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Direct greenhouse gas emissions from low and zero carbon heating systems

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1 Executive summary

1.1 Aims and findings

This report looks at direct, point-of-use greenhouse gas (GHG) emissions[1] associated with zero carbon heating technologies.

Direct emissions refer to those generated by a heating system at point of use, within the curtilage[2] of the building. This is an important component for informing approaches to net-zero buildings in terms of recommended technologies for space and water heating. It is important to note that there are other important factors to consider when identifying appropriate technologies. This includes, for example, embodied emissions, controlled use of biomass, and air quality. While these wider considerations are outside the scope of this study, these are being considered elsewhere by the Scottish Government. Evidence for this report was collated from stakeholder interviews and existing literature.

Direct emissions from direct electric heaters, electric storage heaters, electric boilers, solar thermal technologies, heat pumps[3], heat networks and fuel cells are found to be negligible.

Biomass combustion and hydrogen combustion offer significant emissions savings compared to fossil fuel-based heating, but with varying levels of direct GHG emissions that are important to be aware of.

Direct emissions from biomass combustion

Sustainably sourced biomass fuels are often considered carbon neutral, as the material being burned has already absorbed carbon dioxide (CO_2), and replacement biomass is

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[1] GHGs are defined as carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride and nitrogen trifluoride (Climate Change (Scotland) Act, 2009).
[2] The land and building surrounding a dwelling.
[3] While there is a risk of emissions caused by refrigerant leakage from heat pumps, as discussed in Appendix B, this can be assumed to be negligible in case of correctly installed, pressure tested and correctly functioning systems.

regrown in relatively short timescales.[4] However, combustion of biomass is associated with direct emissions of CO_2, methane (CH_4) and nitrous oxide (N_2O). In accordance with UK Government and Intergovernmental Panel on Climate Change (IPCC) reporting guidelines, this report does not include direct emissions of CO_2 from biomass combustion in the assessment of direct in-building emissions.

If CO_2 emissions from biomass systems are thus considered to be zero, biomass systems show significantly lower GHG emissions than the baseline emissions from a natural gas boiler (which includes CO_2 emissions). Most biomass heating technologies emit less than 2% of total natural gas boiler baseline emissions, with the non-CO_2 emissions from biomass systems arising from emission of N_2O and CH_4. The amount of emissions varies significantly between different biomass technologies, with systems with more controlled fuel feed (e.g. pellet boilers) appearing to perform better than manually fed systems such as log stoves.

Quality of fuel and mode of operation are understood to impact emissions considerably, although there is limited data to quantify this.

Direct emissions from hydrogen combustion

Hydrogen combustion leads to the oxidation of nitrogen, producing oxides of nitrogen (NO_x), which is not a direct GHG, as well as the GHG N_2O. Research on this, however, is limited, with N_2O in particular poorly documented. The limited information available suggests that direct GHG emissions are not significant for hydrogen combustion. Provisional modelling in this report suggests GHG emissions could be less than 0.1% of the total natural gas baseline. However, there is no direct data, and other evidence is currently too limited to support a firm estimate. Further data and evidence will be needed in order to generate firm conclusions on the level of GHG emissions associated with hydrogen combustion for heating.

1.2 Recommendations

Data

A common theme across different technologies is a lack of data and research on direct emissions from both manufacturers and independent researchers; therefore, further research is needed to fill gaps and improve understanding.

Understanding of direct emissions from biomass systems would benefit greatly from more detailed research into CH_4 and N_2O emissions' variation between different biomass technologies (and fuel type/quality). Similarly, there is a need for a focused assessment of N_2O emissions from hydrogen combustion.

In the heat pump sector, refrigerant-related emissions can be assumed to be negligible in case of correctly installed, tested and functioning systems. However, there is a need for better data on refrigerant leakage at different lifecycle stages, including during operation, for different refrigerants and types of heat pump systems to strengthen the evidence base. This may partly be achieved through effective application of existing F-gas Regulations, with more effective reporting and information collection.

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[4] In the context of this report, sustainably sourced biomass refers to biomass fuels where equivalent levels of biomass are able to regrow after harvesting and so reabsorb the carbon dioxide emitted through combustion of the fuel. Other aspects of sustainability in the fuel supply chain, while important, are not within the scope of this report.

Mitigating emissions from biomass combustion

For biomass combustion for heating, there may be an important role for education and awareness raising. Information could be provided to operators/users around types of fuel and fuel quality and how these impact emissions. As with any introduction of tighter controls, this too is subject to gaining improved understanding of how emissions vary by technology, mode of operation, fuel and quality of fuel.

Moreover, as well as supporting improved air quality, controls on fuel quality are likely to result in reduced GHG emissions. In order to confirm this, however, improved understanding of CH_4 and N_2O emissions and their variation across different biomass technologies and by quality of fuel, would be beneficial, as mentioned above.

Glossary

Name	Description
F-gases	Fluorinated greenhouse gases, including hydrofluorocarbons (HFCs), are man-made gases, which can stay in the atmosphere for centuries, contributing to global warming.
F-gas Regulations and certification	From 1st January 2020, the EU Fluorinated Greenhouse Gases Regulation (also known as the EU F-gas Regulation) will ban the use of refrigerants with a Global Warming Potential (GWP) of 2,500 or more in certain refrigeration units. Following the UK's departure from the EU, new GB F-gas Regulations came into effect on 1st January 2021 across Great Britain, effectively transferring the requirements of the current EU regulations directly into GB legislation. This F-gas certification scheme is aimed at businesses working with F-gas refrigeration, air-conditioning and heat pump equipment containing or designed to contain fluorinated greenhouse gases.
Greenhouse Gas (GHG)	Greenhouse gases include water vapour, carbon dioxide, methane, nitrous oxide, ozone and some artificial chemicals such as chlorofluorocarbons (CFCs). GHGs absorb and emit radiant energy within the thermal infrared range, causing the "greenhouse effect".
Global Warming Potential (GWP)	Global Warming Potential is defined as the potential for global warming that a chemical has relative to 1 unit of carbon dioxide, the primary anthropogenic greenhouse gas. In determining the GWP of a refrigerant, the Intergovernmental Panel on Climate Change (IPCC) methodology uses a 100-year integrated time horizon.
Hydrochlorofluorocarbons (HCFCs)	Hydrochlorofluorocarbons have been widely used as refrigerants, introduced as substitute for the ozone-depleting chlorofluorocarbons (CFCs) following the adoption of the Montreal Protocol. HCFCs also deplete the ozone layer, but to a lesser degree than CFCs. The use of HCFCs has been regulated since 1997, and has been banned for use in the EU since 2015.
Hydrofluorocarbons (HFC)	Hydrofluorocarbons (HFCs) are used as refrigerants. They were developed to replace substances that were phased out under the Montreal Protocol. While HFCs do not cause ozone depletion, these refrigerants are now regulated due to their frequently high GWP.

