3] Element Energy & UCL 2019, Analysis on abating direct emissions from 'hard-to-decarbonise' homes
[4] Element Energy 2019, Evidence gathering for electric heating options in off gas grid homes

In the last stage, outlined in Chapter 4, an **analysis of the suitability** of each of the archetypes representing the Scottish domestic building stock for a set of 26 low-carbon heating systems was performed. The suitability of the current and future Scottish domestic building stock for low-carbon heating could therefore be tested and the characteristics and number of homes that are suitable only for a restricted range of low-carbon heating technologies was more closely examined.

2 Technical feasibility of low carbon heating

The suitability of domestic low-carbon heating depends on the available heating technologies and on their compatibility with various characteristics of the homes in question. The following sections illustrate the low-carbon heating technologies considered in this study and factors influencing their suitability.

2.1 Low-carbon heating technologies

The range of low carbon heating systems considered in this study is summarised in Table 1, followed by a brief explanation of the technologies and the assumptions considered in this study.

Table 1: Low-carbon heating technologies considered in this study

Heat pumps	
1	Air Source Heat Pump (ASHP)
2	Ground Source Heat Pump (GSHP)
3	High-temperature ASHP
4	High-temperature GSHP
5	Communal ASHP
Electric resistive heating	
6	Electric storage heating
7	Direct electric heating
8	Electric boiler
Bioenergy boilers	
9	Solid biomass boiler
10	BioLPG boiler
11	Bioliquid boiler (B100)
Low carbon gas	
12	Hydrogen boiler
13	Biomethane grid injection
Hybrid heat pumps	
14	Hybrid ASHP + gas boiler (no hot water cylinder)
15	Hybrid ASHP + gas boiler (with hot water cylinder)
16	Hybrid ASHP + bio-liquid boiler (no hot water cylinder)
17	Hybrid ASHP + bio-liquid boiler (with hot water cylinder)
18	Hybrid ASHP + hydrogen boiler (no hot water cylinder)
19	Hybrid ASHP + hydrogen boiler (with hot water cylinder)
20	Hybrid ASHP + direct electric heating (no hot water cylinder)
21	Hybrid ASHP + direct electric heating (with hot water cylinder)
Heat networks	
22	District heating
Combinations with solar thermal	

23	ASHP + solar thermal
24	Electric storage heating + solar thermal
25	Direct electric heating + solar thermal
26	Electric boiler + solar thermal

The installation of PV technologies, thermal storage or electrical storage were not modelled in our study, but are expected to impact costs, increasing capital cost but generally reducing operating costs of the heating system.

Heat pumps

Domestic heat pumps are central heating systems that can absorb heat from the outside of a building and transfer it to the inside by means of a refrigerant fluid. The main components of a heat pump are an evaporator, a compressor, a condenser and an expansion valve. The refrigerant is circulated from the condenser, where it extracts heat at low temperature from the outside source, to the compressor, where its temperature and pressure are increased. The refrigerant then flows though the condenser, where it releases heat at high temperature to the inside of the building. After circulating through the expansion valve its pressure is finally reduced and the cycle can restart. The energy requirement of a heat pumps corresponds roughly to the electrical power needed to compress and circulate the refrigerant. The performance of a heat pump is highly dependent on the temperature of the outside source and on the temperature at which heat is delivered through the wet system.

Technologies considered in this study are **air source heat pumps (ASHPs)**, absorbing heat from the outside air, and **ground source heat pumps (GSHPs)**, extracting heat from the ground either through a horizontal closed ground loop or a vertical closed ground loop. Both air source and ground source heat pumps operate at optimal performance when producing heating at low temperatures. For comparison, space heating can be delivered by conventional heat pumps with optimal efficiency at temperatures around 35-40°C, while gas boilers are designed to efficiently deliver space heating at temperatures from 60°C and up to 80-90°C. Therefore, the adoption of heat pump heating requires also the installation of emitters that are larger than those utilised for a gas central heating system, in order to ensure sufficient heat is transferred from the low-temperature circulating water to the heated spaces. Additionally, in homes where the pre-existent wet system is composed of very narrow pipes, the installation of conventional heat pumps may require also the installation of new wider pipes that are capable of delivering a high flow rate.

Additionally, a **high-temperature heat pump** is assumed to be capable of producing output temperatures of 65°C[5]. While its upfront cost is generally higher than for a conventional heat pump, a high-temperature heat pump can deliver space heating at a temperature closer to that of a gas boiler. As a consequence, high-temperature heat pumps are unlikely to require the installation of radiators larger than those used in gas boiler heating systems, as opposed to conventional heat pumps.

Finally, a **communal ASHP** system refers to a single ASHP unit delivering heat to multiple flats or terraced houses, assuming a network shared between 6 dwellings.

[5] BEIS 2016, Evidence gathering – Low Carbon Heating Technologies

This study assumes that with the installation of heat pump technologies heating demand is met by the heat pump itself, while hot water demand is met by electric on-demand devices, such as electric taps.

Electric resistive heating

Direct electric heating involves the production of heat from electricity through a resistive element and its delivery via radiators, panel heaters or infrared heaters.

Panel heaters and electric radiators are convector heaters, as they heat the air directly and generate passive convection currents that transfer heat across a room. Infrared heaters, or radiant heaters, transfer heat predominantly via infrared radiation to the surfaces in a room, while the surrounding air is heated indirectly by the room's warm surfaces[6].

For this study, direct electric heating is one of the investigated low-carbon heating options, but also one of the counterfactual heating technologies already present in Scottish homes. Only convector heaters are therefore considered for direct electric heating and radiant heaters are not included, as their use is not very common in Scottish homes. Electricity use of direct electric heating is assumed to occur during the day and is therefore subject to the higher tariffs of peak-time electricity.

Electric storage heating also produces heat from electricity though a resistive element, but typically occurs overnight, taking advantage of the lower electricity tariffs during off-peak times. The heat is absorbed and stored by high thermal mass bricks and later released during the day by a fan blowing air over the heated bricks. An independent heating unit is installed in each room.

Electric boilers produce heat from electricity and transfer it to water, delivering space heating though a wet heating system, either through radiators or through underfloor heaters. Additionally, the boiler may also produce hot water, when in combination with a hot water cylinder.

This study assumes that with the installation of electric resistive heating technologies hot water demand is met by electric on-demand devices, such as electric taps.

Bioenergy boilers

Bioenergy boilers operate in the same way as a conventional natural gas or LPG boiler, burning fuels to heat water in a wet heating system.

A **solid biomass boiler** can burn wood pellets, wood chips or logs to heat up water and deliver space heating via a wet heating system or produce hot water in combination with a hot water cylinder, similar to a conventional gas or electric boiler. Solid biomass requires a large availability of storage space, determined by the relatively low energy density of the fuel and by fuel delivery logistics.

A **bioLPG boiler** is not different from a conventional LPG boiler. Evidence suggests that biopropane can be used as a drop-in fuel in LPG boilers without the need of adaptation. The use of this technology requires the installation of a gas cylinder for the storage of bioLPG.

[6] Element Energy for BEIS 2019, Evidence gathering for electric heating options in off gas grid homes

The use of **bioliquid boiler (B100)**, burning 100% biodiesel was also investigated. While the overall configuration of a bioliquid boiler is similar to that of a standard oil boiler, bioliquid cannot be utilised as a drop-in fuel in existing oil boilers, unless it is utilised in a fuel blend (e.g. B30K, composed of 30% biodiesel and 70% kerosene)[7]. An oil boiler utilising 100% biodiesel requires a few dedicated adaptations, such as an optimised design for the burner. Additionally, the installation of a preheated fuel tank may be required, as biodiesel must generally be stored at a temperature between 5˚C and 15˚C, to ensure it maintains a low viscosity[7]. Particular attention must also be paid to the compatibility of the materials used in the boiler, pipes and storage tank that come in contact with the biodiesel, as some have been reported to degrade more easily than when exposed to conventional diesel[7].

The use of domestic resources for bioenergy in Scotland has the potential to more than double from the current value of 6.7 TWh per year to 14 TWh per year by 2030. However, there is strong market competition and practical constraints which limit the availability and suitability of certain feedstock types. This report has not taken into consideration the availability of bioenergy feedstocks.

Low-carbon gas boilers

Low-carbon gas boilers are heating devices burning low-carbon fuel delivered by the gas grid. The main options that are commonly considered for the decarbonisation of the gas grid are the use of hydrogen or biomethane, either to be used pure or to be blended with natural gas.

Hydrogen boilers investigated in this study are assumed to be burning 100% hydrogen. The technical challenges of burning hydrogen, compared with the combustion of natural gas, are related to a higher flame speed and the associated risk of light-back, as well as a higher creation of NO_x and the higher risk of explosion of unburned gas[8]. The layout of the burner and other components of the hydrogen boiler are therefore adapted to accommodate these technical requirements.

Biomethane grid injection consists of blending a portion of biomethane into the gas grid. The type of heating technology required in the case of biomethane grid injection will depend on the future decarbonisation of the gas grid. In fact, partial or total decarbonisation could be achieved in future though the supply of a gas blend composed of hydrogen and natural gas in varying proportions. In the case of biomethane grid injection, a portion of biomethane would also be added to the blend. While blends with hydrogen concentration below 20 mol% are expected to be compatible with combustion in conventional gas boilers[9], blends with higher hydrogen content would require the installation of a hydrogen boiler.

Hybrid heat pumps

Hybrid heat pumps are low-carbon heating systems that combine a heat pump with a different heating technology, thus integrating the low-carbon performance of a heat pump with the reliability of an additional heating unit as backup for the colder winter months. As heat pump efficiency depends on both the outside temperature and the temperature at which

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[7] NNFCC for BEIS 2019, Evidence Gathering for Off-Gas Grid Bioliquid Heating Options
[8] Frazer-Nash Consultancy for BEIS 2018, Appraisal of Domestic Hydrogen Appliances
[9] HyDeploy 2020, UK's first grid-injected hydrogen pilot gets underway

it delivers heat, the two technologies of a hybrid system are operated alternatively, choosing the technology that offers the highest efficiency and level of thermal comfort at a given time[10].

The hybrid heat pump systems considered in this study combine an **ASHP** with either a **gas boiler**, **bioliquid boiler**, **hydrogen boiler** or **direct electric heating**. Their suitability was analysed both in combination with a hot water cylinder or standalone with no production of hot water. It is assumed that 80% of the annual space heating demand is met by the heat pump and the remaining 20% by the additional heating unit. Hot water demand is entirely met by the additional heating unit, except for hybrid heat pumps with direct electric heating, for which hot water demand is assumed to be met by electric on-demand devices, such as electric taps.

Heat networks

District heating networks deliver heat from a common energy source to a large number of homes through a pipe network. A low-carbon heat network can be operated using a range of technologies such as a heat pump, biomass boiler, or solar thermal unit, or by recovering waste heat from industrial processes[11]. Centrally generated hot water or steam is distributed through an underground pipe network and is delivered to a heat exchanger in each home to produce space heating and hot water on demand.

Solar thermal

Solar thermal collectors can be installed alongside various heating technologies to support the production of hot water. Considered technologies in this study are the combinations of solar thermal with ASHP, electric storage heating, direct electric heating and electric boilers, all requiring the connection to a hot water cylinder to supply hot water. For these combinations, it is assumed that 60% of hot water demand is delivered by the solar thermal system and the remaining 40% is met by the heating system.

2.2 Factors influencing suitability of low-carbon heating

2.2.1 Technical factors

The suitability of homes for the low-carbon heating technologies considered in this study is determined by a range of potential barriers.

Space constraints

Lack of internal space for the installation of large units or large hot water cylinders can affect the suitability for the installation adoption of heat pumps and other heating technologies associated with a hot water cylinder.

Scarce availability of external space can impact the suitability for installation of external components of the heating system, such as a horizontal ground loop for a ground-source heat pump, a gas cylinder for the storage of bioLPG, or a biofuel tank required by a bioliquid boiler. Additionally, it can constitute an obstacle to the implementation of biomass heating, which requires external space for the storage of the fuel. Finally, the lack of wall space for an

[10] Element Energy for BEIS 2017, Hybrid Heat Pumps
[11] Element Energy 2015, Research on district heating and local approaches to heat decarbonisation

external unit or a suitably orientated roof can influence the suitability of an air-source heat pump or solar thermal collectors.

Dwelling type

Communal heat pump systems are most cost-effective when installed in homes located close to each other, such as terraces and flats, due to the lower cost of piping and associated groundwork.

Heat demand

Peak heat demand and peak specific heat demand are two important parameters influencing the suitability of various low-carbon heating technologies. Peak heat demand is here defined as the maximum heat demand of a home at a given time, typically occurring on the coldest winter day and measured in W. This measures the amount of heat that must be supplied to a home to maintain thermal comfort. Peak specific heat demand is calculated as peak heat demand divided by the total floor area of the habitable rooms and is measured in W/m^2. Large specific heat demand is generally associated with homes that are poorly insulated and/or located in cold climates. Large heat demand, on the other hand, can be a result of both large specific heat losses and of large dwelling size.

Heat pumps in dwellings with large **peak specific heat demand** (typically above 150 W/m^2) are at risk of not meeting thermal comfort, as this requires the installation of very large radiators and/or the heat pump to produce space heating at a higher temperature – and reduced energy performance. The average peak specific heat demand across Scottish homes is 87 W/m^2 and only ~1% of Scottish homes are estimated to currently have peak demand above 150 W/m^2.

Additionally, a large **peak heat demand** may be unsuitable for any technology that generates heat from electricity, such as direct and storage electric heating, heat pumps and hybrids. Large peak heat demand of cold winter days may result in an electricity demand triggering the fuse limit of the building, rendering it unsuitable to electric heating technologies. While the efficiency of direct heating and storage heating is assumed to be 100%, the performance factor of heat pumps is expected to decrease with the external temperature. Therefore, while on cold winter days electricity demand will generally increase due to a larger space heating demand, in the case of heat pumps the electricity demand increment will be exacerbated by a reduced performance of the heating technology. In this study it was assumed that heat pump technologies will operate at average external temperature of ~8°C and minimum external temperature of -10°C[12].

While there is not sufficient information available on the fuse limit of individual Scottish homes, it is assumed that typical values will lay in the range of 30A to 100A[13], the latter being the maximum fuse rating available for a single-phase domestic connection. Load increases to up to 100A generally involve the replacement of the fuse alone and are associated with little to no cost, depending on the state of the connection cables and on the network operator (not exceeding a few hundred £[14]). For load increases above 100A, an upgrade to a three-phase connection is also possible for individual dwellings. This is however associated with

[12] Met Office: Northern Scotland: climate
[13] Energy Networks Association 2019, Distribution Network Operator Cut-out Types & Ratings Guidance
[14] SSEN, Service alteration

significant costs, expected to be of the order of a few thousand £, and may require several weeks to be completed, especially if a permit for digging the power cables is required from the local authority[15]. Where an upgrade of the fuse limit would result to be too costly or undesirable, an alternative option would be the installation of an electric battery, to support the supply of power to the heating device, or of a heat battery, to support the delivery of heat to the home alongside the heating system.

The implementation of heating technologies that rely on electricity may not only face suitability obstacles in certain homes but may also represent a burden for the distribution network. Additional costs for network reinforcement must be considered.

In this study, peak heat demand was estimated from the yearly heat demand, assuming peak heating load factor of 16%. In other words, peak heat demand was assumed to be the power that would be provided by the heating system if it were operating for about 3 hours and 50 min per day and delivering the yearly heat demand over the course of one year. Note that this assumption has a large impact on assessment of the number of homes that may be affected by peak heat demand constraints. In fact, a larger peak heating load factor, would result in smaller peak heat demand and therefore also a smaller number of homes in which the implementation of electric resistive heating or heat pumps may trigger the fuse limit or contribute to the risk of not meeting thermal comfort.

Coastal location

Air-source heat pumps located close to the sea are subject to a reduced lifetime, due to the accelerated corrosion of the heat exchanger caused by the salinity of air. Malfunction of the heat pump can be prevented by applying a coating on the heat exchanger; however, this adds to the capex costs of the appliance and may increase operational costs due to maintenance.

Geological characteristics

Local geological characteristics may influence the implementation of GSHP, impacting the suitability for the installation of a vertical ground loop[16].

Gas grid and district heating network proximity

Dwellings located in areas away from the gas grid are not suitable for hydrogen boilers and biomethane grid injection. Similarly, the connection to a district heating network may not be available for homes in areas of low heat density.

Air quality restrictions

Restrictions on air quality may affect the suitability of fuel combustion appliances. In fact, biomass boilers are responsible for the emission of a substantially larger amount of particulate matter (PM2.5) per kWh of heat than gas boilers[17], while high-temperature boiler systems such as hydrogen boilers may produce a high level of NOx emissions[18], adversely affecting local air quality, typically most critical in urban areas. This factor was not included in our suitability assessment.

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15 UKPN, Upgrade electricity: Time and cost

16 Busby et al. 2009, Initial geological considerations before installing ground source heat pump systems

17 BEIS 2018, Renewable heat incentive: biomass combustion in urban areas

18 Frazer-Nash Consultancy for BEIS 2018, Appraisal of Domestic Hydrogen Appliances

Noise pollution

Concerns around noise pollution may discourage the implementation of heat pumps, especially in densely populated urban areas, where multiple units may need to be installed in close proximity. This factor was not included in our suitability assessment.

Complementary measures

The implementation of certain low-carbon heating technologies may involve complementary measures, such as the installation of additional equipment, leading to additional costs and disruption for the occupants:

- Installation or replacement of wet heating system, required when replacing electric resistive heating with low-carbon boilers or generally when installing a heat pump;
- Installation of a hot water cylinder;
- Local network reinforcement;
- Replacement of cooking appliances, required when disconnecting from the gas grid;
- Replacement of electrical wiring or gas pipework;
- Installation of a fuel tank or biomass storage.

2.2.2 Heritage factors

Additional barriers need to be considered when assessing the suitability of low-carbon heating technologies and energy performance upgrades in heritage homes and in old dwellings (pre 1919).

Heritage homes are defined here to include both Listed buildings (Category A, B, C) and homes in Conservation areas, which are respectively buildings and areas of architectural or historic interest, benefiting from statutory protection under the Planning (Scotland) Act 1997. Planning consent is required to make changes to the external appearance and, for listed buildings, to the internal fixtures of these homes.

A recent study[19] by Element Energy for the Committee on Climate Change on hard to decarbonise homes included a high-level analysis of the technical suitability of low-carbon heating technologies and energy performance upgrade measures for heritage homes in the UK, providing both a qualitative and a quantitative appraisal.

Due to the complexity and case-by-case nature of the barriers to retrofit in heritage and old homes, as well as the high level of simplification that would be required to perform a quantitative analysis, this study will only provide a qualitative assessment of the suitability of Scottish heritage homes to low carbon heating and energy efficiency measures. This approach was supported by consultation with experts at Historic Environment Scotland.

Low-carbon heating technologies generally encounter fewer obstacles than energy efficiency measures in their implementation in heritage and old homes, as they require less disruption and integration of new materials. Following considerations on the barriers to implementation

[19] Element Energy 2019, Analysis on abating direct emissions from 'hard-to-decarbonise' homes

of low-carbon heating technologies and energy performance upgrade measures in heritage and old homes were provided by Historic Environment Scotland.

Barriers to low-carbon heating technologies

- **Solar thermal**: Both aesthetics and technical aspects of the installation, such as the roof material, the weight of the collectors and the location of the pipes, can be an obstacle to suitability. Suitability will need to be assessed on a case-by-case basis through the application for planning permission, where required.
- **Bioliquid boiler**: A potential barrier to the implementation of bioliquid boilers is represented by a potential limitation to the installation of a bioliquid tank outside a heritage home, due to aesthetics.
- **GSHP, district heating**: Excavation works and laying pipes on heritage properties can raise complexities due to e.g. archaeological findings. Nevertheless, these obstacles have little impact on suitability of the technology and mainly increase the cost of the installation.
- **ASHP, hybrids**: The main restrictions are related to the placement of the outdoor unit such that it does not affect the external appearance of the dwelling.
- **Less visible** or more standard technologies (communal heating or boilers) are considered to be feasible in all buildings.