Hydrofluoroolefin (HFO)	Hydrofluoroolefins are used as refrigerants and are unsaturated HFCs. This means they are made up of the same atoms as HFCs but contain a carbon-carbon double bond, which means they have a less stable molecular structure and thus decompose faster in the atmosphere.
In-building emissions	The research focus was on direct, in-building greenhouse gas (GHG) emissions. This means that emissions not at point of use were excluded from the scope. This research project does not, therefore, include consideration of emissions from electricity used in heat pumps for example, or the embodied carbon of any of the heating systems. We also do not consider the direct emissions of CO_2 from the burning of biofuels, in line with UK and IPCC reporting guidelines.
Kigali Amendment	This is an amendment to the Montreal Protocol, which added HFCs to the list of chemicals that countries agree to phase out, due to the high global warming potential of HFCs. The UK Government ratified the Kigali amendment in 2017, which came into effect in January 2019.
Manufacturing Readiness Level (MRL)	Manufacturing Readiness Levels are a measure developed by the US Department of Defence to assess the maturity of manufacturing readiness. This allows users to assess the costs and risks that may be associated with production of that particular product. They are defined on a scale from 1 to 10. Level 1 represents where very basic manufacturing implications have been considered, and level 10 being full rate production with streamlining. MRLs are a useful complement to Technology Readiness Levels (TRLs). There can be risks in solely using TRLs when wider considerations of manufacturing barriers have not been taken into account. For example, a product may be made up of a number of standardised individual components all with high TRL. However, if the manufacturing structure in not in place to mass produce these components, the technology would have a lower MRL. However, technologies with low MRLs should not be discounted, but that efforts and/or investment should be focussed on removing barriers to manufacturing. As noted in Section 3 of the main report, stakeholders did not respond to questions on MRLs, providing instead high-level commentary on market penetration and manufacturing and supply issues.
Modified Combustion Efficiencies (MCE)	Modified Combustion Efficiencies can be used to give an indication of what stage of combustion a system is in. For example, the combustion efficiency will be lower during

	the start-up or ignition stages and reach its maximum during normal operation.
Monobloc Heat Pump System	The Monobloc configuration keeps all components of the heat pump within a single outdoor enclosure. Two pipes carry either water, or a mixture of water and antifreeze between the outdoor unit and the interior portions of the overall system.
Montreal Protocol	The Montreal Protocol was originally adopted to preserve and restore the ozone layer and is considered to have been successful to date. The Protocol is an agreement between participating countries to phase out certain ozone-depleting substances. HFCs were used to replace the substances banned in that agreement because they have zero impact on the ozone.
Natural refrigerant	There are an increasing range of ultra-low GWP natural heat pump refrigerants available, including CO_2, ammonia and propane.
Seasonal performance factor (SPF) and Coefficient of Performance (CoP)	Seasonal performance factor (SPF) is the average coefficient of performance (CoP) of a heat pump over the heating season. CoP is the ratio of heat output (kW) to electrical input (kW) at any one time.
Split Heat Pump System	A split system configuration uses refrigerant lines to connect between the outdoor unit, and the indoor unit. The outdoor unit contains the compressor, air to refrigerant heat exchanger, and outdoor air fan. The indoor unit contains the refrigerant to water heat exchanger, circulator, expansion tank, controls, and in some systems an electric resistance element for auxiliary heating.
Technology Readiness Level (TRL)	Technology Readiness Levels are a measure developed by the US Department of Defence to assess the maturity level of a particular technology. They are defined on a scale from 1 to 9. Level 1 represents a technology that is only at the stage of scientific research, and level 9 being full rate deployment. TRLs complement Manufacturing Readiness Levels (TRLs). However, technologies with low TRLs should not be discounted, but that efforts and/or investment should be focussed on removing barriers to deployment. As noted in Section 3 of the main report, stakeholders did not respond to questions on TRLs, providing instead high-level commentary on market penetration and manufacturing and supply issues.

Contents

2 Introduction

This report, prepared by ACE Research (ACE-R) at the Association for Decentralised Energy (ADE) and the Energy Saving Trust (EST), details research findings to support the Scottish Government in understanding the direct, point-of-use greenhouse gas (GHG) emissions[5] associated with zero carbon heating technologies.

2.1 Policy context

In June 2019, the UK Parliament passed legislation requiring the government to reduce the UK's net emissions of GHGs by 100% relative to 1990 levels by 2050. The Scottish Government went further in its Climate Change (Emissions Reduction Targets) (Scotland) Act 2019, requiring net emissions of greenhouse gases to be reduced by 100% relative to 1990 levels by 2045. Interim targets include a 75% emissions reduction by 2030, and 90% by 2040.

In parallel to such ambitious overarching net-zero emissions targets, Scotland has developed specific policies to decarbonise emissions from buildings. In 2021, the Scottish Government (2021a) published the Heat in Buildings Strategy which outlines the steps that will be taken to reduce GHG emissions by at least 68% by 2030 from Scotland's domestic and non-domestic buildings, including both new-build and existing stock.

The Scottish Government is committed to ensuring that, from 2024, new buildings applying for a building warrant must use heating systems which produce zero direct GHG emissions at the point of use. This ambition has been explored through an initial scoping consultation that set out the high-level vision for the New Build Heat Standard (Scottish Government, 2021b).

The Scottish Government has also been consulting on minimum standards applicable to both new build and existing buildings through Building Regulations standards (Scottish Government, 2021c).

2.2 Setting the scene

Significant progress has been made in decarbonising electricity supplies. Policy makers and industry are now focusing on decarbonising heat and reaching net zero across the entire economy.

Whilst there is a good understanding of the carbon dioxide (CO_2) emissions from most fossil fuel combustion systems, there is much less understanding of the impact on emissions of other GHGs from the installation, operation and decommissioning of heating systems, including those considered to be low or zero carbon.

It is vital that these in-building GHG emissions are fully understood and evaluated so that appropriate legislation can be developed to drive specifiers and installers to fit heating systems that genuinely contribute to the ambition of zero emissions.

The wider net zero target requires all GHG emissions to be addressed, whether within the building curtilage or not. However, heating system specifiers usually have little or no influence over the GHG intensity of the electricity, gas or external heat supplies available. It, therefore, makes sense to require those specifiers to meet limits on in-

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[5] GHGs are defined as carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, sulphur hexafluoride and nitrogen trifluoride (Climate Change (Scotland) Act, 2009).

building emissions specifically, while decarbonisation of energy supply continues to be driven by separate regulation and support.

Nevertheless, it will be important to ensure that efforts to reduce both direct (in-building) and indirect (emissions from external supply) GHG emissions happen in a co-ordinated way to avoid unintended consequences, such as the specification of systems that meet the in-building requirement but hamper efforts to decarbonise external supply.

2.3 Project scope

This research project used stakeholder interviews and published literature (see Appendix A for research approach) to look at a range of technologies in domestic and non-domestic new build and existing properties.

The research focus was on direct, in-building GHGs, in keeping with the Scottish Government's proposals to regulate those direct GHGs from heating within the building, with indirect GHGs regulated elsewhere, such as by the UK Emissions Trading Scheme which regulates GHG emissions from generation of electricity. This means that emissions not at point of use were excluded from the scope. This research project does not, therefore, include consideration of emissions from electricity used in heat pumps or direct electric heaters for example. Nor does it include emissions from the production of hydrogen, nor the embodied carbon of any of the heating systems. Notably, our key outputs on direct GHG emissions from the burning of biofuels do not include emissions of CO_2 at point of use, from the burning of biofuels; this is in line with UK Government and IPCC reporting guidelines, recognising that these CO_2 emissions would have occurred anyway during natural decay of the plants, from which biomass is derived.

However, given that all these external factors significantly affect the climate impact of a heating technology choice, we do reference these factors in our conclusions and recommendations to provide appropriate context for our findings.

In addition, the research considers the market maturity and market penetration of each technology, as well as applying the findings to a range of standard building archetypes in order to understand emissions relative to reference heating technologies.

3 Heating technology profiles

This research looks at a range of technologies:

- Zero direct emission technologies, including direct electric heaters, electric storage heaters, electric boilers, solar thermal and solar thermal storage, heat pumps and heat networks.
- Biomass combustion.
- Hydrogen combustion and fuel cells.
- Other technologies.

The research team investigated Manufacturing Readiness Levels (MRLs) and Technology Readiness Levels (TRLs) to understand market penetration rates and deployment barriers for different technology levels. While stakeholders, particularly for heat pumps, did not have commentary on MRLs or TRLs for the technologies in scope specifically, the research team was provided with high level commentary on market penetration and current and potential manufacturing and supply issues.

3.1 Market penetration

The Renewable Heat in Scotland 2019 report (Energy Saving Trust, 2020) provides information on the total number of installations in Scotland of modern solid biomass systems (not including log stoves), heat pumps and solar thermal (Table 1). Percentages of the total housing and non-domestic building stock are also included but are only indications, as the installation numbers are split by size rather than by use type.

Table 1: Market penetration of solid biomass systems, heat pumps and solar thermal (source: Renewable Heat Scotland)

	Domestic scale		**Commercial scale**	
	Number	%	Number	%
Solid biomass	5,000	0.20%	3500	1.75%
Heat pump	16,800	0.66%	350	0.18%
Solar thermal	4,600	0.18%	-	-

The Energy Saving Trust’s Home Analytics database takes information from the Energy Performance Certificate (EPC) Register, the Scottish House Condition Survey and other sources and has been used to provide market penetration figures for other technologies in scope in domestic buildings Table 2). These figures relate specifically to domestic properties rather than being based on system size.

Table 2: Market penetration of direct electric heating and district heating (source: Energy Saving Trust)

	Domestic scale	
	Number	%
Direct electric	302,100	11.86%
District heating	33,100	1.30%

3.2 Zero direct emission technologies

3.2.1 Direct electric heaters

Electric panel heaters

Electric panel heaters use electricity to heat a space through convection heat and consist of a resistive element within a protective casing that can be switched on or off as required. There are no GHGs involved in this process, and thus no direct in-building emissions.

Electric fan heaters

A fan heater operates by using a fan to push air over an internal heating element. There are no GHGs involved in this process, and thus no direct in-building emissions.

Thermal fluid filled radiators

Thermal fluid filled radiators use an electrical element to heat a reservoir of oil or thermal fluid sealed within the radiator unit. Glycol is typically used as the thermal fluid, with negligible GWP and low vapour pressure and, therefore, unlikely to leak to the atmosphere. Thus, direct in-building emissions can be assumed to be zero.

Electric radiant heaters

Electric radiant heaters generate heat using infrared waves. There are no GHGs involved in this process, and thus no direct in-building emissions.

3.2.2 Electric storage heaters

No GHGs are emitted directly within the building, as the heater is based on bricks or ceramics with solid insulation rather than gases or fluids.

3.2.3 Electric boilers

Electric boilers operate by passing running water pass through an element, which is heated by electricity, after which the heated water passes through the buildings heating system to warm the space to a desired temperature. There are no direct in-building emissions associated with this process.

3.2.4 Solar thermal and solar thermal storage

Solar water heating systems, or solar thermal systems, use heat from the sun to warm water providing domestic hot water, rather than space heating. Using solar panels, called collectors which are filled with working fluid which absorbs heat from the sun, heat is transferred to water stored in a hot water cylinder.

The only potential source of GHG emissions from solar thermal systems is through leakage of working fluid[6]. Working fluids differ between systems, but typically used is propylene glycol (a non-toxic liquid with negligible GWP, with low vapour pressure) - which is unlikely to leak into the atmosphere.

Moreover, solar thermal systems should be designed such that any leakage of working fluid is negligible, with a well-designed system not expected to require any refilling of working fluid over its lifetime (Energy Saving Trust, 2019).

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[6] Please note that it is common in life cycle emission assessments of solar thermal systems to allocate emissions to the use phase due to emissions from an assumed fossil-fuelled auxiliary heating system; as this is a separate system, we do not include consideration of any auxiliary heating system in present analysis.

3.2.5 Heat pumps

The only risk of direct in-building GHG emissions from heat pumps is in case of leakage of refrigerant, which can be assumed to be negligible for heat pumps correctly installed, pressure tested and correctly functioning. See Appendix B for detailed considerations around refrigerant emissions and monitoring and mitigation measures, and Appendix C on modelling of refrigerant related emissions.

3.2.6 Heat networks

A heat network is a distribution system of insulated pipes that distributes heat to multiple buildings from a central source. Heat networks are generally not associated with direct, in-building GHG emissions.

In line with our assessment of emissions from heat pumps, emissions can also be assumed to be negligible in case of ambient loop heat networks[7] that rely on heat pump technologies, where the only risk of emissions is due to risk of refrigerant leakage. (See Appendix B for detailed considerations around refrigerant emissions and monitoring and mitigation measures.)

3.2.7 Fuel cells

Fuel cells are electrochemical devices, which generate electricity by a chemical reaction between a fuel (typically hydrogen) and an oxidising agent (typically oxygen). Hydrogen fuel cells produce electricity and heat without any combustion, and it is, therefore,assumed that in-building GHG emissions are zero.

3.3 Biomass combustion

There are a range of biomass technologies and fuels available, including solid, liquid and gaseous options. Sustainably sourced[8] biomass fuels are often considered zero carbon, as the material being burned has already absorbed CO_2 from the atmosphere and replacement biomass can be grown in relatively short timescales, reabsorbing the CO_2 to create a closed carbon cycle.

However, combustion of biomass does produce CO_2 within the curtilage of the building, along with emissions of CH_4 and N_2O.

A range of biomass heating systems are available. Chip, pellet and log boilers, along with pellet and log stoves use solid fuels. While stoves often provide space heating for individual rooms, they can be connected to back boilers to provide heat for an entire property.

BioLPG and BioDiesel heating systems are similar or identical to LPG and diesel-powered systems, but the fuel is produced from biological sources which may be considered sustainable.

3.3.1 Source of in-building emissions

It is worth discussing how each of CO_2, CH_4 and N_2O are formed to understand where the emissions arise.

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[7] An ambient loop heat network is a low temperature system with heat pumps installed in each premises, which use the low-grade heat to heat water to the temperature required for heating and hot water.

[8] In the context of this report, sustainably sourced biomass refers to biomass fuels where equivalent levels of biomass are able to regrow after harvesting and so reabsorb the carbon dioxide emitted through combustion of the fuel. Other aspects of sustainability in the fuel supply chain, while important, are not within the scope of this report.

As with all hydrocarbon and carbohydrate fuels, CO_2 is generated during combustion, as the carbon in the fuel reacts with oxygen in the air to produce CO_2. If the fuel and air mix were to only contain carbon, hydrogen and oxygen, only water and CO_2 would be produced, however due to other components in the fuel and air, other products are also formed.

CH_4 is formed during incomplete combustion of the hydrocarbon fuel (or non-combustion of biomethane). This is most likely to occur during start-up or shutdown as the conditions within the boiler/stove may not be correct to ensure the complete combustion.

N_2O and oxides of nitrogen (NO_x) emissions in biomass predominantly arise from the reaction of nitrogen within the fuels. For combustion occurring at high temperatures, nitrogen in the air can also contribute to these emissions. The relationship between N_2O and NO_X emissions is complex and currently not well understood in this context.