Barriers to energy performance upgrade measures

- **Wall insulation**: The suitability of wall insulation is highly dependent on the wall configuration and on the type of insulating material used. Suitable insulating materials include wood fibreboard, hemp fibre and foam, while phenolic or plastic materials are commonly not accepted. Unfortunately, suitable wood fibreboard panels are often thin and less insulating than phenolic or plastic materials, and result in lower energy savings. It is additionally important to tailor the insulation solution to the wall structure, in order to prevent thermal bridges, to maintain weather-proofing of the external walls and to allow for air circulation to prevent condensation. External wall insulation, in particular, may require the extension of exterior elements, such as pipes and windowsills, in order to maintain the original appearance of the façade. Cavity insulation is generally not suitable, as cavities, where present, are often non-standard.

- **Window glazing**: Secondary glazing is broadly preferred to the substitution of the existing windows with double glazing in listed buildings, as the characteristics and value of the original panels are not replicable.

- **Door insulation**: Poorly insulated old doors should not be replaced with new doors but rather upgraded through draught proofing. This measure is in fact sufficient to significantly reduce heat losses and improve the energy performance of a home, while preserving the heritage value of the original door.

- **Roof insulation**: Obstacles are associated with roof insulation are generally minor. For slate roofs, slate vents should be installed, in order to prevent condensation, as the board onto which slates are mounted will become colder after roof insulation. Alternatively, another available solution is over the roof insulation.

- **Ventilation**: Ventilation measures are generally well tolerated in heritage and old homes.

- **Overheating prevention**: Overheating prevention measures are rarely applicable to heritage homes, due to their high impact on the outer appearance of the dwelling.

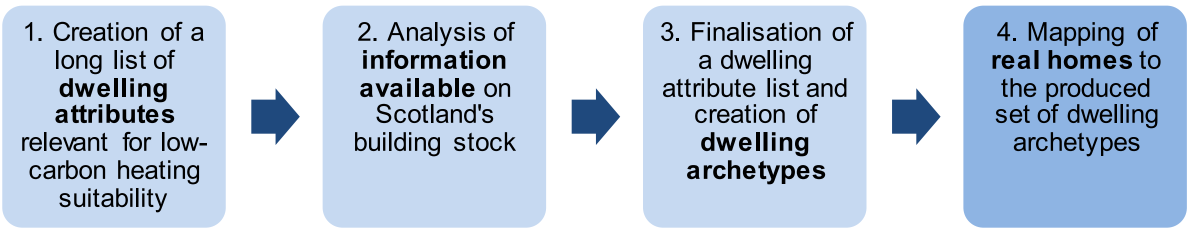
3 Construction of a model representative of Scotland’s domestic building stock

In order to capture the distribution of hard to decarbonise features across Scotland’s existing and future building stock, a stock model was developed. The model was produced based on a set of representative dwelling archetypes and on information about existing homes reported in the Home Analytics database.

The dwelling archetypes utilised in the stock model are defined by a list of attributes that most strongly determine the current and potential energy performance of a home, such as size, insulation type, age, existing heating system and baseline energy demand. Additional factors that directly influence the suitability of a dwelling for low-carbon heating technologies were also included, such as coastal location, space constraints and location on the gas grid or on heat networks.

After the creation of a set of dwelling archetypes, each defined by a unique combination of attribute values, all existing homes listed in the Home Analytics database were associated with the dwelling archetype that best represented their characteristics. The number of existing homes represented by each archetype could therefore be included in the model, quantifying the relevance of each archetype in the Scottish dwelling landscape.

The diagram below illustrates the methodology adopted for the development of a stock model representative of Scotland’s housing stock.



3.1 Creation of a long list of attributes

Based on the thorough analysis of factors influencing suitability of dwellings for the considered low-carbon heating technologies as described in section 2.2, an initial long list of potential attributes was produced. A summary of all considered attributes, together with a description of how each attribute can influence dwelling suitability is summarised in Table 2.

Table 2: Investigated attributes that influence suitability for low-carbon heating

Potential attributes	Potential values	Influence on suitability of low carbon heating
Property type	Detached house, Semi-detached house, Mid-terraced house, End-terraced house,	• Physical space constraints • Availability of roof or outside wall space for heat pump unit or solar thermal array, land for a ground source heat array, storage for biomass/bioLPG etc.

Potential attributes	Potential values	Influence on suitability of low carbon heating
	Small block of flats/property converted into flats, Block of flats, Large block of flats, Flats in mixed use building	• Flats can present challenges in coordinating works from all tenants • High rise can be hard to treat, have restrictions on gas connection etc.
Size	Depending on floor area	• Physical space constraints for e.g. hot water storage cylinder, heat pump and hybrid heat pump units
Age	Depending on date of construction	• Age strongly correlated with aspects of construction type (e.g. solid walls, roof materials) • Even if not listed or in conservation areas, some old/traditional buildings may be subject to similar limitations
Wall type and insulation	Solid, cavity, pre-fab, timber, stone, with various levels of insulation	• Hard to treat wall types do not have low-cost cavity wall insulation options available and/or pose technical difficulties or risks of poor performance • Hard to fill cavities risk poor distribution of filling and resulting thermal bridges • Unfillable cavities must be treated as solid walls, with more expensive external or internal wall insulation
Roof type and insulation	Flat, pitched, accessible/inaccessible (e.g. Mansard roofs) and others, with various insulation levels	• Homes without a loft space, or with an inaccessible loft space (including Mansard roofs) cannot install standard roof insulation
Existing heating system	Gas, Electric resistive, Electric storage, Oil boiler, Solid fuel, Community heating, and others	• Existing heating system impacts what additional works may be required on installing a low carbon heating system – for example, whether this will require a new heat distribution system, hot water cylinder, additional wiring (distributed electric heating)
District heating potential	Located in an area of high heat demand density or not	• Potential for a connection to a local low-carbon district heating network
Gas network location	On or off the gas grid	• Access (or not) to decarbonised gas through the gas grid
Location (urban/rural)	Various categorisations (e.g. Home Analytics has 8 categories): e.g. Large urban area, Remote small town, Accessible rural, etc.	• Bioenergy options less suitable in urban areas due to air quality concerns; more suitable in rural areas close to sustainable sources • Influences likelihood of external space/land for a ground array, or fuel storage facilities

Potential attributes	Potential values	Influence on suitability of low carbon heating
Consumer type (tenure) and fuel poverty	Owner-occupied, private rented, local authority Probability of being in fuel poverty	• Consumer type affects the likelihood of uptake of energy efficiency measures, due to affordability, alignment of tenant and landlord priorities, coordination of works, and ease of regulation (e.g. legislation of standards of private rented homes)
Space constraints	Constrained, Not constrained	• Limited internal space restricts the choice of heating system to those without large units or hot water storage, and limits installation of internal wall insulation
Orientation suitable for solar thermal	North/East/West/South, depending on roof orientation	• Roof orientation impacts suitability of solar thermal collectors
High exposure to wind and rain	Yes, No	• Impacting suitability, effectiveness and cost of wall and roof insulation
Coastal location	Yes, No	• Proximity to the coast can reduce the durability of ASHP, as high air salinity accelerates corrosion of the heat exchanger. • Malfunction of the heat pump can be prevented by applying a coating on the heat exchanger, resulting in added costs.

3.2 Analysis of information available on Scotland's building stock

Home Analytics Scotland is a dataset of energy efficiency variables and property characteristics for the entire Scottish housing stock. It was the primary dataset used to populate the attributes in Table 2 for Scotland’s existing, domestic building stock. The data contained within the database is provided down to the address level and is available to the Scottish Government and local authorities in Scotland to assist in developing, targeting and delivering policies, schemes and programmes designed to improve energy efficiency, install renewable micro-generation technologies, and alleviate fuel poverty.

The Home Analytics dataset is a combination of actual values and modelled values. Actual values are obtained from a variety of sources, such as Energy Performance Certificate (EPC) records, Home Energy Efficiency Database (HEED) and Home Energy Efficiency Programmes for Scotland Area Based Schemes (HEEPS: ABS) installation records, EST’s Home Energy Check (HEC) records, SGN gas meter data, OS AddressBase, OS MasterMap Topography layer and the Scottish Census.

In cases where a property record is not available for a particular variable, models are used to impute (i.e. predict) the value of the variable based on the other building attributes and energy efficiency characteristics of the property. The methodology used to produce the final Home Analytics database depends on the underlying data sources and the variables being modelled. Typically, variables in Home Analytics are imputed using one of four types of models: spatial, statistical, derived or apportioned.

Home Analytics Scotland encompasses a wide range of physical, geographical, energy efficiency and socio-demographic factors. From the attribute list in Table 2, Home Analytics provided data on property type, size, age, listed building and conservation status, wall type and insulation, roof type and insulation, primary fuel type, gas network location, urban/rural classification, tenure, fuel poverty, roof orientation and exposure to wind driven rain. Unfortunately, it could not provide data on roof type (e.g. pitched, flat), specific heating systems (e.g. electric resistive), heat network connection suitability, coastal location or space constraints.

3.3 Archetypes representing Scotland's domestic building stock

The archetypes utilised in the stock model are determined by a list of attributes that can assume a range of values. While the set of attributes is fixed for all archetypes, each archetype is uniquely identified by a different combination of attribute values.

The choice of attributes to be included in the archetype definition was based on the long list of relevant attributes influencing the suitability of low-carbon heating reported in Table 2 and on information provided by Home Analytics on the characteristics of the Scottish housing stock. Additional relevance was placed on keeping the number of archetype and value combinations considered in our modelling to a minimum, so to reduce the computational complexity of the modelling, while ensuring an appropriate coverage and representation of the real housing stock. An overview of the selected attributes and their associated values is provided in Table 3.

Table 3: Attributes selected for the creation of dwelling archetypes

Attributes	Values	Notes
Age	• Pre-1919 • 1919-1991 • Post-1991	The age group 1919-1991 was not further disaggregated, as associated potential restrictions on renovation and materials are expected to be similar among this group.
Property type	• Detached • Semi-detached • Terraced • Flat (block) • Flat (other)	'Semi-detached' includes both semi-detached houses and end-terraced houses, as these are expected to have similar heat demand per unit floor area, having the same number of external walls. 'Terraced' only includes mid-terraced houses. 'Flat (block)' includes homes in large blocks of flats, composed of >15 residential dwellings located within a single building. 'Flat (other)' includes homes in smaller blocks of flats, composed of up to 15 residential dwellings located within a single building.

Attributes	Values	Notes
Size	• Small (< 66 m^2) • Medium (66 – 108 m^2) • Large (> 108 m^2)	Information on total dwelling floor area per habitable room (m^2) collected from Home Analytics was retained in our model and categorised in three bands.
Wall insulation	• SWI - Solid wall insulated • SWU - Solid wall uninsulated • CWI - Cavity wall insulated • CWU - Cavity wall uninsulated with low exposure to wind and rain • CWU exposed - Cavity wall uninsulated with high exposure to wind and rain	For efficient management of the computational parameters, the attributes 'High exposure to wind and rain' and 'Wall type and insulation' were merged. With reference to the parameters indicated in the BRE Report 262 ("Thermal insulation: avoiding risks", 2002), 'high exposure to wind and rain' corresponds to 'very severe' or 'severe' exposure. Similarly, 'low exposure to wind and rain' corresponds to 'sheltered' or 'moderate' exposure.
Roof insulation	• <100 mm • 100-250 mm • >250 mm • Room in roof • No loft	Homes with non-habitable space in the loft were assigned a value according to the thickness of their roof insulation ('<100 mm', '100-250 mm' or '>250 mm'). Homes with habitable space in the loft were assigned the value 'Room in roof' for insulation of less than 200 mm, or the value '>250 mm' for insulation of more than 200 mm. Homes with no access to the loft (e.g. flats) were assigned the value 'no loft'.
Existing heating system	• Gas boiler • Oil boiler • Electric • Other	'Oil boiler' heating systems include both oil and LPG boilers. 'Electric' heating systems include electric storage and direct electric. 'Other' heating systems include: biomass boilers, solid fuel boilers, communal heating and homes with no heating system. The type of pre-existent heat distribution system was not considered a barrier to suitability of heating technologies.
Orientation suitable for solar thermal	• Yes • No	Homes with roofs facing South, South-West or South-East were assigned the value 'Yes'.
Location	• Urban • Rural	Classification based on Scottish Government Urban Rural 8-fold

Attributes	Values	Notes
		Classification 2016[20]. Attribute used to test the suitability of GSHP only.
Coastal location	• Yes • No	Homes located less than 5 km from the coastline were assigned the value 'yes'.
Gas network location	• On gas grid • Off gas grid	'On gas grid' refers to homes located in an area supplied by the gas grid. This includes both homes that already have a connection and homes that do not. 'Off gas grid' refers to homes located away from the gas grid.
District heating potential	• Yes • No	Value 'Yes' was assigned to homes located in areas where current annual heat demand density is above a threshold of 40kWh/m^2/year.

From this list, a set of ~140,000 different **dwelling archetypes** was produced, each representing a unique combination of all chosen attribute values. Each archetype constitutes therefore a simplified representation of a dwelling, equipped with a unique set of physical and geographical characteristics that are useful in the assessment of low-carbon heating suitability.

In order to calculate the stock of each dwelling archetype in the Scottish landscape, all 2.66 million existing homes in Scotland entered in the EST Home Analytics database were aggregated based on the attributes reported in Table 3. The number of existing homes represented by each archetype was therefore included in the model, providing information on the amount of real homes that may be associated with the same suitability constraints of a particular archetype.

A large number of the initial ~140,000 dwelling archetypes resulted to be associated to none of the existing homes. These 'empty' archetypes were therefore discarded and further analysis on the suitability of low-carbon heating was performed only on the remaining set of ~54,000 useful archetypes that resulted to represent existing homes. An overview of the 20 most common dwelling archetypes on the gas grid and off the gas grid is reported in Table 4 and Table 5 respectively.

[20] Scottish Government, Urban Rural Classification 2016

Table 4: Characteristics of the 20 most common archetypes on the gas grid

Archetype ranking	Property Type	Size	Age	Wall Insulation	Roof Insulation (mm)	Heating system	Solar orientation	Coastal location	DH potential	Stock
1	Semi detached	Medium	1919 to 1991	CWI	More than 250	Gas boiler	Yes	No	No	34,973
2	Semi detached	Medium	1919 to 1991	CWI	More than 250	Gas boiler	Yes	Yes	No	27,196
3	Semi detached	Medium	1919 to 1991	CWI	100 to 250	Gas boiler	Yes	No	No	17,189
4	Flat (other)	Small	Pre 1919	SWU	None	Gas boiler	Yes	Yes	Yes	16,463
5	Semi detached	Medium	1919 to 1991	CWI	100 to 250	Gas boiler	Yes	Yes	No	13,083
6	Terraced	Medium	1919 to 1991	CWI	More than 250	Gas boiler	Yes	No	No	11,725
7	Flat (other)	Medium	1919 to 1991	CWI	None	Gas boiler	Yes	Yes	No	11,285
8	Flat (other)	Medium	1919 to 1991	CWI	None	Gas boiler	Yes	Yes	Yes	11,091
9	Flat (other)	Medium	Pre 1919	SWU	None	Gas boiler	Yes	Yes	Yes	10,788
10	Flat (other)	Medium	1919 to 1991	CWI	None	Gas boiler	Yes	No	No	10,740
11	Semi detached	Medium	1919 to 1991	CWI	More than 250	Gas boiler	No	No	No	10,563
12	Flat (other)	Small	Pre 1919	SWU	None	Gas boiler	No	Yes	Yes	10,430
13	Detached	Large	Post 1991	SWI	More than 250	Gas boiler	Yes	No	No	9,606
14	Flat (other)	Small	1919 to 1991	CWI	None	Gas boiler	Yes	Yes	Yes	9,445
15	Semi detached	Medium	1919 to 1991	CWI	More than 250	Gas boiler	No	Yes	No	8,769
16	Flat (other)	Small	1919 to 1991	CWI	None	Gas boiler	Yes	Yes	No	8,498
17	Flat (other)	Small	1919 to 1991	CWI	None	Gas boiler	Yes	No	No	8,383
18	Terraced	Medium	1919 to 1991	CWI	More than 250	Gas boiler	Yes	Yes	No	8,337

Archetype ranking	Property Type	Size	Age	Wall Insulation	Roof Insulation (mm)	Heating system	Solar orientation	Coastal location	DH potential	Stock
19	Semi detached	Medium	1919 to 1991	CWI	More than 250	Gas boiler	Yes	No	Yes	7,862
20	Semi detached	Medium	1919 to 1991	CWU exposed	More than 250	Gas boiler	Yes	No	No	7,588

Table 5: Characteristics of the 20 most common archetypes off the gas grid

Archetype ranking	Property Type	Size	Age	Wall Insulation	Roof Insulation (mm)	Heating system	Solar orientation	Coastal location	DH potential	Stock
1	Detached	Large	Pre 1919	SWU	Room in roof	Oil boiler	Yes	No	No	9,075
2	Semi detached	Medium	1919 to 1991	CWI	More than 250	Electric storage	Yes	No	No	3,937
3	Detached	Large	Post 1991	SWI	Room in roof	Oil boiler	Yes	No	No	3,780
4	Detached	Large	Pre 1919	SWU	Room in roof	Oil boiler	No	No	No	3,162
5	Detached	Large	Post 1991	SWI	More than 250	Oil boiler	Yes	No	No	3,160
6	Detached	Large	Pre 1919	SWU	More than 250	Oil boiler	Yes	No	No	3,089
7	Semi detached	Medium	1919 to 1991	CWI	More than 250	Electric storage	Yes	Yes	No	2,917
8	Detached	Large	1919 to 1991	SWU	More than 250	Oil boiler	Yes	No	No	2,267
9	Semi detached	Medium	1919 to 1991	CWI	100 to 250	Electric storage	Yes	No	No	1,821
10	Detached	Large	Pre 1919	SWU	Room in roof	Oil boiler	Yes	Yes	No	1,815
11	Detached	Large	Pre 1919	SWU	100 to 250	Oil boiler	Yes	No	No	1,784
12	Flat (blocks)	Medium	1919 to 1991	SWI	None	Electric storage	Yes	Yes	Yes	1,757
13	Detached	Large	1919 to 1991	SWU	100 to 250	Oil boiler	Yes	No	No	1,739

Archetype ranking	Property Type	Size	Age	Wall Insulation	Roof Insulation (mm)	Heating system	Solar orientation	Coastal location	DH potential	Stock
14	Terraced	Medium	1919 to 1991	CWI	More than 250	Electric storage	Yes	No	No	1,709
15	Detached	Large	Post 1991	SWI	More than 250	Oil boiler	No	No	No	1,691
16	Detached	Large	Pre 1919	SWU	More than 250	Oil boiler	No	No	No	1,680
17	Flat (blocks)	Small	1919 to 1991	SWI	None	Electric storage	Yes	Yes	Yes	1,649
18	Semi detached	Medium	1919 to 1991	CWI	100 to 250	Electric storage	Yes	Yes	No	1,637
19	Detached	Large	1919 to 1991	SWU	Room in roof	Oil boiler	Yes	No	No	1,598
20	Detached	Large	Post 1991	SWI	Room in roof	Oil boiler	No	No	No	1,581

3.4 Scotland's housing stock in 2017

3.4.1 Calibration of total number of homes

While Home Analytics counts ~2.66 million homes in its database, figures by Scottish Government report ~2.46 million households in Scotland in 2017[21]. The difference in the total figures is likely due to differences in the definition of a dwelling and likely aggregation of multiple units.