Solid biomass fuel

Solid biomass is produced from a wide range of sources around the world but, in terms of heating buildings in Scotland, it is effectively all produced from wood. There is limited data available for the emissions of interest (N_2O and CH_4) from wood-fuelled heating systems. Existing research focusses predominantly on particulate $PM_{2.5}$ and NO_x emissions, due to their impact on air quality, neither of which are within the scope of this report focusing on GHG. We have, therefore, derived emissions from the limited literature available. The approach is covered in Section 3.3.4.

Liquid/gaseous biomass fuel

Liquid and gaseous fuels have a much more consistent combustion process than solid fuels, due to the more homogenous fuel and the ease of mixing with combustion air. The GHGs emitted are the same as for solid biomass, except that fuel nitrogen may be lower, or even zero for biomethane, while combustion temperatures can be higher. N_2O emissions are, therefore, more likely to come from oxidation of nitrogen in the air than from nitrogen in the fuel.

GHG reporting conversion factors provide fixed emission factors for CO_2, CH_4 and N_2O for many biofuels, and we found no evidence to support deviating from these.

3.3.2 Market penetration

Biomass heating systems are technically and commercially well-established technologies. Wood fuel combustion systems have been popular in many countries for many years, and in Scotland modern wood fuel systems have become increasingly common since the introduction of the Renewable Heat Incentive (RHI), alongside traditional log stoves.

BioLPG, biodiesel and biomethane are designed to be burnt in existing conventional gas and oil boilers. The technology is, therefore, well established and widespread, but the penetration of the fuels is largely negligible. Biomethane is being produced in significant quantities but is largely injected into the gas grid, where it forms part of the natural gas supply that is used in this report as the baseline, rather than in the form of bespoke low-carbon heating systems for buildings.

3.3.3 Monitoring and mitigation

As noted above, there has been little measurement of GHG emissions from biomass heating systems to date in either laboratory or real-world environments. A significant programme of measurement would be required across the range of systems, fuels and operating practices before accurate estimates of likely emissions could be generated.

CO_2 emissions are well understood and can be deduced from fuel usage and combustion efficiency, but measurement of CH_4 and N_2O requires specialist equipment and has rarely been carried out, even in laboratory conditions. Actual monitoring of in-situ emissions in buildings is, therefore, unlikely to be practical except in the largest systems.

Mitigation may be possible through further standards for manufacture and installation of systems, and for quality of fuels, but also through guidance on better operation of systems, especially manually-fed systems such as log stoves. The efficiency can vary greatly depending on how it is used by the consumer.

Improved combustion efficiency links closely to reduced CH_4 emissions, and is likely to also reduce NO_x emissions. It may also lead to reduced N_2O emissions, as less nitrogen from the combustion air is oxidised and this may limit N_2O production. However, there is no evidence to confirm or quantify a direct or consistent correlation, and there is even the potential for reduced NO_x to mean an increase in N_2O (Kiwa, 2018).

3.3.4 Emissions assessment methodology: biomass

The GHG emission factors for biomass systems are based on a combination of the three gases which are applicable: CO_2, CH_4 and N_2O. Different methods are required for solid and liquid/gaseous fuels and are presented briefly below and in more detail in Appendix D. Each of the combined factors is based purely on the total kWh of fuel required, with currently no data available to apply factors for other variables (e.g. system size).

We have developed indicative GHG factors for a range of wood-burning systems, based on the limited data available. Due to the above shortcomings in the data, individual results are not rigorous enough to support policy decisions that differentiate between technologies, and are presented here to indicate the potential scale of the issues and whether further research is justified.

Emissions factors for CH_4 and N_2O were derived for each solid fuel technology using data from Bhattu et al. (2019) and Tsupari *et al.* (2005) and are summarised below (for full details see Appendix D).

1. CH_4 emission estimated for each technology at start-up and normal operation.
2. N_2O emissions estimated in two ways:
   - A constant ratio between CH_4 and N_2O emissions reported by Tsupari *et al.*
   - A constant value for all solid biomass based on the report by Tsupari *et al.* – this is thought to be more accurate as while the CH_4 emissions vary depending on combustion efficiency, N_2O emissions should be fixed as it is based on the nitrogen content of the fuel which for wood fuel can be assumed to be relatively constant
3. CH_4 and N_2O emissions are combined to give the values in Table 3.

Table 3: Solid biomass emissions by technology

Technology	**Methane emissions ($kgCO_2e/kWh$)**	**Nitrous oxide emissions ($kgCO_2e/ kWh$)**	**Total emissions ($kgCO_2e/ kWh$)**
15kW pellet boiler	1.3×10^{-3}	$0.2\text{-}0.9\times10^{-3}$	$1.5\text{-}2.2\times10^{-3}$
6kW pellet stove	0.5×10^{-3}	$0.2\text{-}0.4\times10^{-3}$	$0.8\text{-}0.9\times10^{-3}$
30kW log boiler	2.0×10^{-3}	$0.2\text{-}1.5\times10^{-3}$	$2.3\text{-}3.5\times10^{-3}$
4.6kW adv log stove	3.0×10^{-3}	$0.2\text{-}2.2\times10^{-3}$	$3.3\text{-}5.2\times10^{-3}$
8kW adv log stove	22.0×10^{-3}	$0.2\text{-}15.7\times10^{-3}$	$22.2\text{-}37.7\times10^{-3}$

6kW simple log stove	7.0×10^{-3}	$0.2\text{-}5.0\times10^{-3}$	$7.2\text{-}11.9\times10^{-3}$
Chip boiler	0.3×10^{-3}	0.2×10^{-3}	0.6×10^{-3}

For these cases we have assumed a CO_2 GWP of 0 in line with the UK methodology. Technically, this is ignoring significant in-building emissions of a GHG but is in line with the established approach of assuming that these emissions make no net contribution to global warming. For completeness we have included figures in Appendix G using a GWP of 1 for biomass CO_2, effectively treating these emissions in the same way as fossil carbon. It should be stressed that these figures do not represent any real assessment of the possible impact of biomass emissions – they are included simply to demonstrate the impact of different approaches to CO_2 accounting in this context. In principle, it would be possible to establish appropriate GWP factors for some common biofuel supply chains, but that is outside the scope for this project.

For liquid/gaseous fuels, as mentioned above, we found no evidence to support deviating from the BEIS (2021) reporting guideline factors for common bioliquids and gases. We, therefore, used the published CH_4 and N_2O factors to calculate direct GHG emissions for these fuels, with the combined emissions shown in Table 4. As with solid biomass, CO_2 was assumed to have a GWP of zero. Emissions were calculated for each archetype assuming the same efficiency factors as for gas systems (see Section 0).

Table 4: Combined emissions for liquid / gaseous fuels (BEIS, 2021)

Fuel type	**Combined emissions (kgCO$_2$e/kWh)**
HVO (biodiesel)	0.00373
BioLPG (40%)	0.08598
BioLPG (100%)	0.00030
Biomethane	0.00038

3.4 Hydrogen

Hydrogen can be burnt in boilers in much the same way as natural gas to provide hot water for space heating and domestic hot water supply. Hydrogen can be blended with natural gas to provide a fuel with reduced carbon content. However, any blend with significant CH_4 content would still produce significant CO_2 emissions and would, therefore, be out of scope for this study. There is also the potential for pure hydrogen to be made available via the existing gas grid, which would allow buildings to be heated by hydrogen if fitted with appropriate boilers. Hydrogen contains no carbon, so CO_2 is not produced at the point of combustion, and hydrogen boilers are often described as a zero-carbon heating option.