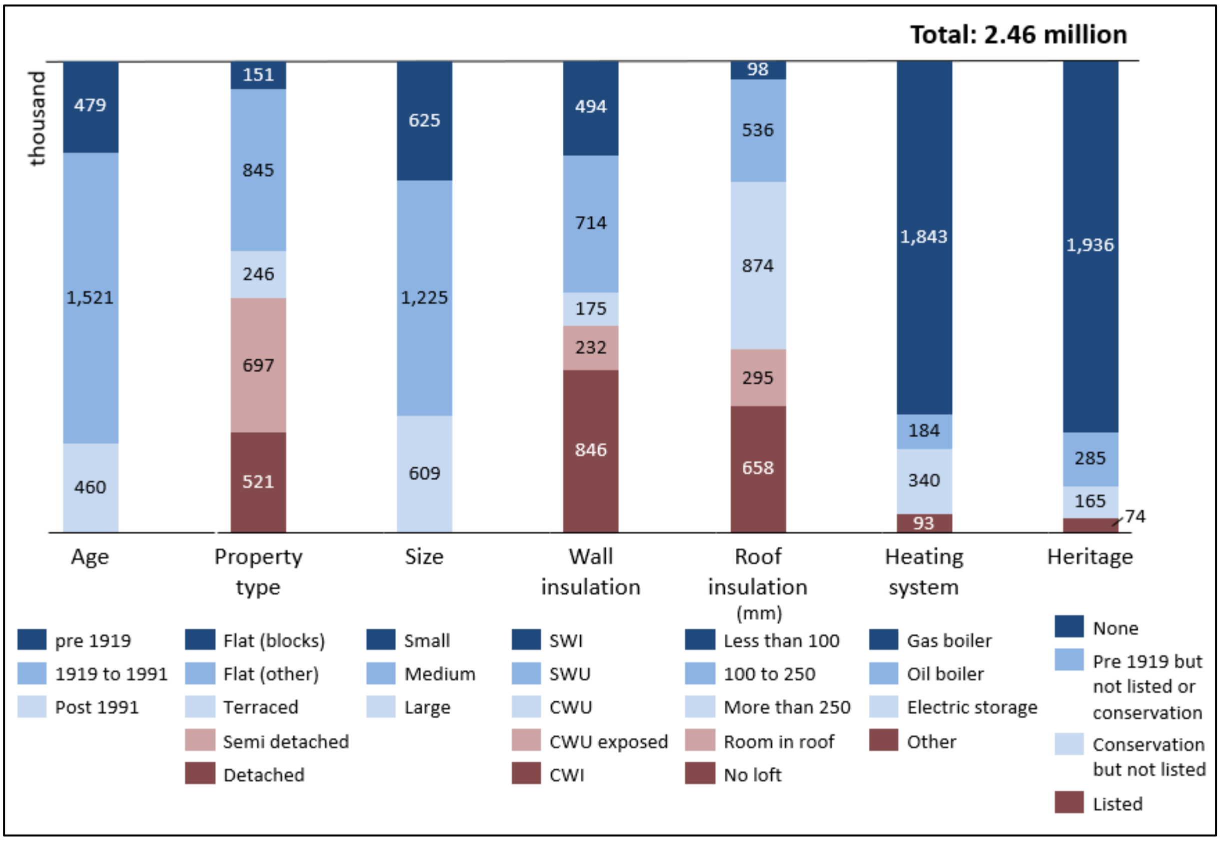
In order to render the stock model compatible with the official figures by Scottish Government, a calibration was performed by applying a multiplication factor to the number of homes assigned to each dwelling archetype, so that the total number of homes included in the model would add to 2.46 million.

3.4.2 Results

An initial useful output of the stock model is a representation of the characteristics of the current Scottish housing stock, based on a set of interesting attributes. Figure 1 reports the breakdown of homes in the stock according to their age, property type, size, wall insulation, roof insulation, existing heating system and heritage status. The assessment of the current state of the Scottish housing stock is based on information available for the year 2017.

[21] Scottish Government 2019, Scottish Government 2020, Annual compendium of Scottish energy statistics

Figure 1: Breakdown of Scotland's housing stock in 2017 depending on various attributes



3.5 Scotland's housing stock in 2040

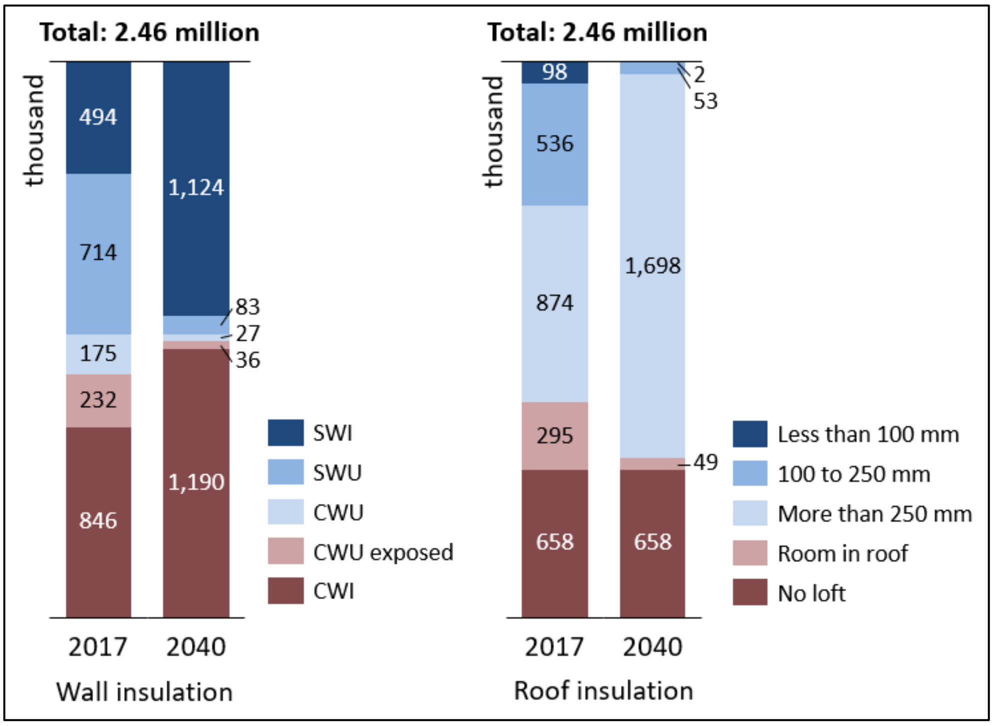
The suitability of low-carbon heating technologies within the Scottish housing stock will change over time as homes become more energy efficient.

The Energy Efficient Scotland Route Map, published in May 2018, sets a target for all owner-occupied homes to reach EPC band C by 2040, where technically feasible and cost effective. Energy efficiency measures that will therefore need to be implemented between 2017 and 2040 in homes with lower energy efficiency performance include measures that will modify some of the characteristics of a home. In particular, modifications that are relevant for this study include the type of insulation and annual space heating demand.

In order to assess the influence of the implementation of expected energy upgrade measures on the characteristics of the existing building stock in 2040, EST's Portfolio Energy Assessment Tool (PEAT) was used to forecast future changes. A detailed description of the analysis performed with PEAT is reported in the appendix on page 76.

The influence of the implementation of energy efficiency measures considered by PEAT on the characterisation of the housing stock primarily affects two of the modelled attributes: wall insulation and roof insulation. Other attributes are more tied to the characteristics of the home structure and can therefore not be modified. Figure 2 reports the breakdown of homes in the stock in terms of the types of wall insulation and roof insulation in 2040 and compares these with the corresponding figures for 2017, before the implementation of the energy efficiency upgrade measures.

Figure 2: Modification of Scotland's housing stock after the implementation of energy efficiency upgrades



The number of homes with wall insulation (Solid Wall Insulated or Cavity Wall Insulated) is expected to increase from 54% of the stock in 2017 to 94% in 2040, with nearly two thirds of wall insulation upgrade interventions performed on solid wall homes.

While 27% of dwellings in Scotland are not connected with their building's roof and therefore require no roof insulation (value "no loft"), the number of homes with roof insulation of less than 250 mm thickness or with poorly insulated room-in-roof is expected to reduce from 38% of the stock in 2017 to 4% in 2040.

3.6 Technical suitability of selected low-carbon heating technologies

In order to assess which dwelling archetypes of the stock model are suitable for the investigated heating technologies, assumptions were made around the compatibility of the technologies with the dwelling characteristics described by the archetype attributes. An overview of these assumptions is reported in Table 6. Findings around the suitability of each archetype were later utilised to assess the suitability of Scotland's building stock in 2017 and 2040.

Table 6: Technical suitability matrix

	Heating systems	Heat demand	Dwelling type					Space constraint		District heating		Solar thermal		Coastal location		Gas network	
			Detached	Semi-detached	Mid-terrace	Flat (block)	Flat (other)	Yes	No	Yes	No	Yes	No	Yes	No	On gas grid	Off gas grid
1	ASHP	(1)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	(4)	Y	Y	Y
2	GSHP	(1)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y
3	High-temperature ASHP	(2)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	(4)	Y	Y	Y
4	High-temperature GSHP	(2)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y
5	Communal ASHP	(1)	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	(4)	Y	Y	Y
6	Electric storage heating	(2)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
7	Direct electric heating	(2)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
8	Electric boiler	(2)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
9	Solid biomass boiler	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
10	BioLPG boiler	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y
11	Bioliquid boiler B100	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y
12	Hydrogen boiler	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
13	Biomethane grid injection	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
14	Hybrid HP + gas	(2)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	(4)	Y	Y	N
15	Hybrid HP + gas (hwc)	(2)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	(4)	Y	Y	N
16	Hybrid HP + bioliquid	(2)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	(4)	Y	N	Y
17	Hybrid HP + bioliquid (hwc)	(2)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	(4)	Y	N	Y
18	Hybrid HP + hydrogen	(2)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	(4)	Y	Y	N
19	Hybrid HP + hydrogen (hwc)	(2)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	(4)	Y	Y	N
20	Hybrid HP + direct el.	(2)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	(4)	Y	Y	Y
21	Hybrid HP + direct el. (hwc)	(2)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	(4)	Y	Y	Y
22	District Heating	Y	Y	Y	Y	Y	Y	Y	Y	(3)	N	Y	Y	Y	Y	Y	Y
23	ASHP + solar	(1)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N	(4)	Y	Y	Y
24	Electric storage + solar	(2)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
25	Direct electric + solar	(2)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
26	Electric boiler + solar	(2)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y

Legend:

Y	Suitable for all dwellings
(…)	Suitable for some dwellings under specified conditions. See numbers below.
N	Unsuitable for all dwellings

(1) Up to 150 W/m^2 peak demand or fuse limit
(2) Fuse limit
(3) 20% of dwellings in an area with a heat network assumed not to connect
(4) Added cost to account for the need for anti-corrosive coatings

Heat demand – Specific heat loss

Homes with specific peak heat loss rate above 150 W/m^2 were considered unsuitable for the use of conventional heat pumps, as the heat delivered even by large emitters would unlikely meet the heating demand, due to the low temperature at which space heating is provided.

Heat demand – Fuse limit

The installation of electric resistive heating or heat pumps was considered unsuitable in homes with large heat demand, if resulting in peak electrical power consumption exceeding the maximum fuse limit of 100A. Due to the uncertainty of the actual fuse limit values of individual Scottish homes, a sensitivity analysis over a range of potential values was performed. Fuse rating values chosen for the sensitivity analysis were 60A, 80A and 100A. While typical values of fuse rating for single-phase domestic connections in Scotland range from 30A to 100A, modern cut-outs are assumed to have a fuse rating of 60A or higher[22], which can be upgraded to up to 100A typically at no cost for the homeowner. Fuse rating values smaller than 60A were considered not sufficiently interesting for the sensitivity analysis, as these are expected to be found in a limited portion of the domestic building stock.

Dwelling type

Communal ASHP were assumed to be unsuitable for detached, semi-detached and end-terrace homes. All other types of dwellings were considered suitable, due to the reduced length of pipes needed for the connections and thus higher cost-effectiveness.

The dwelling type was also utilised to estimate the overall suitability of homes for the installation of **GSHP and high-temperature GSHP**. In addition to the space, peak specific heat demand and fuse limit constraints, the suitability of a dwelling for GSHP and high-temperature GSHP is also influenced by the geology of the location and on the availability of outside space. In particular, the installation of a vertical ground loop may be impacted by local geological characteristics[23] whereas the installation of horizontal ground loop arrays is predominantly influenced by the availability of sufficient outside area, roughly estimated to be around twice the surface area of the dwelling[24]. Given the lack of information on the geological characteristics of the locations of homes provided by Home Analytics, an overall assessment of the suitability of GSHP and high-temperature GSHP was performed, solely on the basis of the building type and the location in urban or rural areas.

Detached homes are more likely than other dwelling types to have the available outdoor space for the installation of a horizontal ground loop. Additionally, outdoor space availability is more likely to be scarce for the same set of dwelling types in urban areas, when compared to rural areas. A similar approach was taken when considering the installation of a vertical ground loop, as the access and operation of heavy machinery required for the drilling is incompatible with a small garden, if present. An overview of our assumptions on GSHP suitability is summarised in Table 7.

[22] Energy Networks Association 2019, Distribution Network Operator Cut-out Types & Ratings Guidance
[23] Busby et al. 2009, Initial geological considerations before installing ground source heat pump systems
[24] The Renewable Energy Hub UK, A Complete Guide to Heat Pumps in 2020

Table 7: GSHP and high-temperature GSHP suitability

Dwelling type	Dwelling type suitability	Scotland's total stock	Suitable stock
Urban – Detached homes	10%	222,000	22,000
Urban – Terraced or semi-detached homes	5%	639,000	32,000
Urban – Flats	2%	825,000	17,000
Rural – Detached homes	78%	299,000	233,000
Rural – Terraced or semi-detached homes	56%	305,000	171,000
Rural – Flats	56%	170,000	95,000

Suitability assumptions for rural areas are in accordance with the '"high" technical assumptions' scenario of suitability for the RHI Phase II[25].

Space constraint

In order to identify dwellings in which space is constrained, total dwelling floor area per habitable room was calculated. Homes with total dwelling floor area per habitable room smaller than 18m^2 were classified as space constrained, in line with the assumptions of the recent work for the CCC on 'Hard to Decarbonise Homes'[26]. These dwellings were assumed to be unsuitable for the installation of conventional, high-temperature and hybrid heat pumps, due to their additional requirement of a large hot water cylinder for the production of hot water.

District heating

The potential availability of district heating for Scottish homes was assessed on the basis of local heating demand, assuming that district heating networks will be put in place if not already existing in areas where demand for heat is sufficiently high and concentrated. District heating potential was attributed to all homes located in areas in which current annual heat demand density is above a threshold of 40kWh/m^2/year. Heat demand density was calculated both at Data Zone level and on each square of a grid with 1 km^2 resolution, with either of the two tests being sufficient to qualify a home for district heating potential. Data Zones offer good spacial resolution in urban areas, but span over much larger areas outside of cities. The additional assessment of heat density over the 1 km^2 mesh is therefore useful to identify rural areas of localized high heat density that would otherwise not have emerged from the datazone analysis. From this analysis, 32.5% of the Scottish housing stock results compatible with the connection to a potential district heating network. The same analysis performed exclusively on data zones would have produced a smaller compatibility of 27.3% of the stock.

Finally, 80% of homes for which a connection to district heating is possible were assumed to be suitable for district heating, based on expected connection rates and prospective deployment of heat networks in areas with high heat density in line with the assumptions of the recent work for the CCC on 'Hard to Decarbonise Homes'[26].

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[25] AEA for DECC 2012, RHI Phase II – Technology Assumptions
[26] Element Energy & UCL 2019, Analysis on abating direct emissions from 'hard-to-decarbonise' homes

Solar thermal

The suitability of a dwelling for solar thermal was based on the orientation of its roof, and suitability was assigned to homes with roofs facing South, South-West or South-East.

Coastal location

The relative distance from the coast was calculated for each home based on its geographical location. Homes located less than 5 km from the coastline were assigned ‘Coastal location’ value ‘yes’.

While the coastal location of a home alone was not considered a sufficient barrier to the suitability of any technology, additional costs were assumed for the use of air-source heat pumps, due to the necessary measures required to prevent accelerated corrosion of the heat exchanger. Additional costs are expected to arise from the capex premium for the installation of a ‘coastal’ model of heat pump or from the application of a corrosion protection coating on the heat exchanger of a conventional model.

Gas Network location

Homes located outside of areas supplied by the gas grid were considered unsuitable for the adoption of hydrogen boilers, biomethane grid injection, and any of their combinations with heat pumps in a hybrid heating system, as these technologies rely on the fuel being delivered by the gas grid.

On the other hand, homes located in areas supplied by the gas grid were assumed to be incompatible with bioLPG and bioliquid boilers. However, no suitability restriction was posed on biomass boilers, which are assumed to be compatible with both homes on and away from the gas grid.

Current advice by the Committee on Climate Change (CCC)[27] discourages the extensive use of bioenergy for domestic heating, especially in homes where alternative heating solutions are available. Given the similarities in technology and operations of both bioLPG and bioliquid boilers with hydrogen boilers, it was assumed that hydrogen boilers would be preferred to bioLPG or bioliquid boilers in homes located on the gas grid. However, due to the technical differences between biomass boilers and hydrogen boilers, it was assumed that biomass boilers could represent a valid alternative to hydrogen boilers also in some homes located on the gas grid.

[27] CCC 2018 Biomass in a low-carbon economy

4 Suitability of low carbon heating options across Scotland's housing stock

4.1 Barriers to suitability of the housing stock

This section explores the number and the types of homes in the Scottish building stock that are affected by some of the most relevant constraints to the implementation of low-carbon heating. These include space constraints, location off the gas grid, fuse limits and peak specific heat demand. In this section the number of affected homes, and an overview of their characteristics according to the main defining attributes, are reported for each of the four main constraints.

Note that the analysis reported in this section focusses on describing the extent to which a single constraint is present across the housing stock, analysing only one constraint at a time, while not accounting for the others. Conversely, the suitability of the stock to a particular low-carbon heating technology is not determined by one constraint alone, but rather by a combination of a wide set of constraints, described in section 2.2. The overall suitability of the housing stock to each of the considered low-carbon heating technologies is later discussed in Section 4.3.

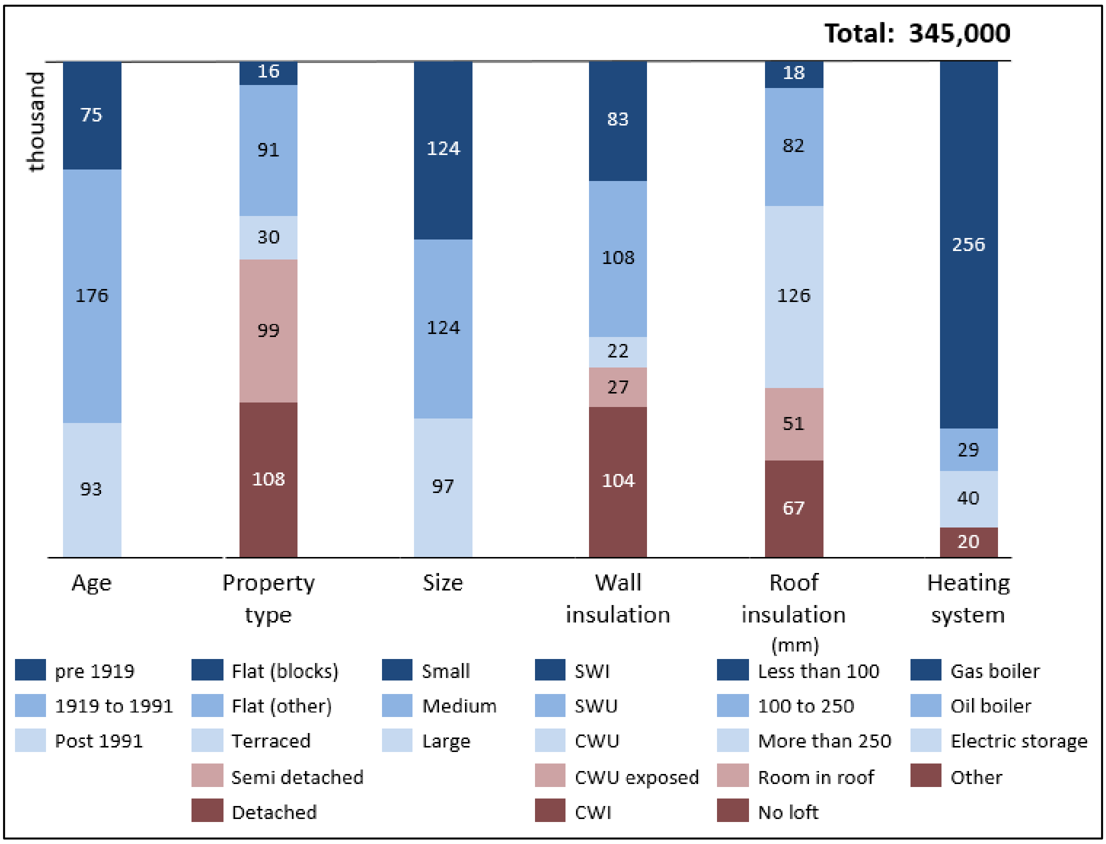
4.1.1 Space constraint

In this study, homes with total dwelling floor area per habitable room smaller than $18m^2$ are considered space constrained. A space constraint is relevant when assessing the suitability of a dwelling to technologies that require a large amount of space for the installation of their equipment. This was assumed to be the case for all conventional, high-temperature and hybrid heat pumps, due to their additional requirement of a large hot water cylinder for the production of hot water.

Figure 3 reports the number of homes currently affected by the space constraint in 2017, as well as a breakdown of their age, property type, size, wall insulation, roof insulation and existing heating system. For comparison with the characteristics of the current entire Scottish housing stock in 2017, see Figure 1 on page 37.

Energy efficiency measures aimed at improving the EPC rating of Scottish homes leading to 2040 as considered in our analysis with PEAT, were assumed to have no impact on the floor area or on the number of habitable rooms. Therefore, the relevance of the space constraint for Scotland's building stock is considered to remain unvaried over the analysed timeframe.

Figure 3: Number and characteristics of homes affected by space-constraint in 2017



The number of homes affected by the space constraint results to account for about 14% of Scotland's housing stock.

The portion of homes that results show to be affected by the space constraint tends to be composed of more newer homes, compared with the overall age distribution of the Scottish dwelling stock. In fact, homes built after 1991 compose 27% of the constrained stock, as opposed to 19% of the national stock. Conversely, homes built between 1919 and 1991 account for 51% of the constrained stock, against 62% of the national figure. Finally, homes built before 1919 represent 22% of the constrained stock and 19% of the overall stock.

Space constrained homes include a smaller share of flats (-8%) and a larger share of detached houses (+10%) than the national average. Additionally, homes affected by the space constraint result to include more homes with a small floor area below 66 m^2 (+10%), fewer with medium area comprised between 66 and 108 m^2 (-14%) and roughly the same amount of homes with large area over 108 m^2 (+3%), when compared with the national distribution. While detached houses have on average a larger floor area than flats, the number of habitable rooms in detached houses is also generally larger. These figures suggest that the proportion of total floor area and the number of habitable rooms is more likely to be smaller than 18m^2 in detached houses than in flats.

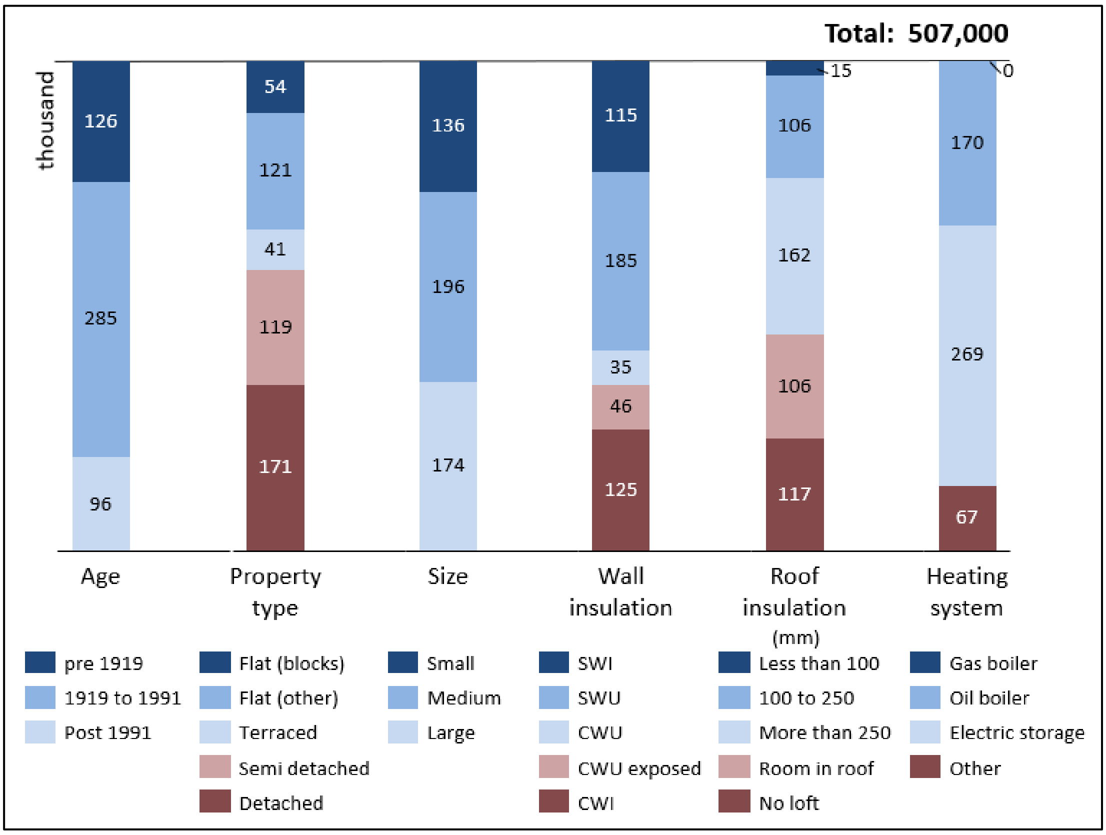
Except for the above highlighted differences, the remaining attributes of the space constrained stock appear to generally match those of the national stock, suggesting that the space constraint does not affect any type of home in particular, when looking at its insulation type and existing heating system.

4.1.2 Location off the gas grid

A connection to the gas grid is fundamental for the installation of heating technologies that rely on low-carbon gas, such as hydrogen boilers, natural gas boilers with biomethane grid injection and hybrid heat pumps with natural gas. In this study it is assumed that homes located in an area on the gas grid are suitable for these technologies, regardless of whether these homes currently have a connection to the grid or not. The suitability constraint will therefore affect only homes that are located in areas away from the gas grid.

The number of homes located off the gas grid, as well as a breakdown of their age, property type, size, wall insulation, roof insulation and existing heating system are reported in Figure 4. For comparison with the characteristics of the entire Scottish housing stock, see Figure 1 on page 37.

Figure 4: Number and characteristics of homes located off the gas grid in 2017



Homes that are located off the gas grid result to amount to about 21% of Scotland's housing stock.

Gas boilers are installed in 99% of homes located on the gas grid. Predictably, no homes with gas boilers figure in the portion of stock located off the gas grid. The distribution of the other three counterfactual heating technology categories (oil boiler, electric storage heating and other) in homes off the gas grid is therefore proportional to that of the Scottish housing stock, with a preference for electric storage heating (53%), followed by oil boilers (34%) and other heating systems (13%).

While the age distribution of the affected stock is roughly comparable with that of the Scottish stock, the property type distribution is significantly different. Homes in blocks of flats that are located off the gas grid are almost double (11%) the number of homes in blocks of flats in the national stock (6%). Additionally, more detached homes and fewer flats (other) result to be located off the gas grid than the national distribution of the property type. In fact, while homes located off the gas grid are composed of 24% of flats (other) and 34% of detached houses, the two categories respectively account for 34% and 21% of the national stock.

Additionally, this constraint impacts on more homes with a large floor area over 108 m^2 (+10%) and fewer homes with medium floor area comprised between 66 and 108 m^2 (-11%), than the national distribution. Finally, homes in the constrained stock are more likely to have solid walls (+10%) than the rest of the stock.

4.1.3 Fuse limit

The implementation of heating technologies that involve a large peak consumption of electrical power may be restricted by the fuse rating of the electrical connection of a home. In fact, the total current drawn by the heating device and all other domestic appliances together should never exceed the fuse limit of the electrical cut-out.

Therefore, an assessment was performed on the number and type of homes for which fuse rating would pose a restriction to the implementation of some of the most relevant low-carbon heating technologies utilising electricity: electric storage heating, direct electric heating and air source heat pumps. The limit on the implementation of each technology had to be assessed separately, due to their different types of power demand.

Additionally, due to the uncertainty of the actual fuse limit values of individual Scottish homes, this analysis was performed for three different potential fuse limit values (60A, 80A and 100A), each time assuming that all homes in the entire housing stock have the same value of fuse limit. Fuse upgrades to up to 100A, the maximum value available for a single-phase domestic connection, generally involve the replacement of the fuse alone and are associated with little to no cost, depending on the state of the connection cables and on the network operator.

The number of homes that may be affected by the fuse limit constraints for each of these technologies are reported in Figure 5, Figure 6 and Figure 7 respectively, each showing the portion of the affected stock for the considered range of fuse limit values in 2017 and 2040.

Figure 5: Number of homes restricted by fuse rating to the installation of electric storage heating in 2017 and 2040, depending on fuse limits of 100, 80 and 60 A

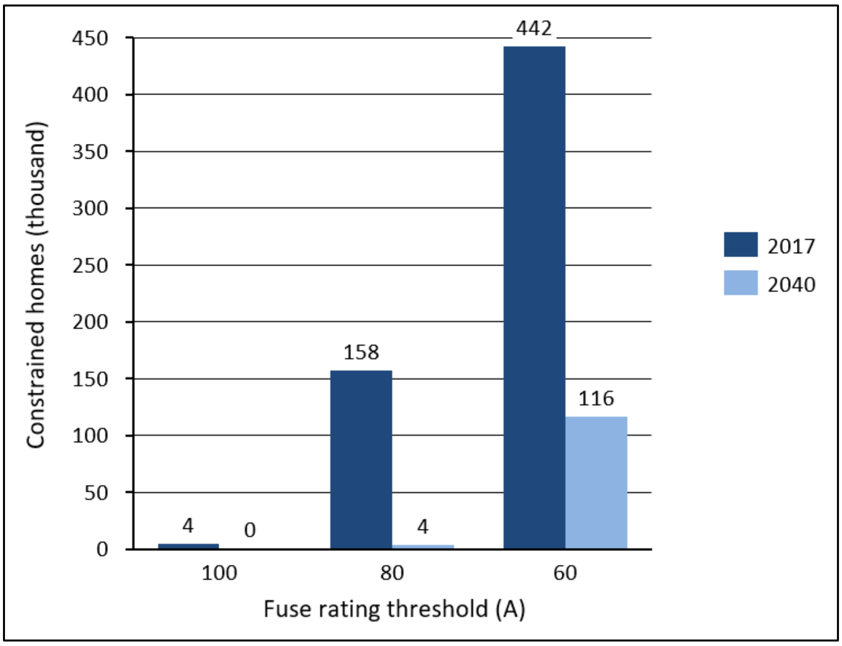


Figure 6: Number of homes restricted by fuse rating to the installation of direct electric heating in 2017 and 2040, depending on fuse limits of 100, 80 and 60 A

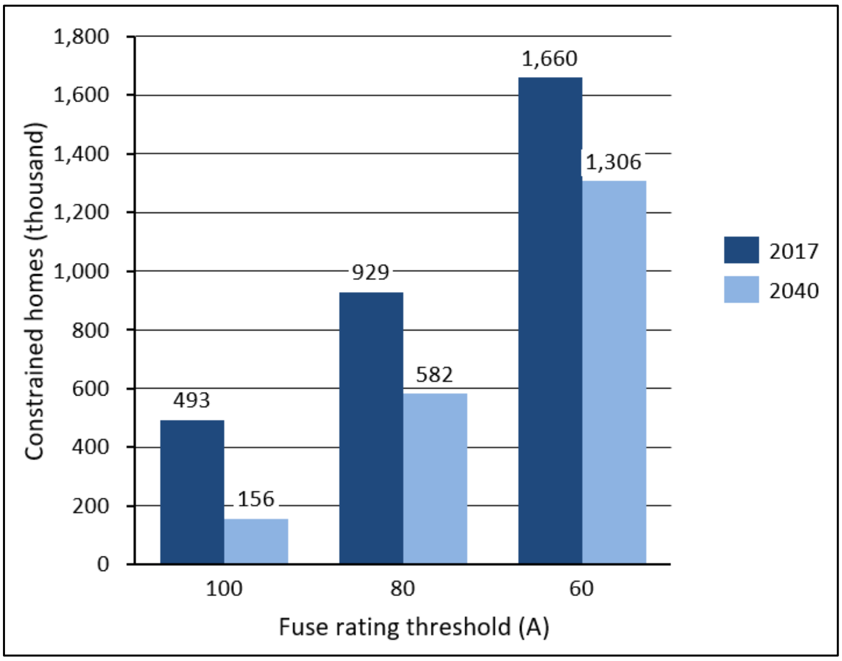
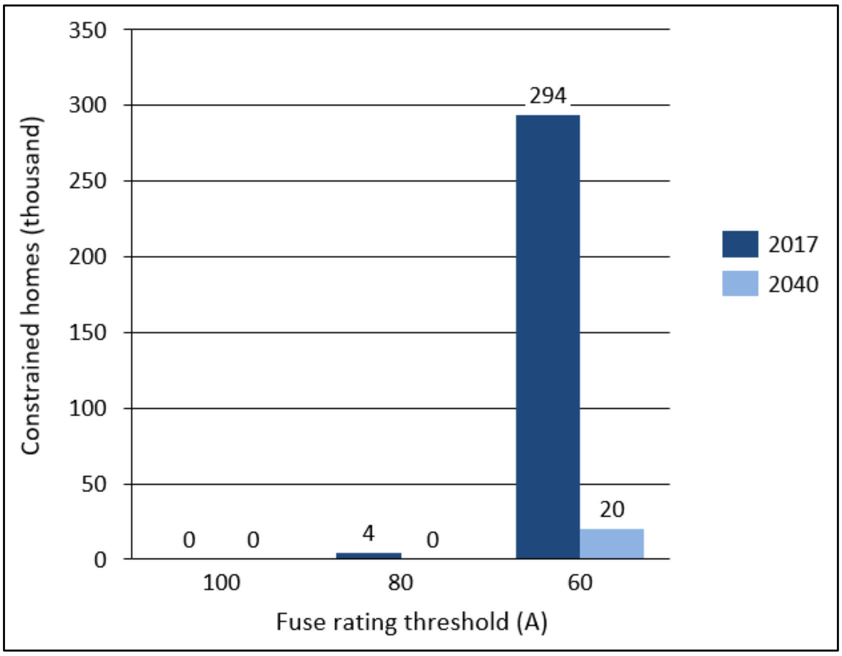


Figure 7: Number of homes restricted by fuse rating to the installation of air source heat pumps in 2017 and 2040, depending on fuse limits of 100, 80 and 60 A



For all three technologies, low values of fuse limit result in a larger number of homes affected by the constraint, as this is equivalent to a more stringent test.

A large portion of homes are affected by the fuse limit constraint for the installation of direct electric heating compared to storage heating. While thermal efficiency is 100% for both technologies and the total electrical energy drawn is also the same, storage heating is advantaged by operating overnight, when fewer other appliances are switched on[28]. This means that storage heating can draw a higher peak power than direct electric heating and more homes with large heating demand result to be suitable for this technology.

The number of constrained homes for the installation of ASHP is significantly lower than for the two electric resistive heating technologies, due to the heat pump's efficiency being much larger than 100%. Even on the coldest days of the year, the COP is expected to be between 2 and 3, resulting in a low power consumption and in a lower number of homes restricted by fuse limit for the installation of this technology. Note however that this analysis does not consider the additional load required for domestic fast charging of an electric vehicle, which may significantly increase the number of homes restricted by fuse limits.

The number of homes affected by the fuse limit constraint is expected to decrease substantially between 2017 and 2040. Efficiency upgrade measures implemented to the building result in better insulation, lower space heating demand and thus a lower demand of power to test against the fuse limit. The number of homes constrained by fuse limit in the installation of ASHP in 2040 is well below 1% for any fuse rating.

Finally, the characteristics of homes affected by the fuse limit constraint were also investigated, assuming a fuse rating of 80A for the entire housing stock. The results for

[28] The additional electrical load associated with domestic fast charging of an electric vehicle was not considered in this study but may negatively impact the suitability of electric storage heating more than direct electric heating, if the charging occurs overnight.

electric storage heating, direct electric heating and air source heat pumps are reported respectively in Figure 8, Figure 9 and Figure 10. The diagrams report the number of affected homes, as well as a breakdown of their age, property type, size, wall insulation, roof insulation and existing heating system. For comparison with the characteristics of the entire Scottish housing stock, see Figure 1 on page 37.

Figure 8: Number and characteristics of homes restricted by fuse rating to the installation of electric storage heating in 2017 for fuse limit of 80 A

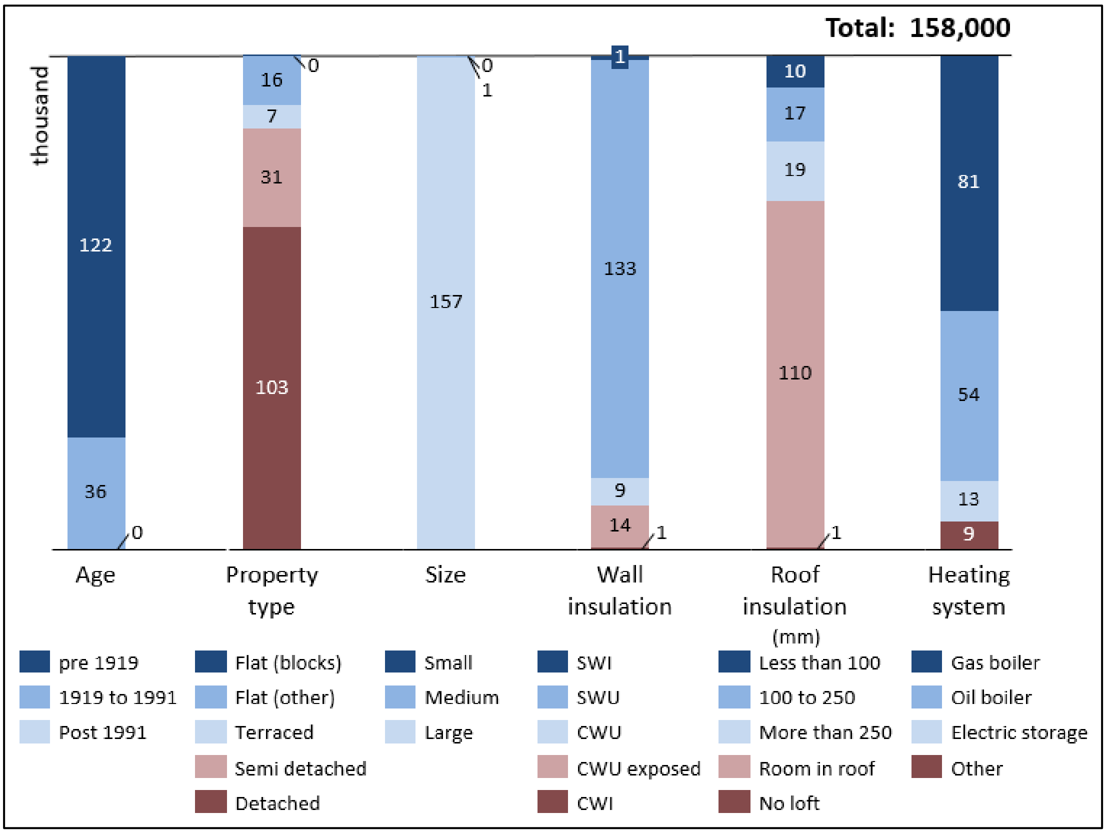


Figure 9: Number and characteristics of homes restricted by fuse rating to the installation of direct electric heating in 2017 for fuse limit of 80 A