Hydrogen can also be used to drive a fuel cell – a solid state device that produces both electricity and heat. Fuel cells can be used as combined heat and power (CHP) systems within buildings to provide space heating as well as electricity for use in the building, and for export.

3.4.1 Source of in-building emissions

Hydrogen is understood to produce no carbon emissions at the point of use, as you burn hydrogen in oxygen to produce heat and water. However, due to the presence of nitrogen in the air, NO_x and (very probably) the GHG N_2O are produced. While not a direct GHG, NO_x emissions from boilers are routinely measured to ensure compliance with the Ecodesign limits (for air quality rather than GHG purposes), whereas no monitoring data is available on emissions of the GHG, N_2O, and the relationship between the two is not understood sufficiently to quantify.

Hydrogen burns at a higher temperature than natural gas, which would imply higher NO_x emissions. However, tests on domestic hydrogen boilers have shown NO_x emissions (an air pollutant) of 22 mg per kWh of gas, compared to 40 mg per kWh for natural gas. One industry expert, interviewed for this research, believed this was due to shorter retention time within the high temperature flame zone. In the absence of evidence to the contrary, they took this to suggest that N_2O (GHG) emissions would be similarly lower for hydrogen than for natural gas.

Hydrogen fuel cells produce electricity and heat without any combustion, and it is, therefore, assumed that in-building GHG emissions are zero.

3.4.2 Market penetration

Hydrogen is not available as a fuel in the UK outside of some small trials of a few hundred homes. Hydrogen boilers are, therefore, not being purchased or installed outside of these trials. Hydrogen ready boilers have been produced as prototypes at domestic and non-domestic sizes, and are being used in those trials, but are not currently offered commercially.

We understand that at least two major domestic gas boiler manufacturers would be ready to roll out commercial hydrogen models at scale within a matter of months should a market develop. We are not aware of hydrogen fuel cells being installed in buildings in Scotland at present.

3.4.3 Monitoring and mitigation

There is currently no monitoring of N_2O emissions from hydrogen boilers. As there is no available data on N_2O emissions from hydrogen combustion, it cannot be confirmed whether this technology is associated with GHG emissions or warranting of the introduction of monitoring and mitigation measures. Based on data showing low emissions of the related gases, NO_x, it may be expected that N_2O GHG emissions are negligible, in which case there would be little need for mitigation or in-situ monitoring. However, the research team would recommend that further testing is required to confirm whether levels of N_2O emissions are indeed negligible.

3.4.4 Emissions Assessment Methodology: Hydrogen combustion

Due to the lack of data on GHG emissions from hydrogen boilers, the factor we have chosen to use is based on information obtained from interviews with industry experts. The only relevant emissions are N_2O, generated by high combustion temperatures.

There are no reported data on N_2O for hydrogen boilers. However, if we were to assume that the same ratio of N_2O to NO_x for natural gas combustion applied also to hydrogen combustion, it would be possible to estimate emissions of N_2O, on the basis of measured NO_x emissions from hydrogen boilers.

Based on one manufacturer's measured emissions of 22 mg NO_x per kWh fuel used by the hydrogen boiler and 40 mg NO_x per kWh for natural gas, corroborated by similar results from one other manufacturer, we could scale the UK GHG reporting factor for N_2O for natural gas to one for hydrogen using the equation below, where NOx_{H2} and NOx_{NG} are the measured NO_x emissions from a hydrogen and natural gas boiler, respectively, N_2O_{NG} is the N_2O emission factor for natural gas in $kgCO_2e/kWh$ and N_2O_{H2} is the overall N_2O emissions for a hydrogen boiler in $kgCO_2e/kWh$:

$$\mathrm{N_2O_{H2}} = \mathrm{N_2O_{NG}} \times \frac{\mathrm{NOx_{H2}}}{\mathrm{NOx_{NG}}} = \mathrm{N_2O_{NG}} \times \frac{22}{40}$$

Notably, the combustion of hydrogen and the combustion of natural gas differ in terms of temperature and other physical characteristics, and we cannot, therefore, be certain that nitrogen oxidation and reduction processes are equivalent, or, therefore, that the N_2O to NO_x ratio would necessarily be the same, or even similar. Figures calculated on the basis of these assumptions can, therefore, only give an indication of the possible scale of emissions in the absence of any data to support a firm estimate, and should be interpreted with care.

Further data and evidence will be needed in order to generate firm conclusions on the level of GHG emissions associated with hydrogen combustion for heating.

3.5 Other technologies

Based on a review of current innovation projects and trials as well as stakeholder interviews, we have not identified any further technologies under development for consideration in this report.

Current innovation projects include hybrid solutions using a mix of technologies reviewed above (e.g. solar assisted heat pump systems). Emissions from such systems can be assumed to correspond to those of each individual technology involved, as discussed above.

One area of innovation, which may warrant further investigation in the future, is around fuel mixes, as the mixing of biogas with hydrogen appears to increase NO_x (and most likely N_2O).

4 Benchmarks and property archetypes

In order to assess emissions from low-carbon heating technologies relative to conventional heating technologies, this project used a set of building archetypes to estimate emissions from low-carbon technologies. The team used two benchmark scenarios of heating based on gas central heating and hybrid heat pump/gas boiler systems, respectively. This section briefly describes the two benchmark scenarios and the property archetypes across domestic and non-domestic sectors.

The primary benchmark for all archetypes is a new gas combination central heating boiler system:

- The main in-building GHG emissions are CO_2 which are related directly to the amount of gas consumed, and hence closely linked to the annual heating demand. Efficiency is the only scaling variable.
- Other emissions include CH_4 during start-up and N_2O at certain operating temperatures, both of which are very small relative to CO_2 emissions.
- The key parameter is, therefore, the fuel used in kWh. The UK Government reported GHG factor is, therefore, suitable for this scenario (BEIS, 2021).

The alternative benchmark for all archetypes is a hybrid heat pump and gas combination boiler system:

- This benchmark will be presented as a range of emissions due to the variability in the proportion of heat supplied by each heating system.
- We have assumed the entire hot water demand is met by the gas combination boiler.
- The space heating demand met by the heat pump will vary between 48% and 89% as presented in Element Energy's (2017) report for BEIS. We have selected heat pumps from single homes only (i.e. large heat pumps serving multiple homes have not been included).
- GHG emissions will be calculated as in the standalone gas boiler benchmark.
- Heat pump emissions are similar or equal to stand alone heat pump emissions, although a smaller heat pump would be required. We have assumed a scaling factor of 0.71 to the standalone heat pump in line with the ratio used in Element Energy's report.
- Key parameters are kWh produced, heat pump capacity, heat pump refrigerant charge and proportion of gas contribution to heat load (which cannot be set other than arbitrarily).

Archetypes: Archetypes were defined for domestic and non-domestic sectors, each of which were divided into existing buildings (with lower fabric efficiency) and new build (with higher fabric efficiency). Archetypes were defined based on key factors impacting system size, system efficiency and sub-optimal operation, as set out in Table 5.