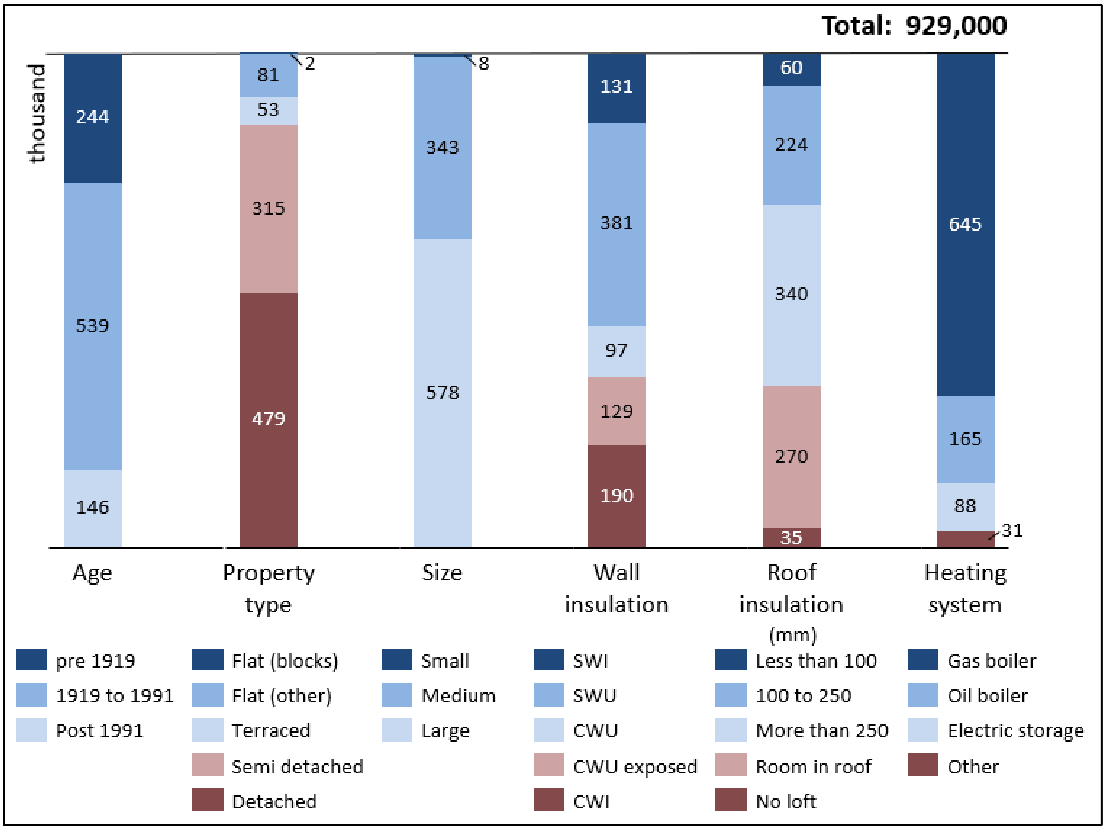
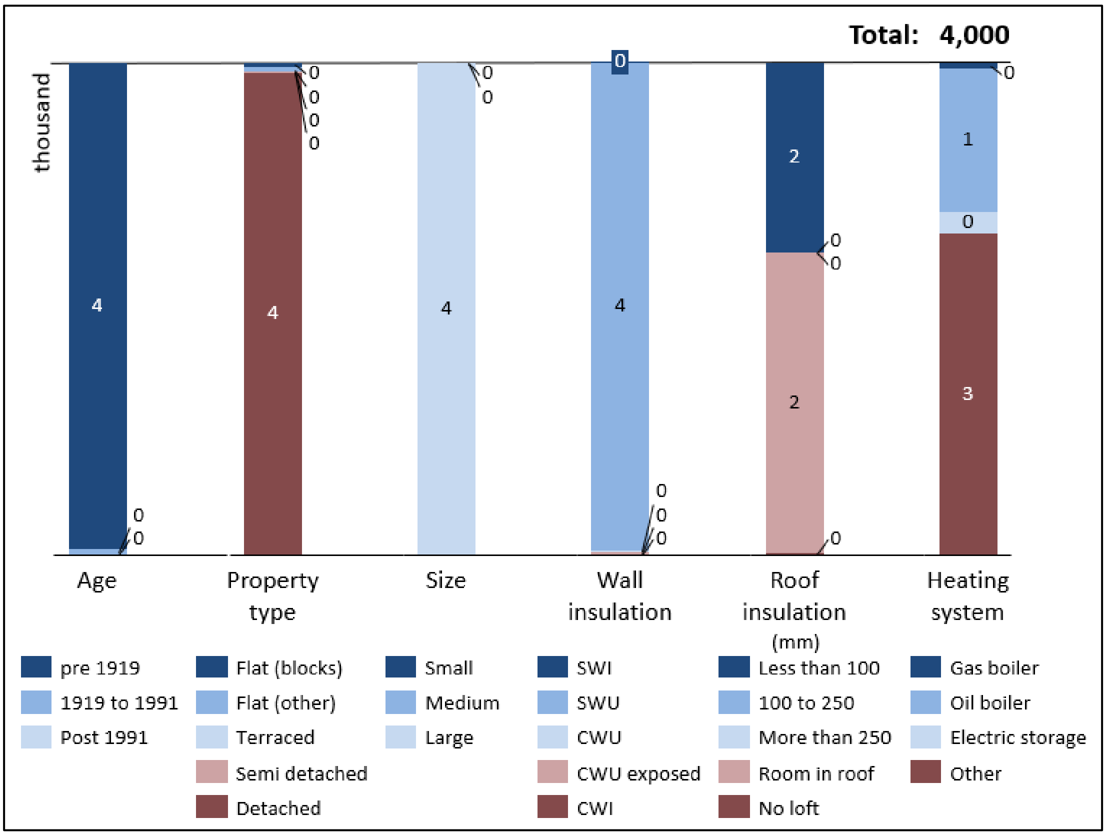


Figure 10: Number and characteristics of homes restricted by fuse rating to the installation of air source heat pumps in 2017 for fuse limit of 80 A



Dwellings that are constrained by the fuse limit for the installation of heating technologies that rely on electricity are typically those with a large peak heating demand. In fact, depending on the efficiency of the technology, a large peak heating demand is likely to result in large peak electrical consumption and a current which may exceed the fuse rating of the cut-out.

In fact, homes that are affected by the fuse limit constraint for all three technologies are predominantly older, larger in size, less insulated and are types of homes that are more exposed to the weather compared with the national distribution.

The share of older homes built before 1919 is larger among the homes affected by fuse limit for the installation of storage heating and ASHP, likely because these two technologies allow for a larger peak heating demand than direct electric heating, and older homes are generally associated a larger heat loss.

For all three technologies, the affected stock tends towards large uninsulated homes, including a large share of detached homes with large floor area over 108 m^2 and mostly with uninsulated solid walls.

4.1.4 Peak specific heat demand

Peak specific heat demand, here intended as the total heat demand of a dwelling divided by the total floor area of the habitable rooms, can be an obstacle for the implementation of air-source and ground-source heat pumps.

Heat pump technologies operate with optimal performance when delivering space heating at low flow temperature of about 35-40°C, which is considerably lower than that of conventional boilers. As a consequence, emitters of comparably larger size must be installed, in order to ensure sufficient heat transfer to the rooms. For homes with a considerable specific heat demand (or, equivalently, heat loss) the maximum size of emitters that can reasonably be installed may be insufficient to ensure thermal comfort, particularly on cold winter days with the highest peak heating demand.

To obviate the problem, conventional heat pumps can technically also be operated to deliver space heating at higher temperatures up to 60-65°C, at the expenses of performance. However, according to the EU Renewable energy directive[29], heat pumps operating with very low performance are no longer considered as renewable heating technologies. In fact, the minimum average seasonal performance factor (SPF)[30] must be higher than 2.5.

In our analysis we are assessing the number of homes that are restricted for the installation of heat pumps by too large a peak specific heat demand. This is such that thermal comfort might not always be met by the device when operating at an SPF compatible with the EU Renewable energy directive.

The heat pump emitter guidance table provided by MCS and reported in Table 8 illustrates the relation between the specific heat loss of a dwelling (column 1), space heating flow

[29] Official Journal of the European Union, Renewable energy directive (2013/114/EU)
[30] The seasonal performance factor is a measure of the efficiency of a heat pump. It is defined as the ratio between the heat delivered by the HP and the electrical energy supplied to the HP over one year.

temperature (column 2), space heating SPF for both GSHP and ASHP (columns 3 and 4), and the compatible size of various types of emitters together with the appropriateness of the solution (columns 5, 6 and 7). For any value of specific heat loss up to 150W/m^2, ASHPs can operate at a “renewable” SPF of 2.5 delivering heat at a flow temperature of up to 50°C. Differently, GSHPs appear to always achieve an SPF higher than 2.5 while delivering heat at flow temperatures up to 60°C. In fact, the SPF of a GSHP is generally larger than that of an ASHP operating at the same flow temperature. This is mainly due to the heat source of GSHPs (the ground) having a higher average temperature and heat capacity.

Considering the colours indicating emitter appropriateness in columns 5-7 and explained in the legend at the bottom, the installation of an **ASHP** operating at flow temperature of max 50°C is considered appropriate in any case for heat loss rates of up to 100 W/m^2. For heat loss rates comprised between 100 W/m^2 and 150 W/m^2, however, there is a varying degree of risk of thermal comfort not being met by the ASHP. Finally, the installation of an ASHP in homes with specific heat loss above 150 W/m^2 is not advisable.

The range of flow temperatures at which a **GSHP** can deliver renewable heat is sufficient to ensure thermal comfort in homes with heat loss of up to 150W/m^2, but the installation of GSHP in homes with specific heat loss above 150 W/m^2 is not advisable.

Based on the above considerations, the number and type of Scottish homes that may be constrained by a too large peak specific heat demand in the installation of ASHP were assessed for a range of values of specific heat loss of 100, 120 and 150 W/m^2. Each threshold includes homes with a different degree of risk to thermal comfort, as classified below:

<100 W/m^2	Suitable and likely to meet thermal comfort
100 - 120 W/m^2	Suitable but **some risk** of not meeting thermal comfort
120 - 150 W/m^2	Suitable but **high risk** of not meeting thermal comfort
>150 W/m^2	Technically unsuitable

Table 8: MCS Heat pump emitter guidance table[31]

Room specific heat loss	Heating circuit flow temperature °C	Space heating SPF		Oversize factor		
		GSHP	ASHP	Fan Convector / Fan-assisted Radiator	Standard Radiator	Fan Coil Unit
<30 W/m²	35	4.3	3.6	4.3	6.8	5.0
	40	4.1	3.4	3.1	4.3	3.5
	45	3.7	3.0	2.4	3.1	2.6
	50	3.4	2.7	2.0	2.4	2.1
	55	3.1	2.4	1.7	1.9	1.7
	60	2.8	2.1	1.4	1.6	1.5
30 - 50 W/m²	35	4.3	3.6	4.3	6.8	5.0
	40	4.1	3.4	3.1	4.3	3.5
	45	3.7	3.0	2.4	3.1	2.6
	50	3.4	2.7	2.0	2.4	2.1
	55	3.1	2.4	1.7	1.9	1.7
	60	2.8	2.1	1.4	1.6	1.5
50 - 80 W/m²	35	4.3	3.6	4.3	6.8	5.0
	40	4.1	3.4	3.1	4.3	3.5
	45	3.7	3.0	2.4	3.1	2.6
	50	3.4	2.7	2.0	2.4	2.1
	55	3.1	2.4	1.7	1.9	1.7
	60	2.8	2.1	1.4	1.6	1.5
80 - 100 W/m²	35	4.3	3.6	4.3	6.8	5.0
	40	4.1	3.4	3.1	4.3	3.5
	45	3.7	3.0	2.4	3.1	2.6
	50	3.4	2.7	2.0	2.4	2.1
	55	3.1	2.4	1.7	1.9	1.7
	60	2.8	2.1	1.4	1.6	1.5
100 - 120 W/m²	35	4.3	3.6	4.3	6.8	5.0
	40	4.1	3.4	3.1	4.3	3.5
	45	3.7	3.0	2.4	3.1	2.6
	50	3.4	2.7	2.0	2.4	2.1
	55	3.1	2.4	1.7	1.9	1.7
	60	2.8	2.1	1.4	1.6	1.5
120 -150 W/m²	35	4.3	3.6	4.3	6.8	5.0
	40	4.1	3.4	3.1	4.3	3.5
	45	3.7	3.0	2.4	3.1	2.6
	50	3.4	2.7	2.0	2.4	2.1
	55	3.1	2.4	1.7	1.9	1.7
	60	2.8	2.1	1.4	1.6	1.5

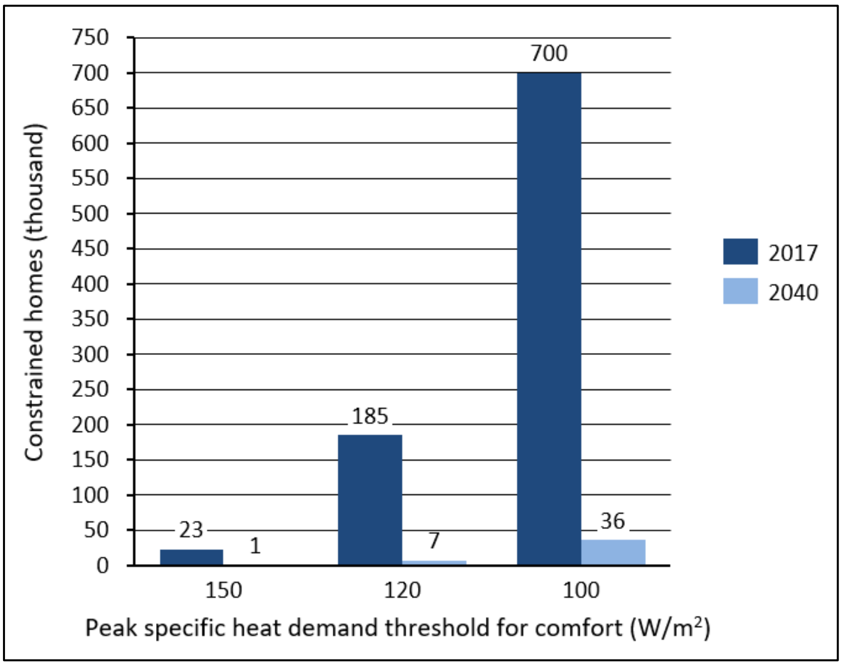
Legend:

Go ahead - System can perform at the stated efficiencies with the selected emitter design.	**Caution** - System can perform at these design conditions with extra consideration on the emitter and heat pump design	**Reduce fabric and ventilation heat loss** - System can perform at these design conditions but emitter sizes are likely to be excessive

[31] MCS, Heat Emitter Guide for Domestic Heat Pumps

The number of homes that may be affected by the peak specific heat demand constraint in the installation of an ASHP is reported in Figure 11, showing the portion of the affected stock for the considered range of specific heat loss values in 2017 and 2040.

Figure 11: Number of homes restricted by specific heat demand to the installation of ASHP in 2017 and 2040, depending on peak specific heat demand thresholds of 150, 120 and 100 W/m^2



The number of homes that are constrained by peak specific heat demand for the installation of ASHP is significantly larger than the number of homes constrained by the fuse limit constraint for the installation same technology. Additionally, the two constraint groups overlap significantly for ASHP, as almost all homes that are constrained by fuse limit are also constrained by peak specific heat demand[32].

Additionally, the characteristics of the affected homes were more closely investigated, considering the portion of the stock with peak specific heat demand of 120 W/m^2 or below. The results are shown in Figure 12 and Figure 13 for 2017 and 2040 respectively and report the number of affected homes, as well as a breakdown of their age, property type, size, wall insulation, roof insulation and existing heating system. For comparison with the characteristics of the entire Scottish housing stock, see Figure 1 on page 37.

[32] 96% of homes constrained by fuse limit result to be constrained also by peak specific heat demand, considering fuse limit 80A and specific heat demand of 120W/m^2 in 2017.

Figure 12: Number and characteristics of homes restricted by specific heat demand to the installation of ASHP in 2017 for peak specific heat demand threshold of 120 W/m²

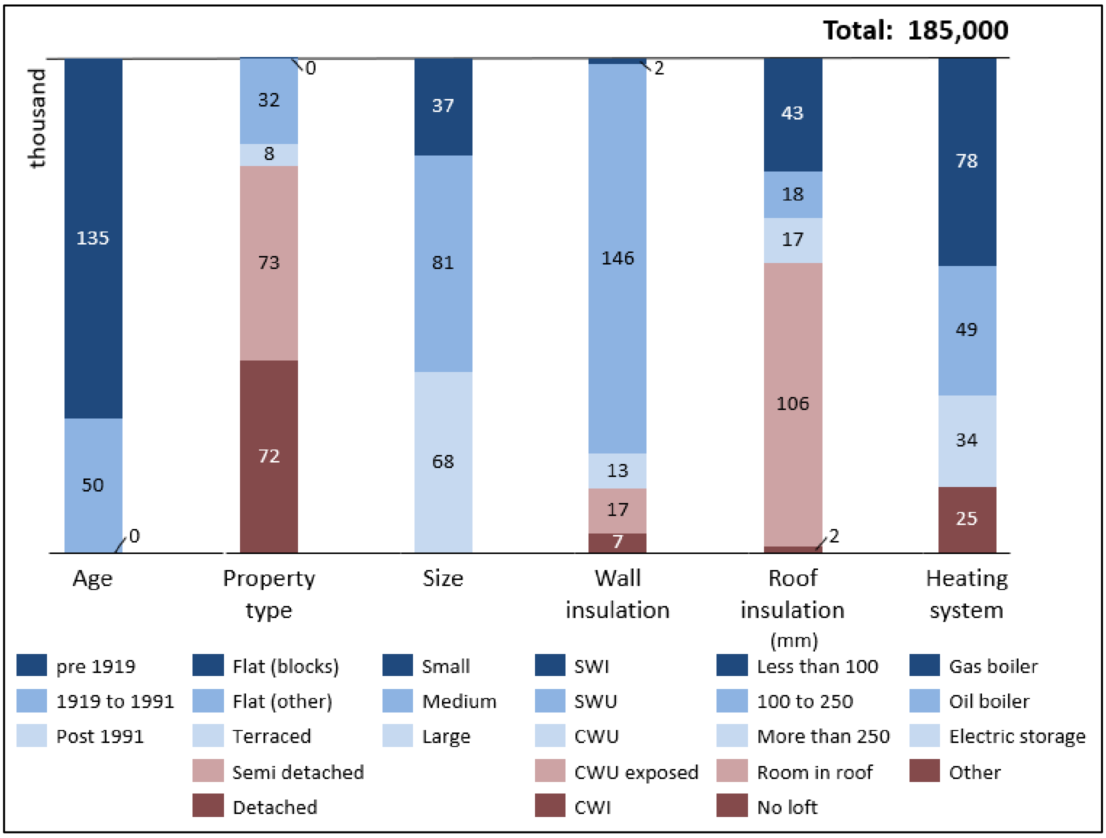
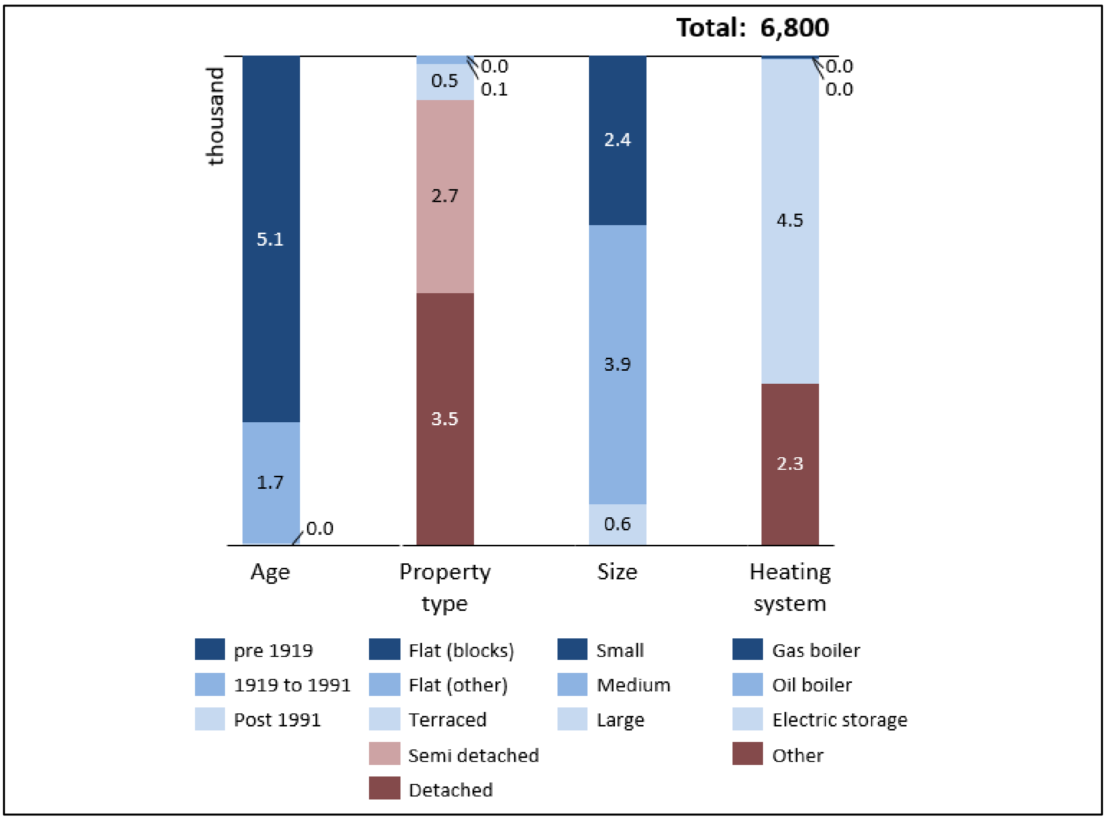


Figure 13: Number and characteristics of homes restricted by specific heat demand to the installation of ASHP in 2040 for peak specific heat demand threshold of 120 W/m²



In the case of homes affected by the peak specific heat demand constraint, the share of older homes built before 1919 is larger than for the national average (+54%). Additionally, more frequent is the presence of detached homes (+18%) and homes with uninsulated solid walls (+50%), describing homes with large space heating demand but without particularly larger floor area than the national average.