Table 5: Archetype factors and parameters

Factor	Building parameters
Installed capacity	Building size, heat loss coefficient, internal set temp, hot water demand
Annual heat demand	As above, plus occupancy pattern
Operating schedule	Occupancy pattern
Flow temperature	Heat distribution system, heat loss coefficient, internal set temperature

4.1 Domestic archetypes

Three property types were selected to demonstrate potential emissions from domestic properties. These were further divided based on the level of insulation to highlight the range of emissions that might be experienced:

- New build – based on the latest Scottish Government (2021d) energy standards for new builds (advanced case).
- Existing, insulated – a typical well insulated existing property modelled using Dynamic Engine, a Standard Assessment Procedure (SAP) based energy model.
- Existing, uninsulated – a typical poorly insulated existing property modelled using Dynamic Engine.

Table 6 shows the domestic archetypes selected, together with their heating demand and the assumed heat pump flow temperatures which will determine the efficiency of the heat pump system. The set point temperature was assumed to be 21°C and the occupancy profile was set to the SAP default. For further details of the modelling assumptions used, please see Appendix E.

Table 6: Domestic archetypes definitions

Archetype	Floor area (m^2)	Space Heating Demand (kWh/yr)	Hot Water heating demand (kWh/yr)	Heat pump flow temperature
4 bed detached, new build	141	2378	2688	35°C
3 bed semi, new build	84	935	2498	35°C
2 bed ground floor flat, new build	70	562	2426	35°C
4 bed detached, insulated	129	10330	4231	55°C
3 bed semi, insulated	88	5455	4115	55°C
2 bed ground floor flat, insulated	74	5573	2050	55°C
4 bed det, poorly insulated	129	24859	4231	55°C
3 bed semi, poorly insulated	88	13866	4115	55°C
2 bed GF flat, poorly insulated	74	7228	2050	55°C

4.2 Non-domestic archetypes

Non-domestic archetypes were agreed on with the project steering group and further split into three types: new-build, well-insulated existing and poorly-insulated existing. It should be noted that these properties represent potential properties within these archetypes and may not represent the 'average' within each category. This is due to limited availability of data to carry out detailed analysis of non-domestic archetypes.

Table 7 shows the non-domestic archetypes for new build and existing properties. The full tables showing the breakdown for each type of building can be found in Appendix E. To establish the required characteristics presented in the tables, the following assumptions were made:

- Total floor area was estimated based on typical sizes of known buildings within the specific archetype (based on the Energy Performance Certificate register (Energy Saving Trust)).

- Annual space heating and water demand was calculated based on published Chartered Institution of Building Services Engineers (CIBSE) benchmarks for each archetype (CIBSE, 2008, 2012).
- The flow temperatures are possible for each archetype; while they may not be the most common, as this data is unavailable. These are assumed based on EST's best estimate.
- Load factor assumed based on EST knowledge of typical factors observed in Scottish government reporting projects.
- Capacity was calculated based on total heating demand and load factor.

Table 7: Non-domestic archetype definitions showing range from new build ("New") to poorly insulated existing buildings ("Existing"). "HW" abbreviates Hot Water.

Archetype	**Characteristics**	**Total floor area (m^2)**	**Annual space heating load (MWh)**		**Annual water heating load (MWh)**		**Typical flow temp. (°C)**	**Typical load factor (gas)**	**Assumed system capacity (kW) (gas)**	
			New	**Existing**	**New**	**Existing**			**New**	**Existing**
Hospital	High temp, high HW, 24/7	25000	1208	8300	1023	5050	75	45%	566	3387
Care home	High temp, med HW, 24/7	2000	97	664	45	220	75	45%	36	224
Leisure centre	Med temp, high HW, long hours	15000	1109	7625	193	1346	55	35%	425	2926
Hotel	Med temp, med HW, 24/7	1500	129	420	165	293	65	40%	121	167
Office	Low temp, low HW, short hours	20000	84	1422	52	158	45	15%	104	1202
School	Med temp, low HW, short hours	2300	44	340	29	38	60	15%	55	287
Community centre	High temp, low HW, v short hrs	500	11	84	7	9	75	15%	14	71
DIY store	Low temp, v low HW, long hours	5000	35	912	8	48	45	35%	14	313
Light industrial	V low temp, low HW, short hours	1500	109	153	8	24	35	15%	101	122
Warehouse	Low temp, no HW, long hours	250	18	42	2	4	45	25%	10	20

5 In-building emissions by technology

This section presents the findings of assessments of direct emissions from biomass combustion and hydrogen combustion, respectively, compared against the two benchmark scenarios of heating by gas boiler and hybrid heat pump. Findings are summarised in Table 8 and Table 9.

For details of how the GHG emissions from the two benchmark scenarios have been calculated, see Appendix F.

For detailed results of emissions modelling for biomass and hydrogen, see Appendix G.

Table 8: Summary results for domestic archetypes. Results for biomass and hydrogen are based on limited data and, therefore, have a large uncertainty associated with them. Please refer to Sections 3.3 and 3.4 for details.

Archetype		**Gas boiler benchmark emissions (kgCO$_2$e/yr)**	**Hybrid heat pump relative to gas boiler benchmark**	**Comparison of low carbon heating systems to gas boiler benchmark**				
				Biomass				
				Solid fuel boilers	**Log stoves**	**LPG; biomethane**	**Biodiesel**	**Hydrogen**
Scottish Government new build advanced	4 bed detached	1124	62% - 80%	0.4% - 1.2%	1.8% - 20.3%	0.2%	2.3%	<0.1%
	3 bed semi	780	79% - 89%	0.4% - 1.2%	1.7% - 19.8%	0.2%	2.2%	<0.1%
	2 bed flat	686	86% - 93%	0.4% - 1.1%	1.7% - 19.6%	0.2%	2.2%	<0.1%
Existing insulated	4 bed detached	3133	40% - 68%	0.4% - 1.2%	1.8% - 20.9%	0.2%	2.3%	<0.1%
	3 bed semi	2096	53% - 75%	0.4% - 1.2%	1.8% - 20.5%	0.2%	2.3%	<0.1%
	2 bed flat	1636	38% - 67%	0.4% - 1.2%	1.8% - 20.9%	0.2%	2.3%	<0.1%
Existing poorly insulated	4 bed detached	6144	26% - 60%	0.4% - 1.2%	1.8% - 21.3%	0.2%	2.4%	<0.1%
	3 bed semi	3839	34% - 65%	0.4% - 1.2%	1.8% - 21.0%	0.2%	2.4%	<0.1%
	2 bed flat	1979	33% - 64%	0.4% - 1.2%	1.8% - 21.1%	0.2%	2.4%	<0.1%

Table 9: Summary results for non-domestic archetypes (continues next page)