After the implementation of energy efficiency upgrades that will increase the EPC rating of Scottish homes to level C or above, the age category distribution of homes affected by the peak specific heat demand constraint in 2040 is roughly the same as in 2017. Affected homes in 2040 are composed of more detached houses (+13%) and fewer flats (other) (-16%) than the 2017 constrained stock. The 2040 stock also comprises more small and medium homes and fewer large homes, as well as more homes utilising heating technologies off the gas grid.

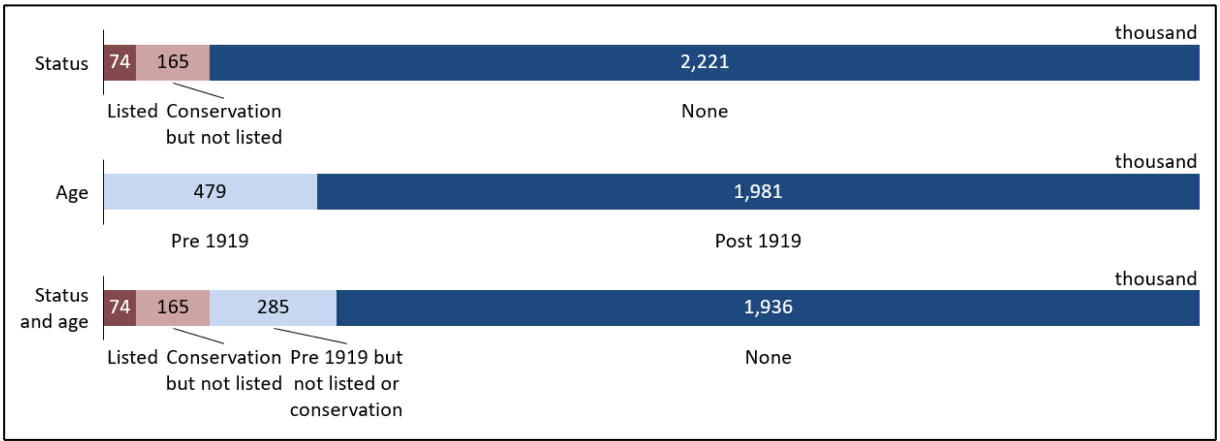
The planned efficiency upgrade measures result therefore as insufficient to reduce peak specific heat demand enough for the installation of ASHP in old, small-medium sized detached or semi-detached houses off the gas grid. These are potentially individual homes located away from urban areas.

4.2 Heritage and old homes

Listed buildings and homes in conservation areas are respectively buildings and areas categorised to be of architectural or historic interest. Planning permission may be required to make changes to the external appearance of these homes. Additionally, listed building consent may be required to make changes to both external appearance and internal fixtures of listed homes. Given the additional hurdles that could thus potentially be encountered in the installation of low-carbon heating technologies and the implementation of energy performance upgrade measures in these homes, the number of heritage dwellings in Scotland's housing stock was assessed. Additionally, old dwellings (pre 1919) were also investigated, as these buildings may often present similar issues to those of heritage buildings, according to our consultation with Historic Environment Scotland.

The impact of the peculiar characteristics and restrictions of heritage and old homes on the suitability and costs for the implementation of low-carbon heating was not assessed, due to the complexity and case-by-case nature of the barriers to retrofit, as well as the high level of simplification that would be required to perform a quantitative analysis. This approach was supported by consultation with experts at Historic Environment Scotland.

Figure 14: Number of heritage homes, homes in conservation areas or old homes, as of 2017



Listed homes account for 3% of Scotland's housing stock, whereas homes that are located in conservation areas but are not listed account for an additional 7% of the stock. While roughly 19% of buildings in Scotland are reported to have been built before 1919, a significant portion of these are also included in the portion of homes that are listed or located in conservation areas. As a consequence, older homes that are neither listed nor located in conservation areas amount to 12% of the total housing stock.

The total portion of heritage and old homes in Scotland is therefore estimated to amount to about 21% of the housing stock. Given the large portion of homes that may be affected by additional requirements and restrictions in the implementation of energy performance measures and installation of low-carbon heating technologies, and given the uncertainty about the impact of these restrictions on suitability and costs, it is advisable that these parameters are further investigated.

4.3 Suitability of heating technologies

The combination of all four main constraints analysed in the previous sections, as well as additional minor constraints summarised in Table 6, was applied to the characteristics of Scotland's building stock to assess the suitability of each home for the considered low-carbon heating technologies. The results of this assessment are reported in Figure 15 and Figure 16 for the year 2017 and 2040 respectively.

The assessment was performed for three combinations of peak specific heat demand and fuse limit. The results obtained applying most stringent threshold combination (100W/m^2 and 60A) refer to the stock which is in any case likely to be suitable for a specific technology. The additional portion of the stock that results from the analysis with the medium threshold combination (120W/m^2 and 80A) describes the portion of the stock the suitability of which is not ruled out but may carry some risk. The additional portion of suitable stock assessed using the high threshold combination (150W/m^2 and 100A) quantifies the stock which is likely suitable but with high risk of its suitability.

Figure 15: Percentage of homes compatible with each technology in 2017; the sensitivity of suitability was tested against three combinations of peak specific heat demand and fuse rating

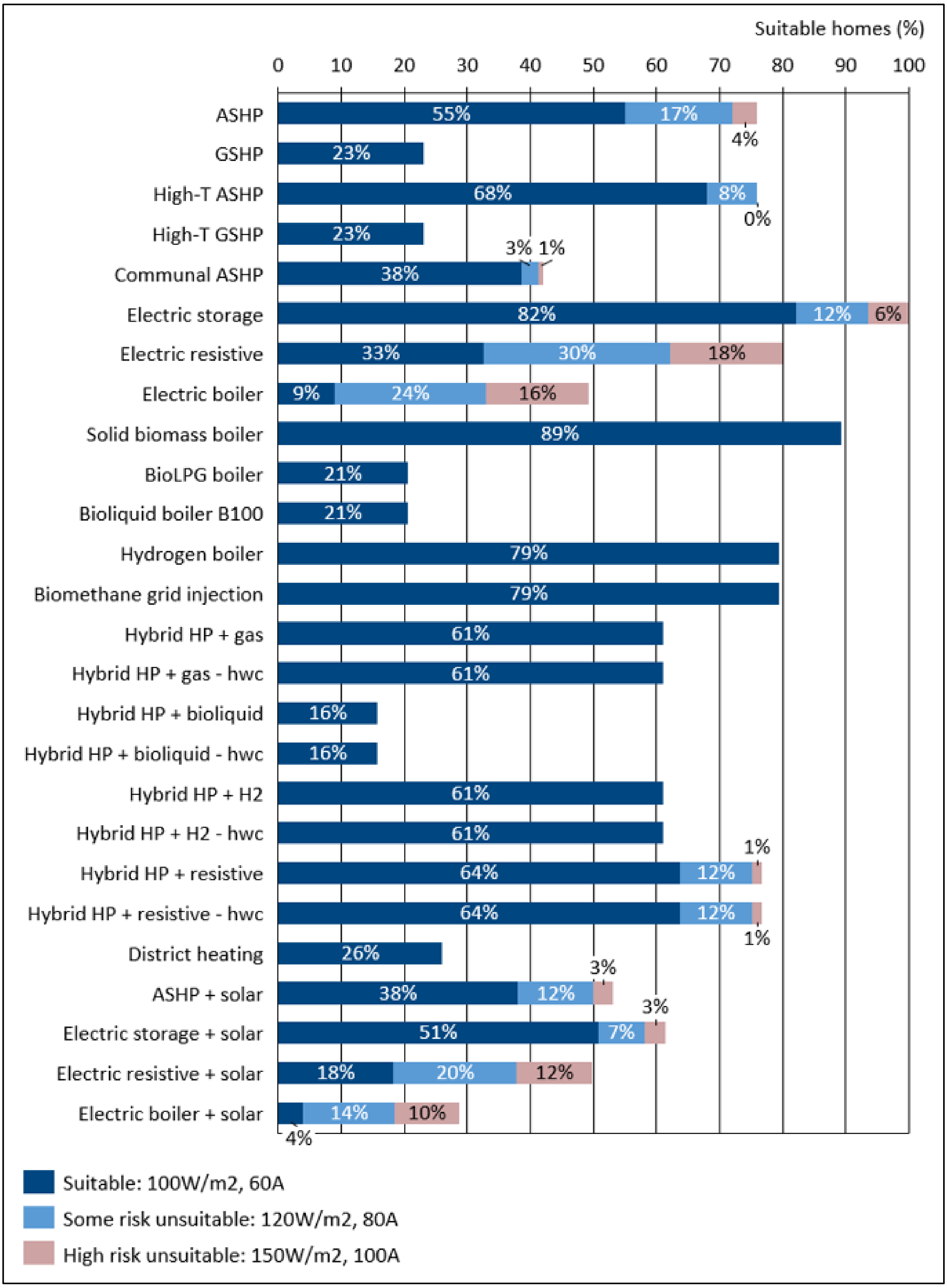
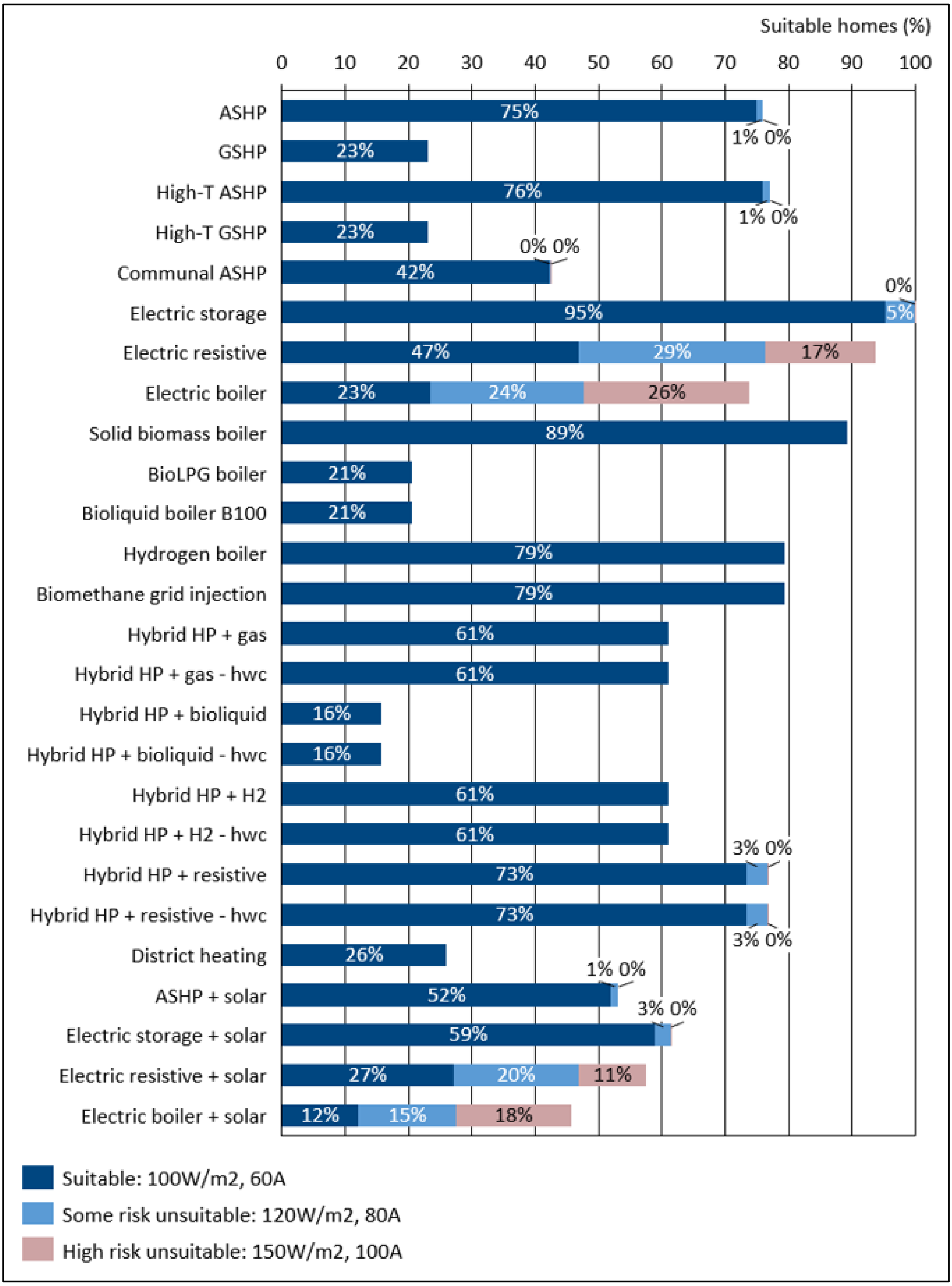


Figure 16: Percentage of homes compatible with each technology in 2040; the sensitivity of suitability was tested against three combinations of peak specific heat demand and fuse rating



ASHP and high-temperature ASHP

The suitability of ASHP is predominantly determined by a combination of three constraints: space, fuse limit and peak specific heat demand. On the other hand, the suitability of high-temperature ASHP depends on two of these: space and fuse limit, but not peak specific heat demand.

The portion of the stock which is completely ruled out for ASHP and high-temperature ASHP is similar in 2017 and remains unchanged in 2040. These homes, amounting to ~24% of the overall stock, roughly correspond to the same fraction of the stock and are ruled out almost exclusively by the space constraint.

In fact, the energy efficiency upgrade measures considered in this study for bringing Scottish homes to EPC band C (or above) by 2040 are fabric measures that **do not impact the space constraint**. Therefore, these measures will not reduce the number of homes that are completely ruled out for ASHP and high-temperature ASHP.

The same measures, however, result in a general reduction in the heating demand of homes and therefore **impact the peak specific heat demand constraint** and the fuse limit constraint. In particular, fewer homes are affected by the specific heat demand constraint in 2040, resulting in significantly fewer homes for which the installation of an ASHP is associated with a risk of meeting thermal comfort.

In summary, while thermal comfort is at risk of not being met without appropriate energy efficiency fabric measures being carried out in some of the suitable homes with the installation of an ASHP in 2017, the installation of a high-temperature ASHP would ensure thermal comfort in homes where energy fabric measures or an upgrade to low-temperature wet system may not be feasible. While overall suitability of both technologies does not vary significantly in 2040 (which it is assumed by this work that energy efficiency fabric measures will have been carried out), the advantage of high-temperature ASHP over conventional ASHP is lost, as the reduced space heating demand allows for both technologies to meet thermal comfort equally.

GSHP and high-temperature GSHP

The suitability of GSHP and high-temperature GSHP is much lower than that of ASHP due to the additional requirements for the installation of a ground loop in a sufficiently large, accessible and geologically suitable plot. As the main constraints for these technologies are the space constraint and geological characteristics of the location, the suitability of both GSHP and high-temperature GSHP is similar and does not vary between 2017 and 2040, similar to the air-source technologies.

Communal ASHP

The suitability for communal ASHP is lower than that of individual ASHP due to additional constraint posed on the suitable dwelling type (with detached, semi-detached and end-terrace houses deemed unsuitable).

Electric resistive heating

While electric storage and direct electric heating are technically easy to implement in most homes, the relevance of the fuse limit constraint for these technologies is very important, due to their lower efficiency compared with that of heat pump technologies. This can be observed in the higher fragmentation into the three suitability risk categories. While very few homes are limited by fuse rating in the implementation of electric storage heating, a large portion is restricted for the installation of direct electric heating by the same constraint. This is due to the larger number of domestic appliances that are consuming electricity while direct electric heating is operating, thus reducing the amount of power that the heating devices can draw before exceeding the fuse limit. This also results in a larger share of suitable homes in 2040, due to a reduced space heating demand.

Similar considerations are also valid for electric boilers, which are operating during daytime and at an even lower efficiency than direct electric heating and are thus constrained by fuse limit in an even larger number of homes.

Bioenergy boilers

Solid biomass boilers, bioLPG boilers and bioliquid boilers are not suitable in all homes, due to the requirement of space for the volume of their storage/equipment. In addition, bioLPG boilers and bioliquid boilers are overall less suitable, as they were assumed to be only considered for homes that are located off the gas grid.

Low-carbon gas boilers

Hydrogen boilers and biomethane grid injection are assumed to be technically suitable in all buildings that are located on the gas grid. The validity of our assumption around the technical suitability of hydrogen boilers will need to be backed by further evidence, as the technical and safety case for hydrogen in the gas network and for the use for heating and in other gas using equipment is still being made, through relevant BEIS-led projects.

Hybrid heat pumps

The suitability for hybrid ASHP technologies is based on the combined suitability of its two main components: the ASHP and the additional heating source. The suitability of the ASHP component is evaluated applying the same constraints as for conventional ASHP but considering a lower peak heat demand, and compatibly with the reduced load delivered by the ASHP component in a hybrid system. The suitability of the additional source is evaluated considering that this technology will be the one supplying peak heat demand of a home, as it will be the only component operating on cold winter days.

Solar thermal

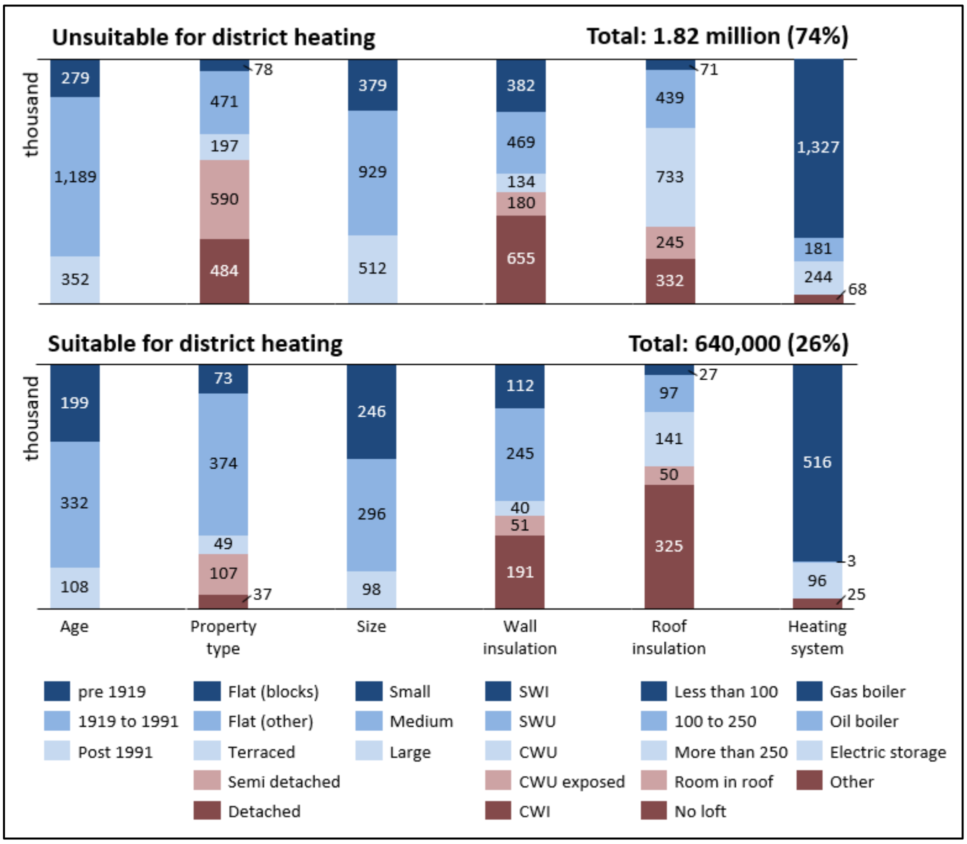
The suitability for systems including solar thermal collectors is based on the suitability of the main heating system component, with the additional requirement of the availability and appropriate orientation of a roof on which to secure the collectors.

4.4 Homes compatible with district heating

The characteristics of homes compatible with district heating were more closely analysed.

Figure 17 reports a comparison between the portion of the stock expected to be suitable and unsuitable for district heating. For both categories the number of homes as well as a breakdown of their age, property type, size, wall insulation, roof insulation and existing heating system are reported.

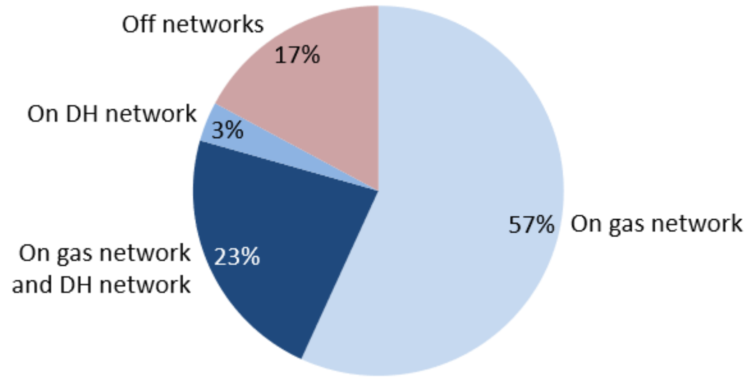
Figure 17: Number and characteristics of homes suitable and unsuitable for district heating



A comparatively smaller portion (26%) of Scottish homes are expected to be suitable for district heating. These are expected to be predominantly represented by flats (of any type) built between 1919 and 1991, with small area and uninsulated walls. This finding reflects the initial assumption of heat networks located in areas of high heat demand density, therefore often coinciding with densely populated areas where flats are a more common dwelling type.

The use of gas boilers is more widespread in homes suitable for district heating than in unsuitable homes (+8%). The reason for this is that homes suitable for district heating are also more likely to be located in areas supplied by the gas grid (87%) than the national average (79%). Figure 18 shows a breakdown of Scotland's housing stock according to the projected availability of district heating and the location on the gas grid.

Figure 18: Portion of Scottish stock on gas and district heating networks



4.5 Dwellings with limited suitability

While many Scottish homes result to be suitable for a wide variety of low-carbon heating options, a significant share of homes is likely to be suitable only for a limited range of heating technologies. A restriction in the choice of heating system for a portion of the stock may carry some disadvantages and/or risks for the decarbonisation of domestic heating, especially if dwelling suitability is limited to expensive heating options or technologies that are not readily available. Most relevant risks are associated with following low-carbon heating technologies:

- **Electric resistive heating:** the reliance on electric resistive heating technologies for the decarbonisation of domestic heating might result in high costs. Included technologies are electric storage heating, direct electric heating, electric boilers and their respective combinations with solar thermal.
- **Bioenergy**: the implementation of low-carbon heating based on bioenergy relies on the future access to sufficient biomass feedstock and might therefore be subject to fuel availability uncertainty. Considered technologies are solid biomass boilers, bioLPG boilers, bioliquid boilers and hybrid heat pumps with bioliquid boilers as secondary source.
- **Decarbonised gas grid**: the availability of technologies that are supported by a decarbonised gas grid is tied to the future delivery of low carbon gas through the grid and might therefore be subject to implementation uncertainty. In fact, a strategic decision on the decarbonisation of the gas network through the supply of hydrogen will likely be based on the outcome of further studies on the technical suitability and safety of the use of hydrogen. Affected technologies are hydrogen boilers and hybrid heat pumps with hydrogen boilers as secondary source.
- **District heating**: similarly, the availability of district heating will predominantly depend on the scale of the development of heat networks and could therefore be subject to implementation uncertainty.

A less severe implementation risk may be associated with the adoption of heat pump technologies, as this would require measures to upgrade the electricity grid. When compared with the above discussed risks affecting other heating technologies, the implementation risk of the heat pump options is expected to be very mild, as a reinforcement of the electricity network is expected to be performed to also support the adoption of electric vehicles with domestic charging.

The extent to which Scotland's housing stock may be restricted in the implementation of low-carbon heating technologies was more closely investigated. Each of the technologies considered in this study was assigned to a technology group (see Table 9), characterised by the above-described risks. Homes that result from our analysis to be suitable for the installation of technologies from only a few of the technology groups are deemed as most "at risk".

Table 9: Technology groups and level of risk

Heat pumps	District heating	Decarbonised gas	Electric resistive	Bioenergy
• ASHP • GSHP • High-T ASHP • High-T GSHP • Communal ASHP • Hybrid HP with gas boiler • Hybrid HP with direct electric heating • ASHP with solar	• District heating	• Hydrogen boiler • Hybrid heat pumps with hydrogen boiler	• Electric storage heating • Direct electric heating • Electric boiler • Electric storage heating with solar • Direct electric heating with solar • Electric boiler with solar	• Solid biomass boiler • BioLPG boiler • Bioliquid boiler
Lower risk	Higher risk			

Note that the actual number of Scottish homes for which a future implementation of low-carbon heating technologies could be problematic or not feasible may be higher than the figures provided by our analysis, due to the limited extent of constraints and obstacles included in our initial assumptions.

Based on the assumptions of this study, results suggest that all Scottish homes could have at least one of the investigated technologies applied. Additionally, the majority of homes result to be suitable for at least one of the lower-risk technologies of the "heat pump" group, accounting for ~81.3% of the stock when considering fuse limit of 80A and peak specific heating demand of 120 W/m^2 in 2040.

The remaining stock is therefore limited to the implementation of heating technologies from the higher-risk categories, and accounts for 18.7% of the stock for thresholds of 80A and 120 W/m^2 in 2040 but is expected to comprise 19.3% of the stock for thresholds of 60A and 100 W/m^2 in 2040.

The portion of the stock resulting unsuitable for heat pump technologies in 2040 is reported in Table 10, broken down into 16 categories with various combinations of technology choice restriction (and therefore various degrees of combined risk). The reported figures on the right refer to the portion of homes that can choose from all groups indicated in the respective row on the left at the same time. Sufficient condition for the suitability for a technology group is the suitability for at least one of the included technologies (e.g. homes suitable for bioLPG boilers are considered suitable for the "Bioenergy" group).

Table 10: Number of homes with restricted choice of suitable technologies, considering fuse limit of 80A and peak specific heating demand of 120 W/m² in 2040

	Suitable technologies for homes with restricted choice				Homes with restricted choice	% of stock
1	District heating	Decarb. gas	Electric resistive	Bioenergy	20,000	0.8%
2	District heating	Decarb. gas	Electric resistive	–	112,000	4.5%
3	District heating	Decarb. gas	–	Bioenergy	1	0%
4	District heating	Decarb. gas	–	–	40	0%
5	District heating	–	Electric resistive	Bioenergy	22,000	0.9%
6	District heating	–	Electric resistive	–	0	0%
7	District heating	–	–	Bioenergy	70	0%
8	District heating	–	–	–	0	0%
9	–	Decarb. gas	Electric resistive	Bioenergy	136,000	5.5%
10	–	Decarb. gas	Electric resistive	–	90,000	3.6%
11	–	Decarb. gas	–	Bioenergy	60	0%
12	–	Decarb. gas	–	–	60	0%
13	–	–	Electric resistive	Bioenergy	78,000	3.2%
14	–	–	Electric resistive	–	0	0%
15	–	–	–	Bioenergy	1,200	0.05%
16	–	–	–	–	0	0%
TOTAL					**459,000**	**18.7%**

No homes in the Scottish housing stock are restricted in their technology choice to district heating only (see row 8 in Table 10) or electric resistive heating only (row 14), and less than 100 are restricted to decarbonised gas technologies only (row 12).

However, a more consistent number of homes are restricted to choosing from technologies in the bioenergy group only (row 15) or from other technologies deemed "at risk".

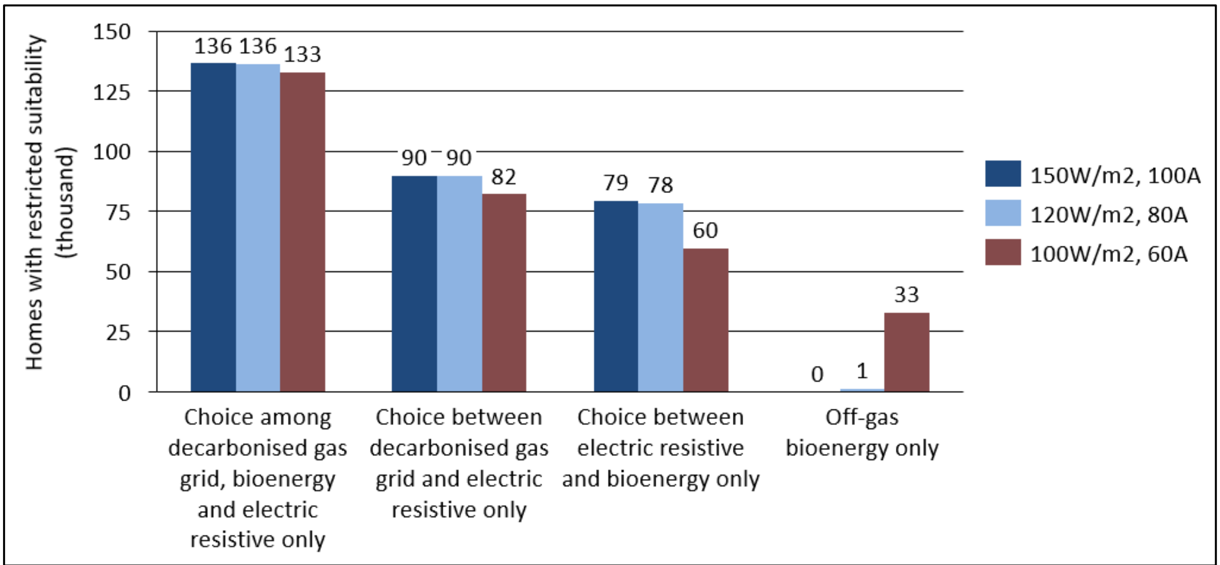
Four combinations in particular are identified as most at risk, due to their restricted selection of suitable technologies and the relatively large number of affected homes:

- **Row 9: 136,000 homes** that must choose among decarbonised gas, electric resistive and bioenergy technology groups only. These homes are potentially at risk of incurring in high costs (electricity) or the uncertain availability of the selected technology (decarbonised gas and bioenergy).
- **Row 10: 90,000 homes** that must choose between decarbonised gas and electric resistive technology groups only. These homes are potentially at risk of incurring in high running costs (electricity) or the uncertain availability of the selected technology (decarbonised gas).

- **Row 13: 78,000 homes** that must choose between electric resistive and bioenergy technology groups only. These homes are potentially at risk of incurring in high running costs (electricity) or the uncertain availability of the selected technology (bioenergy).
- **Row 15: 1,200 homes** that can only choose bioenergy technology group only. These homes are potentially at risk of uncertain availability of the selected technology.

Figure 19 reports the number of homes estimated to be comprised under these categories in 2040, considering a range of values of peak specific heat demand and fuse rating as utilised in the previous suitability analysis (see sections 4.1.3 and 4.1.4). The four assessed categories are placed in order of implementation risk, with lower risk on the left and higher risk on the right.

Figure 19: Number of homes with restricted suitability in the most relevant four categories, considering various combinations of fuse limit and peak specific heating demand in 2040



Note that higher thresholds of peak specific heat demand, measured in W/m^2, increase the suitability of heat pump technologies, whereas high values of fuse limit, measured in Ampere, increase the suitability of electric resistive heating technologies. However, given how little the suitability of heat pump technologies is expected to vary depending on the peak specific heat demand threshold in 2040, it is appropriate to assume that the number of homes in each category depends almost exclusively on the chosen value of fuse limit.

While each of the four investigated combinations represents a portion of the stock which is highly dependent on the specific heat demand and fuse limit thresholds considered, these are never exceeding 150,000 homes or 6% of the total stock each.

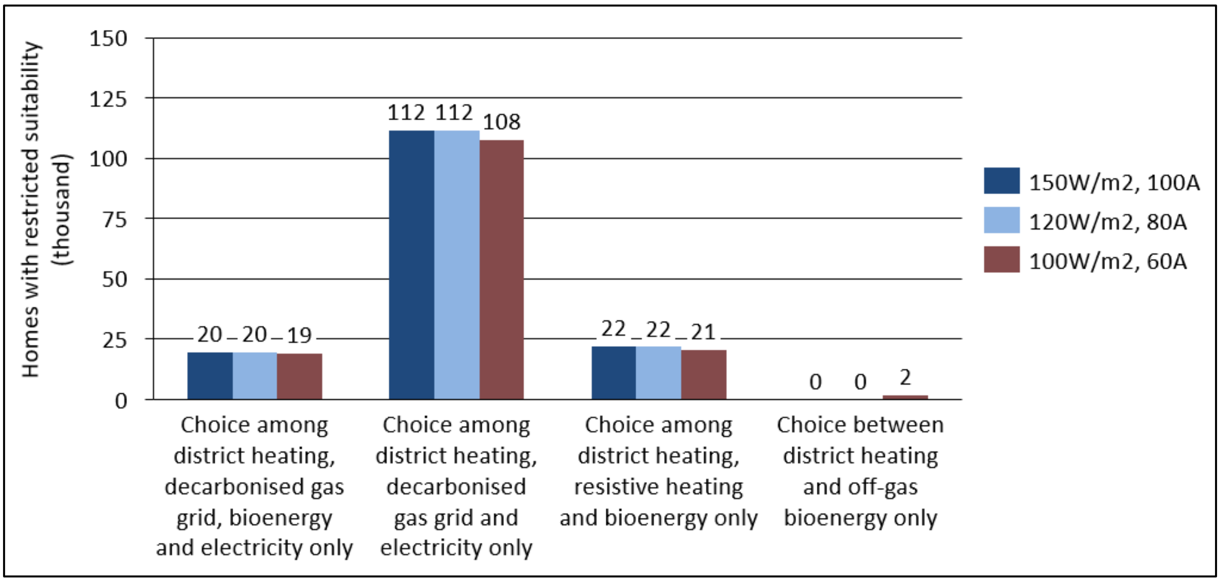
The number of homes included in the first **three categories on the left** in Figure 19 (corresponding to **rows 9, 10 and 13** in Table 10) is smaller for smaller values of fuse limit, as these three categories are defined by the suitability also for electric resistive heating. In fact, a lower fuse limit threshold corresponds to a smaller number of homes suitable for the installation of electric resistive heating technologies.

Conversely, the number of homes included in the last **category on the right** in Figure 19 (corresponding to **row 15** in Table 10) is larger for smaller values of fuse limit and peak specific heat demand. In fact, low fuse limit values correspond to fewer homes resulting to be suitable for electric resistive heating. Therefore, a portion of homes that for higher fuse limit threshold values would fit into the "electric resistive and bioenergy" category (row 13) for low fuse limit values, fall into the "bioenergy only" category (row 15) and add up to the number of homes that would fall into the "bioenergy only" category also with higher values of fuse limit. Additionally, a smaller value of peak specific heat demand results in a larger number of homes unsuitable for the installation of heat pump technologies, which may also contribute to populate the category "bioenergy only" (row 15). The contribution of the varying peak specific heat demand threshold is, however, much smaller than that of the fuse limit.

Categories in rows 1-8 in Table 10 correspond to the same combinations of categories in rows 9-16, with the additional requisite of the suitability for **district heating.** While the main concerns around restricted technology suitability regard categories in rows 9-16, in the event that district heating networks in Scotland would not develop to the expected capacity, those homes in categories in rows 1-8 would need to be added to the count of homes in categories in rows 9-16.

A similar assessment was therefore performed on homes belonging to the categories in rows 1,2, 5 and 7, corresponding to the above analysed categories 9, 10, 13 and 15 but with the addition of the suitability for district heating. The results of this analysis are reported in Figure 20.

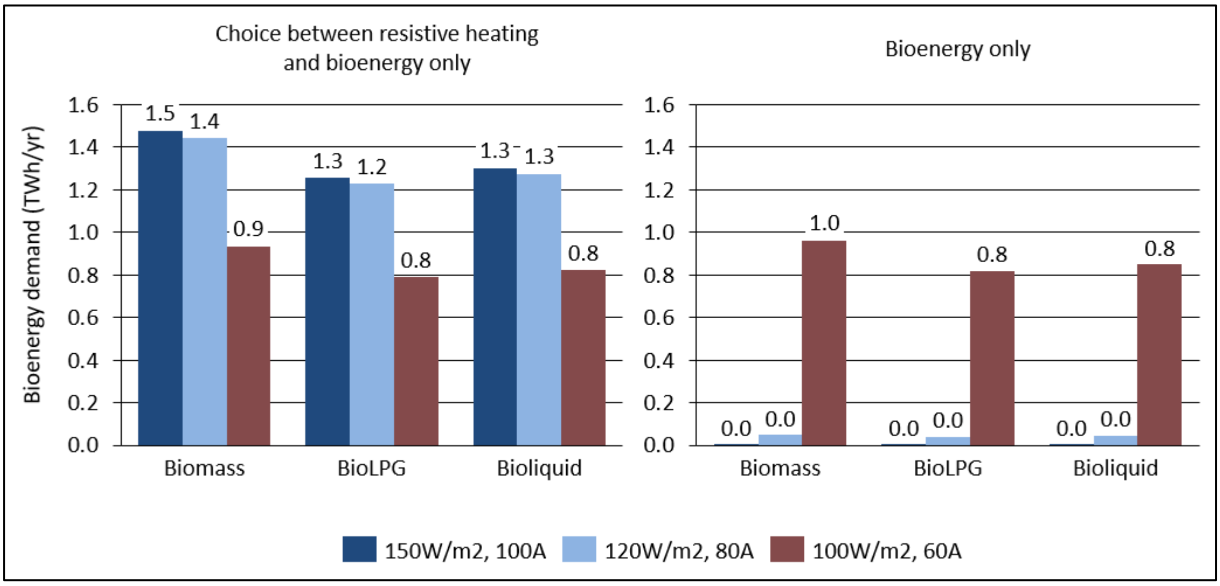
Figure 20: Number of homes with restricted suitability in the most relevant four categories with district heating in 2040



If district heating were not implemented, the number of homes included in the four above mentioned categories at risk (rows 9, 10, 13 and 15) would increase in total by roughly 50%. As homes that would have been suitable for district heating are generally located in urban areas, they will generally be dwellings that are smaller in size and less exposed to the weather. Their energy demand would thus be relatively low, increasing their suitability for electric resistive heating technologies. Additionally, location in an urban area is also generally associated with location in an area supplied by the gas grid. As a consequence, if district heating were not implemented, the number of homes included in four above mentioned categories at risk would generally increase, with the largest increase expected for the second category, i.e. homes suitable for decarbonised gas and electricity only.

The bioenergy demand of Scottish homes was estimated for the two portions of the stock associated with the categories “electric resistive and bioenergy only” (row 13) and for “bioenergy only” (row 15). The fuel demand was estimated assuming that all homes in both categories would install a bioenergy-based heating technology. The results are reported in Figure 21, showing different fuel demands depending on the type of biofuel used (biomass, bioLPG or bioliquid B100) and for a range of peak specific heat demand and fuse limit.

Figure 21: Bioenergy resource required if all dwellings in each restricted category were supplied by bioenergy-based heating technologies in 2040



Due to the different efficiency of the various bioenergy-based heating technologies, a slightly different fuel demand is associated with the use of each fuel type, while delivering the same amount of heat. The variations related to the values of peak specific heating demand and fuse limit are due to the change in the number of homes that are limited to installing a bioenergy-based heating technology.

Total bioenergy demand from both categories is lower than 2 TWh/yr for all considered values of peak specific heating demand and fuse limit. For comparison, the current bioenergy availability in the UK was well over 100 TWh/yr in 2014[33] and is likely to lie between 130 and 350 TWh/yr in 2050[34].

When considering peak specific heat demand of 100W/m^2 and fuse limit of 60A, total fuel demand of both categories amounts to 630,000 tonnes of biomass, 230,000 litres of bioLPG and 200 litres of bioliquid B100[35].