Archetype		Gas boiler benchmark emissions ($kgCO_2e/yr$)	Hybrid heat pump relative to gas boiler benchmark	Comparison of low carbon heating systems to gas boiler benchmark			
				Biomass			Hydrogen
				Solid fuel	LPG; biomethane	Biodiesel	
SG New Build Advanced	Hospital	469,479	11% - 52%	0.28% - 1.05%	0.16% - 0.21%	2.0%	<0.1%
	Care home	29,904	11% - 52%	0.73% - 1.05%	0.16% - 0.21%	2.0%	<0.1%
	Leisure centre	267,957	11% - 52%	0.29% - 1.07%	0.16% - 0.21%	2.0%	<0.1%
	Hotel	87,948	11% - 52%	0.29% - 1.06%	0.16% - 0.21%	2.0%	<0.1%
	Office	27,678	12% - 53%	0.29% - 1.08%	0.16% - 0.21%	2.0%	<0.1%
	School	15,175	12% - 53%	0.74% - 1.06%	0.16% - 0.21%	2.0%	<0.1%
	Community centre	3,736	12% - 53%	0.73% - 1.05%	0.16% - 0.21%	2.0%	<0.1%
	DIY store	45,179	11% - 52%	0.75% - 1.08%	0.16% - 0.21%	2.0%	<0.1%
	Light industrial unit	26,810	12% - 53%	0.3% - 1.09%	0.16% - 0.21%	2.0%	<0.1%
	Warehouse	4,518	11% - 52%		0.16% - 0.21%	2.0%	<0.1%
Existing well Insulated	Hospital	1,989,497	11% - 52%	0.28% - 0.28%	0.16% - 0.21%	2.0%	<0.1%
	Care home	135,581	11% - 52%	0.28% - 1.05%	0.16% - 0.21%	2.0%	<0.1%
	Leisure centre	814,959	11% - 52%	0.29% - 1.07%	0.16% - 0.21%	2.0%	<0.1%
	Hotel	78,051	11% - 52%	0.29% - 1.06%	0.16% - 0.21%	2.0%	<0.1%
	Office	321,548	12% - 53%	0.29% - 1.08%	0.16% - 0.21%	2.0%	<0.1%
	School	54,095	12% - 53%	0.29% - 1.06%	0.16% - 0.21%	2.0%	<0.1%
	Community centre	13,158	12% - 53%	0.73% - 1.05%	0.16% - 0.21%	2.0%	<0.1%
	DIY store	151,616	11% - 52%	0.29% - 1.08%	0.16% - 0.21%	2.0%	<0.1%
	Light industrial unit	27,776	12% - 53%	0.3% - 1.09%	0.16% - 0.21%	2.0%	<0.1%
	Warehouse	5,800	11% - 52%		0.16% - 0.21%	2.0%	<0.1%

Archetype		Gas boiler bench-mark emissions (kgCO$_2$e/yr)	Hybrid heat pump relative to gas boiler benchmark	Comparison of low carbon heating systems to gas boiler benchmark			
				Biomass			Hydrogen
				Solid fuel	LPG; biomethane	Biodiesel	
Existing poorly insulated	Hospital	2,810,559	11% - 52%	0.28% - 0.28%	0.16% - 0.21%	2.0%	<0.1%
	Care home	186,107	11% - 52%	0.28% - 1.05%	0.16% - 0.21%	2.0%	<0.1%
	Leisure centre	1,846,006	11% - 52%	0.29% - 0.29%	0.16% - 0.21%	2.0%	<0.1%
	Hotel	121,760	11% - 52%	0.29% - 1.06%	0.16% - 0.21%	2.0%	<0.1%
	Office	321,548	12% - 53%	0.29% - 1.08%	0.16% - 0.21%	2.0%	<0.1%
	School	78,509	12% - 53%	0.29% - 1.06%	0.16% - 0.21%	2.0%	<0.1%
	Community centre	19,684	12% - 53%	0.28% - 1.05%	0.16% - 0.21%	2.0%	<0.1%
	DIY store	195,371	11% - 52%	0.29% - 1.08%	0.16% - 0.21%	2.0%	<0.1%
	Light industrial unit	32,305	12% - 53%	0.3% - 1.09%	0.16% - 0.21%	2.0%	<0.1%
	Warehouse	8,904	11% - 52%		0.16% - 0.21%	2.0%	<0.1%

5.1 Biomass

The results for domestic and non-domestic biomass systems are similar when compared relative to the gas baseline.

Biomethane and 100% BioLPG have the lowest emissions at around 0.2% of the gas baseline or less.

Chip and pellet boilers have emissions of up to 1.2%, with biodiesel between 2.0 and 2.5%.

Log stove emissions appear to range from less than 2% to more than 20% of the gas baseline emissions. This partly represents the uncertainty in the results given the limited data but is also a reflection of the widely reported variability in performance of log stoves.

There is a level of uncertainty in all these results, but we have attempted to represent this through the range of figures presented. Further in situ measurement of CH_4 and N_2O emissions will be needed to determine actual GHG emissions of different systems and operating practices with certainty.

Nevertheless, all the biomass systems appear to provide significant GHG reductions compared to a gas boiler, with most systems offering a 98% reduction or more in direct emissions. This is assuming CO_2 emissions are effectively excluded by giving them a GWP of zero. If CO_2 emissions are included with a GWP of 1 then all biomass systems have higher GHG emissions than a gas boiler. However, this is not how biomass CO_2 emissions are reported under UK or international reporting guidelines.

5.2 Hydrogen combustion

For both domestic and non-domestic systems, GHG emissions from hydrogen systems are considerably lower than for natural gas and appear to be very low indeed (possibly less than 0.1%). Although hydrogen combustion would not appear to be 100% zero GHG emissions, the figures presented here suggest that emissions are much lower than most other low carbon heating technologies.

However, emissions data for hydrogen is limited, with no reported data on emissions of the GHG, N_2O. Figures presented in this report should, therefore, be interpreted with care, as these are estimates based on reported measurement of NO_x emissions only (which is not itself a GHG), and assumptions around the relationship between N_2O to NO_x emissions, as discussed in section 3.4.4. Specific research into N_2O emissions from hydrogen combustion would be beneficial to increase confidence in the conclusions.

6 Conclusions and recommendations

6.1 Technology assessment and direct emissions

6.1.1 Technologies with zero direct emissions

Several of the technologies reviewed under this research project were found to have no direct, in-building GHG emissions. These include:

- direct electric heaters;
- electric storage heaters;
- electric boilers;
- solar thermal and solar thermal storage;
- heat pumps[9];
- heat networks; and
- fuel cells.

6.1.2 Biomass

While biomass fuels are often considered zero or low carbon (as the biomass material itself has already absorbed CO_2, and biomass can be replaced in relatively short timescales), there are various in-building emissions associated with the combustion of biomass. This includes emissions of CO_2, CH_4 and N_2O. In accordance with UK and IPCC reporting guidelines, this report did not include direct emissions of CO_2 from biomass combustion in the assessment of direct in-building emissions.

If CO_2 emissions from biomass combustion are thus considered to be zero, biomass systems show significantly lower direct emissions than the gas baseline (which includes CO_2 emissions), with most technologies emitting less than 2% of the gas baseline. Emissions vary significantly between different technologies, with systems with more controlled fuel (e.g. pellet boilers) appearing to perform better.

Notably, quality of fuel is understood to impact emissions considerably, although there is limited data to quantify this in relation to GHGs.

6.1.3 Hydrogen

Combustion of hydrogen leads to emission of NO_x, including the GHG N_2O. Research on these emissions, however, is limited, with N_2O in particular poorly documented.

Results, largely based on expert views, suggest that direct emissions are not significant for hydrogen combustion, but more research is needed to enable confident conclusions.

6.1.4 Emissions and factors outside the project scope

This study focused on emissions within the curtilage of the building, to inform approaches to target setting for, and regulation of, zero emission heating in buildings. While building regulations may not be the context within which to address broader indirect emissions, it is nonetheless important to contextualise these findings in the wider context of the climate impact of different technologies. Policy and technology choices around heating technologies must be made with awareness of the full climate impact of

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[9] Notably, there is a risk of emissions caused by refrigerant leakage from heat pumps, as discussed in Appendix B, but this can be assumed to be negligible in case of correctly installed, pressure tested and correctly functioning systems. Moreover, refrigerant usage is regulated under F-Gas Regulations, and are outside the scope of building regulations.

technology choice when specifying a building heating system. It should be noted that many of these indirect emissions are subject to other forms of regulations. For example, GHG emissions from electricity generation and industrial processes are regulated through the UK Emissions Trading Scheme.