A breakdown of the age, property type, size and existing heating system of the portion of the stock belonging to the most relevant four categories of homes with limited technology choice (corresponding to rows 9, 10, 13 and 15 in Table 10) is reported in Figure 22. For a

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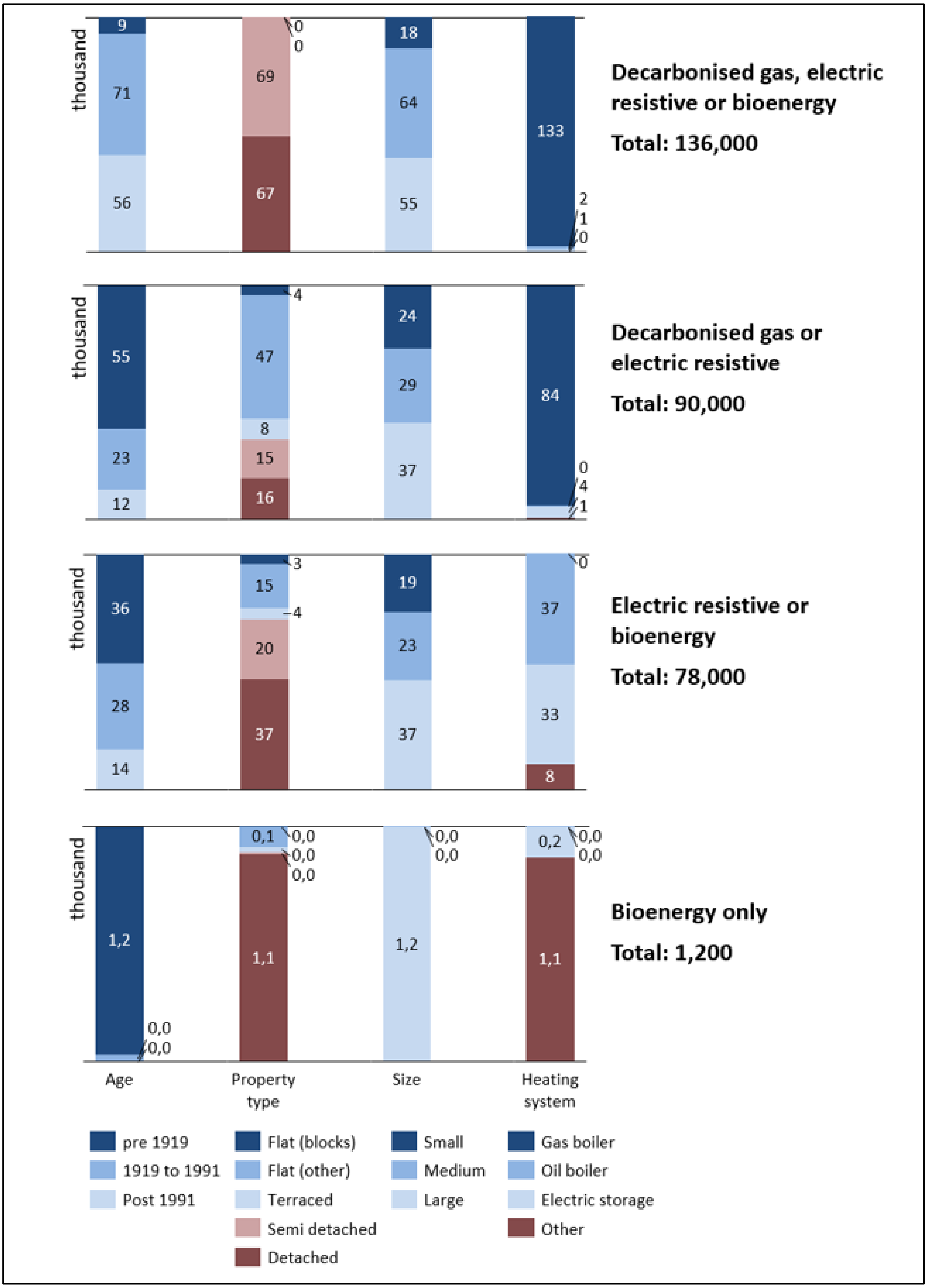
[33] NNFCC, Bioenergy
[34] Element Energy 2019, Hy-Impact Series - Hydrogen production with CCS and bioenergy
[35] Assuming 1 tonne of air-dry wood fuel = 3 MWh, 1 L of bioLPG = 6.9 kWh, 1 L of bioliquid = 8.4 kWh

comparison with the characteristics of the entire Scottish housing stock, see Figure 1 on page 37.

Figure 22: Composition of homes with restricted suitability in the most relevant four categories, for fuse limit of 80A and peak specific heating demand of 120 W/m² in 2040



The first category “decarbonised gas grid, bioenergy or electricity only” (corresponding to row 9 in Table 10) includes a larger portion of new homes built after 1991 (+23%) and a larger share of detached and semi-detached homes (+50%) than the national distribution. These homes also report more often a large floor area over 108 m^2 (+15%). Homes falling within this category are mostly new homes that are not suitable for heat pump technologies due to the lack of space for the installation of the system’s equipment.

The category “decarbonised gas grid or electricity only” (corresponding to row 10 in Table 10) reports more older homes than the national distribution (+42%), more flats (+16%) and fewer detached or semi-detached homes (-15%). Homes in this category are likely located in urban areas, where they are more likely to be located close to the gas network. Furthermore, urban areas present more flats and fewer detached homes than the national average, and have therefore on average a smaller heating demand and smaller area. Therefore, heating demand is likely to be low enough to accommodate electric resistive heating without exceeding the fuse rating, but will also not offer sufficient space for the installation of heat pumps.

In the category “electric resistive or bioenergy” (corresponding to row 13 in Table 10) there is a large share of older homes built before 1919 (+27%), detached homes (+26%) and large homes with floor area over 108 m^2 (+22%). This category describes homes located away from the gas grid, that are sufficiently well insulated to allow for the installation of electric resistive heating but cannot install heat pump technologies due to space constraints.

Finally, the last category “off-gas bioenergy only” (corresponding to row 15 in Table 10) presents a distribution of characteristics that favour large, old, detached houses. These are large individual homes located away from the gas grid with a large heating demand that precludes the installation of both heat pump technologies and electric resistive heating technologies.

5 Conclusions

5.1 Main results and discussion

The key findings of this study provide interesting learnings on the composition of Scotland's housing stock and on its potential interaction with a wide range of low-carbon heating technologies that will be essential for the decarbonisation of domestic heating in Scotland. Main results are the following:

- **The characteristics of the insulation of the existing stock will change over time in order to comply with the requirements set by the Energy Efficient Scotland Route Map**, with the target for all owner-occupied homes to reach EPC band C by 2040. Most effective fabric energy performance upgrade measures investigated in this study are wall and roof insulation. These result to reduce the space heating demand of most dwellings enough for it to have an impact on the suitability of some of the considered heating technologies.
- **The feasibility of the implementation of low-carbon heating in heritage homes will need to be assessed individually.** While the installation of low-carbon heating technologies in heritage homes provides relatively similar obstacles as in non-heritage homes, the implementation of energy performance upgrade measures might be more difficult and will require to be assessed on a case-by-case basis. In fact, listed buildings and homes in conservation areas require planning consent to make changes to the external appearance or to the internal fixtures. Additionally, old dwellings built before 1919 were reported by Historic Environment Scotland to often present similar issues to those of heritage buildings. Heritage and old homes account for ~22% of Scotland's housing stock, with ~3% of listed homes, ~7% homes in conservation areas but not listed and ~12% of homes built before 1919 but not listed or in conservation areas.
- **The fuse limit constraint affects the implementation of electric resistive heating more than heat pump technologies.** While there is uncertainty about the fuse limit of individual Scottish homes, it is assumed that most likely values are 60, 80 and 100 A. The number of homes that might be constrained by fuse limit in the installation of ASHP is significantly lower than for the installation of electric storage heating and direct electric heating, due to the higher efficiency of heat pumps. Furthermore, the number of homes affected by the fuse limit constraint decreases substantially between 2017 and 2040, due to the lower space heating demand enabled by the implementation of energy performance upgrade measures.
- **The installation of heat pumps is not advisable in homes with peak specific heat demand above 150 W/m^2.** Peak specific heat demand could constitute a barrier to the implementation of heat pumps, due to the low flow temperature at which space heating is delivered. The installation of an ASHP results to be advisable for heat loss rates of up to 100 W/m^2, while homes with heat loss rates comprised between 100 W/m^2 and 150 W/m^2 might incur in risk of thermal comfort not being met by the heat pump system. Finally, the installation of heat pumps in homes with specific heat loss above 150 W/m^2 is considered not suitable.
- **In 2040 ASHP and high-temperature ASHP are expected to be equally suitable in Scottish homes.** The overall suitability of the stock for ASHP and high-temperature ASHP is similar and does not change over time with the reduction of space heating

demand, as it is almost exclusively determined by the space constraint. However, in 2017 a portion of homes that are suitable for ASHP are still at risk of not meeting thermal comfort. On the other hand, the installation of a high-temperature heat pump in those homes would guarantee thermal comfort. Finally, the advantage of high-temperature ASHP over conventional ASHP is lost in 2040, as the reduced space heating demand allows for both technologies to meet thermal comfort equally.

- **Electric storage heating is expected to have a larger suitability than direct electric heating**. While very few homes are limited by fuse rating in the implementation of electric storage heating, a large portion is restricted for the installation of direct electric heating by the same constraint. This is due to the larger number of domestic appliances that are consuming electricity while direct electric heating is operating, thus reducing the amount of power that the heating devices can draw before exceeding the fuse limit.
- **Homes with limited choice of suitable low-carbon heating options may be more subject to implementation risk**. Four main groups of dwellings with limited suitability were identified, including homes that are suitable for (a) decarbonised gas, bioenergy and electricity only, (b) decarbonised gas and electric resistive heating only, (c) electric resistive heating and bioenergy only, (d) bioenergy only. Depending on the chosen technology, these homes are at risk of incurring in high costs (electricity) or not being able to rely on the availability of the technology (decarbonised gas grid and bioenergy). Depending on the chosen specific heat demand and fuse rating, homes with restricted suitability could amount to up to ~20% of the housing stock.
- **While there are no concerns around sufficient availability of bioenergy to cover heating demand, the resource may be directed to use in other sectors**. The bioenergy resource required if all dwellings in restricted categories were supplied by bioenergy-based heating technologies is many times smaller than the current bioenergy availability in the UK. However, the Net Zero report by the CCC advises against the use of the available biomass for domestic heating: "The level to which sustainable low-carbon biomass production can be increased is finite, given land constraints and competition from other uses (e.g. food production). It is therefore important to pursue ways of using this finite resource that maximise its contribution to emissions reduction. This means combining bioenergy with CCS."[36]

5.2 Recommendations for further work

Given the complex nature of the application of retrofit measures in heritage and old homes, it is advised that this area is investigated in more detail. In particular, the suitability of energy efficiency measures in homes should be assessed separately for each of the different materials available. Such study would greatly benefit from the engagement of local stakeholders involved in retrofit projects (e.g. Scottish Land and Estates), who can provide real data and information on the types of materials applied, their suitability and costs currently in use.

Additionally, more detailed information could be gathered on the values of fuse rating of Scottish homes, in order to assess suitability for the correct values of each home, rather than through a sensitivity analysis.

[36] CCC 2019, Net Zero – The UK's contribution to stopping global warming

Appendix

PEAT analysis

Portfolio Energy Assessment Tool (PEAT)

PEAT is a browser-based assessment tool which converts address-level data from Home Analytics into a format that can be processed by the Dynamic Engine (DE), EST's SAP-based interactive calculation engine. The DE uses the known information about each home to determine the suitability for various energy efficiency retrofit measures. These measures are considered based on a hierarchy of cost-effectiveness (i.e. the most cost-effective measures are considered first).

The output from PEAT includes a package of recommended measures for each property, the SAP rating improvement as a result of those measures being installed, as well as the total cost of the measure and associated fuel and emissions savings.

PEAT enables users to model different energy efficiency uptake scenarios by inputting various parameters:

- ***Measures template*** – a list of the energy efficiency and renewable energy measures;
- ***Costing template*** – a list of the assumed installation and/or variable costs associated with each measure in the measure template;
- ***SAP target*** – an optional SAP score threshold that can be set to reflect a desired policy outcome. Measures will be applied up to the point that a property reaches the target SAP score;
- ***Per property budget*** – an optional £ limit (e.g. £15,000) that can be set to constrain per property spending on retrofit measures. No additional measures are applied to the property once the budget is reached.

PEAT assumptions

To run a scenario, PEAT requires 20 points of address-level details about a home's building fabric, heating system, energy efficiency, consumption, etc. Unfortunately, the information provided by the archetype attributes chosen for the suitability analysis as outlined in Section 3.3 was insufficient to conduct a PEAT analysis, as these included only 12 attributes. Additionally, many of these attributes had been overly simplified or were not relevant inputs to PEAT. Therefore, a second set of PEAT-specific archetypes was produced using Home Analytics, with the only purpose of running a PEAT scenario and producing information on the potential characteristics of Scotland's housing stock in 2040. The results could then be mapped back to the initial set of dwelling archetypes to be used for the suitability analysis.

Some generalisations about certain segments of the 2017 stock were made to keep the total number of unique archetypes manageable, balancing processing time with archetype specificity and the scope of the project. Our main assumptions included the following:

- **All properties were assumed to have double or triple glazed windows**. As dwellings with single-glazed windows are less energy efficient than those with double or triple glazing, this assumption could lead to underestimating their space heating demand and energy costs in our modelling. However, according to the information recorded in Home Analytics, only 10% of the current housing stock in Scotland is categorised as buildings with single-glazed windows. Additionally, a good portion of these homes is likely to have partial or double glazing on a share of their window area, as the window type categorisation of dwellings is based on the most common type of window glazing. Therefore, considering that (a) the number of homes registered as single-glazed is relatively low, that (b) these will also have on average less than 100% single-glazed windows, and that (c) the PEAT results will successively be aggregated using a weighted average approach to align with the final stock model, the impact of this assumption on the accuracy of space heating demand and energy costs in the model is likely to be minimal.

- **All cylinder tanks were assumed to have a foam insulation jacket with a thickness of less than 50mm**. Cylinder insulation reduces heat loss from the hot water tank, subsequently reducing energy demand. For properties with no cylinder insulation, this assumption will underestimate heating costs and therefore, saving opportunities. It will also overestimate potential costs and savings compared to cylinders with thicker insulation (50-79mm, 80+mm). Since foam insulation thickness of less than 50mm is the most commonly occurring value in the stock and represents a middle ground between the extremes, this assumption is unlikely to have a material impact on the PEAT measure calculations.
- **All properties with four habitable rooms were assumed to have five habitable rooms**. More habitable rooms in a dwelling typically translate into a larger floor area and higher space heating demand, all things being equal. However, given the similarities in terms of total floor area and other building fabric conditions between homes with four habitable rooms and those with five, it was prudent to combine these attributes into a single attribute category ('4-5 habitable rooms'). This reduced the number of unique archetypes in the analysis, which significantly improved the processing time of the PEAT model.

By applying these assumptions, the 2.66 million properties in Home Analytics were categorised into approximately 71,000 unique archetypes. These archetypes differ from the 54,000 used in the final stock model because they were constructed using a different (more detailed) set of variables than those used to formulate the final stock model. As shown in Table 12 and Table 13, one archetype in the final stock model can encompass several PEAT archetypes.

The measures used in this analysis and their associated costs are summarised in Table 11. The fixed cost is the base cost of the measure. The variable cost captures additional installation expenses that change based on the size of the home or the retrofit area (e.g. per m^2 of wall or floor area). The average final cost provides an indicator of the average total retrofit cost for each measure, across all PEAT archetypes. Heating system upgrades were assessed separately, through our low-carbon heating suitability analysis. Therefore, these measures were not included in the PEAT measure template.

Table 11: PEAT Measure Assumptions and Costs

PEAT Measure	Assumptions	Fixed cost	Variable cost	Average final cost
Replace low energy lighting with compact fluorescent (CFL) light bulbs	All light bulbs are low energy	£0	£2.49	£18.61

Draught proofed external doors	Doors 100% draught proofed	£0	£9.88	£27.93
Loft insulation top-up	Total U-value of 0.16W/(m^{2}K) achieved	£158	£2.03	£297.99
Insulation for flat roofing	Total U-value of 0.25W/(m^{2}K) achieved	£0	£32.02	£1,913.63
Room in roof walls and sloping parts, 100mm insulation	100 mm phenolic rigid board of R-value 4.35m^{2}K/W added	£966	£19.25	£1,627.62
Internal wall insulation	100mm internal solid wall insulation of R-value 2.5 m^{2}K/W added	£2,100	£61.44	£6,111.86
Cavity wall insulation	Cavity insulation of R-value 0.77 m^{2}K/W added	£250	£2.63	£412.06
External wall insulation	100mm external solid wall insulation of R-value 2.5 m^{2}K/W added	£5,250	£93.39	£10,988.30
Hard to treat cavity wall insulation	Cavity insulation of R-value 0.77 m^{2}K/W added	£250	£2.63	£413.20
New insulated uPVC external doors	Total U-value of 2W/(m^{2}K) achieved	£0	£220.09	£698.19
A-rated glazing (uPVC)	Total U-value of 1.5W/(m^{2}K) achieved (1.42 with curtains). G-value = 0.63	£1,873	£120.85	£3,994.27
Suspended wooden floor insulation	Total U-value of 0.169W/(m^{2}K) achieved, draught factor = sealed (suspended)	£0	£28.50	£2,009.49

The Energy Efficient Scotland Route Map, published in May 2018, sets a target for all owner-occupied homes to reach EPC band C by 2040, where technically feasible and cost effective. Consistent with this target, the PEAT analysis simulated which efficiency measures would be required to achieve an SAP target of 69 (EPC Band C) by 2040. This means that PEAT would apply suitable measures (i.e. measures which could technically be installed in a home) in order of their cost-effectiveness, until (i) its SAP target was reached or (ii) there were no more suitable measures left to apply. Note that due to a low starting SAP score and/or a lack of suitability for PEAT measures, some homes could not reach the SAP target.

No per property budget was applied during the PEAT scenario analysis.

PEAT outputs

The key outputs of the PEAT scenario analysis included the following variables by PEAT archetype:

- Flags for each of the above 12 measures indicating if they had been applied
- The total cost of each measure (£ p.a.)

- The total fuel bill savings of each measure (£ p.a.)
- The net effect of the measure package on energy demand (kWh p.a.)
- The net effect of the measure package on CO_2 emissions (tCO2 p.a.)
- Starting and ending SAP score

Additional variables from Home Analytics were also provided alongside these PEAT outputs to provide context for the results and to inform the low-carbon heating system suitability analysis. These included:

- Count of Unique Property Reference Numbers (UPRNs)[37] by PEAT archetype
- Average floor area (m^2)
- Average SAP boiler efficiency

Six of the measures considered in the PEAT analysis directly impacted the building attributes upon which the final archetypes were constructed. These relate to wall insulation (cavity, internal, external, hard to treat) and roof insulation (top-up, room-in-roof walls and sloping parts). Two additional fields (updated wall insulation, updated roof insulation) were appended to the PEAT results to indicate if any of these measures were applied during the analysis. Fuel switching and measures related to the heating system were excluded from the PEAT analysis, as these were addressed separately in the suitability analysis of low carbon heating technologies in Section 4.

Mapping results to archetypes

To map the results from PEAT back to the initial set of dwelling archetypes used in the suitability analysis, a weighted-average approach was utilised.

For **continuous variables** the value associated with each final archetype value was calculated as the weighted average of the variable of interest (e.g. energy consumption) assumed by the PEAT archetypes included. The weight assigned to each PEAT archetype was proportional to the number of UPRNs it represented, as shown in Table 12.

Table 12: Example of PEAT mapping for continuous variables

Final Archetype	PEAT Archetype	UPRNs	Weight (UPRN %)	Variable Value	Weighted-Average Value	Final Archetype Value
1	1.1	4,000	0.40	100	40.0	105.3
	1.2	1,000	0.10	115	11.5	
	1.3	2,500	0.25	105	26.3	
	1.4	2,500	0.25	110	27.5	
2	2.1	3,000	0.60	90	54.0	82.0
	2.2	1,000	0.20	70	14.0	
	2.3	1,000	0.20	75	14.0	

Similarly, for **binary categorical variables** (e.g. a flag indicating if the cavity wall insulation measure was applied) the final archetype value was calculated as the weighted average of the binary flag value (0 or 1). As shown in Table 13, the output of this calculation is the

[37] UPRN is the unique property reference number assigned to each property in the Home Analytics tool.

proportion of homes in the final archetype that are projected to embody a specific variable in the future (e.g. 75% of archetype 1 will have cavity wall insulation installed in 2040).

Table 13: Example of PEAT mapping for binary categorical variables

Final Archetype	PEAT Archetype	UPRNs	Weight (UPRN %)	Cavity Wall Insulation Flag	Weighted-Average Value	Final Archetype Value
1	1.1	4,000	0.40	1	0.40	0.75
	1.2	1,000	0.10	1	0.10	
	1.3	2,500	0.25	0	0.00	
	1.4	2,500	0.25	1	0.25	
2	2.1	3,000	0.60	0	0.00	0.40
	2.2	1,000	0.20	1	0.20	
	2.3	1,000	0.20	1	0.20	

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