GHG emissions from the generation and supply of grid electricity are significant. While the grid carbon factor continues to fall, until the electricity grid is further decarbonised, the full climate impact of all the direct electric heating technologies will be higher than presented here, despite there being no direct in-building emissions.

Similarly, the global warming impact of hydrogen use will vary greatly depending on whether the hydrogen comes from methane reformation, methane reformation with carbon storage, electrolysis from off-peak renewable electricity generation or other sources. The impact of hydrogen production will far outweigh the impact of any in-building emissions.

Emissions associated with biomass vary across fuel supply chains and by the extent and timescale over which the CO_2 emitted in combustion is reabsorbed by new growth following harvesting. Assessment of these factors is beyond the scope of this report, but a view needs to be taken on their impact, in order to assess the validity of assuming a GWP of zero for CO_2 emissions from biomass combustion.

6.2 Recommendations

Key recommendations are summarised under three main themes: data, mitigating emissions from biomass combustion, and new heating systems requirements.

6.2.1 Data

A common theme across different technologies is a lack of data and research on direct emissions from both manufacturers and independent researchers; a key overarching recommendation, therefore, is to conduct further research and gather data on direct emissions across the different technologies:

- <u>Biomass combustion:</u> More detailed research is required into CH_4 and N_2O emissions variations between different biomass technologies, fuel types, fuel quality and operating practices to determine the scale and scope for improvement in in-building GHG emissions.
- <u>Hydrogen combustion:</u> Direct measurement of N_2O emissions from hydrogen combustion would provide more confidence in the assessment of direct emissions from hydrogen-based heating.
- <u>Heat pumps:</u> While refrigerant related emissions from heat pumps can be assumed to be negligible for correctly installed and functioning heat pumps, this is an area characterised by much uncertainty due to lack of data. Better data is needed on refrigerant leakage at different stages (installation, servicing, operation, decommissioning), for different refrigerants and for different types of heat pump systems. This may partly be achieved through better enforcement of existing F-gas Regulations, with stricter reporting requirements relevant to consider.

6.2.2 Mitigating emissions from biomass combustion

Improved education and awareness raising is an important factor in reducing emissions from biomass combustion. This includes education and awareness raising around types of fuel and fuel quality and how these impact on emissions. It also includes educating operators/users on what to burn and not to burn in biomass systems to reduce emissions. This is likely to complement existing efforts to improve operating practices to limit NO_x and particulate emissions. However, it will be important to ensure that approaches to reduce GHG emissions, and particularly N_2O, do not conflict with the guidance around minimising emissions of NO_x and particulate matter, given the pressing need to control air quality. This is subject to gaining improved understanding (as discussed above) of how emissions vary by technology, fuel and quality of fuel.

Moreover, tighter controls on fuel quality could be considered, subject to improved understanding of CH_4 and N_2O emissions and their variation across different biomass technologies and by quality of fuel, as mentioned above.

6.2.3 Requirements for new heating systems

There are plans to introduce requirements that new heating systems in Scotland should produce zero direct GHG emissions at the point of use. It will be crucial to develop a definition of the term “zero direct greenhouse gas emissions”, which makes it clear and explicit what is included as ‘direct’ emissions, and what is excluded from this definition, as well as the interpretation of what qualifies as ‘zero’ emissions.

Particularly in the case of heat pumps, it will be important to clarify the extent to which refrigerant related emissions are included or excluded from this definition. If a definition was developed to encompass emissions only during operation of a technology for space and water heating, this would exclude refrigerant related emissions during installation, servicing and decommissioning of heat pumps, which 1) is where the greatest risk of emissions occurs and 2) is regulated under existing F-Gas Regulations. Additionally, a zero direct emissions requirement could be reasonably defined to apply to technologies operating under normal operating conditions for a system which is properly maintained and serviced.

A restrictively narrow definition of “zero direct emissions” could lead to a dramatic increase in the installation of direct electric heating, and a significant setback to any plans to roll out heat pumps at scale. This would significantly delay progress in decarbonising heat from buildings. It would also increase electricity consumption over and above existing plans to electrify heat, adding additional strain to the electricity grid and potentially delaying wider decarbonisation of the grid. This would go against the objective of the potential regulation of in-building emissions, and so careful consideration of definitions and interpretations will be critical to achieving the intended and desired outcomes.

A balanced approach could take the form of setting a maximum level of in-building emissions, for example as a percentage of the equivalent gas baseline and requiring new heating systems to meet this limit. This would require new emissions testing for several of the technologies covered in this report. While the onus to conduct testing could be placed on manufacturers wishing to sell heating products into this market, there would likely be a need for some independent testing to be carried out prior to limits being set.

There may be an argument for setting higher limits for in-building emissions initially and reducing them over time, to allow the heat pump market, in particular, to move gradually towards the use of lower GWP refrigerants in heat pumps.

References

BEIS. (2020a). Heat pump manufacturing supply chain research project - Final report. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/943712/heat-pump-manufacturing-supply-chain-research-project-report.pdf

BEIS. (2020b). HEAT PUMP MANUFACTURING SUPPLY CHAIN RESEARCH PROJECT FINAL REPORT. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/943712/heat-pump-manufacturing-supply-chain-research-project-report.pdf

BEIS. (2021, June). Greenhouse gas reporting: conversion factors 2021. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021

Bhattu, D., Zotter, P., Zhou, J., Stefenelli, G., Klein, F., Bertrand, A., Temime-Roussel, B., Marchand, N., Slowik, J. G., Baltensperger, U., Prévôt, A. S. H., Nussbaumer, T., el Haddad, I., & Dommen, J. (2019). Effect of Stove Technology and Combustion Conditions on Gas and Particulate Emissions from Residential Biomass Combustion. Environmental Science & Technology, 53(4). https://doi.org/10.1021/acs.est.8b05020

BREEAM. (2018). Pol 01 Impact of refrigerants. https://www.breeam.com/BREEAM2011SchemeDocument/content/12_pollution/pol01.htm

BSRIA. (2020, January). BSRIA’s view on refrigerant trends in AC and Heat Pump segments. News. https://www.bsria.com/uk/news/article/bsrias_view_on_refrigerant_trends_in_ac_and_heat_pump_segments/

BSRIA. (2021). Provisional Heat Pump Group Results 2021 Q2.

CIBSE. (2008). Technical Manual TM46: Energy benchmarks. CIBSE TM46. https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q20000008I7evAAC

CIBSE. (2012). Energy efficiency in buildings Energy efficiency in buildings. In Energy World (Issue 9). https://www.scopus.com/inward/record.uri?eid=2-s2.0-0024096986&partnerID=40&md5=f272c50cfb2e58e36e8eed986e0562ae

Climate Change Committee. (2020). The Sixth Carbon Budget F-gases. https://www.theccc.org.uk/publication/sixth-carbon-budget/

Climate Change (Scotland) Act, (2009). https://www.legislation.gov.uk/asp/2009/12/contents

Commission Regulation (EU) No 206/2012, Pub. L. No. 206/2012, Official Journal of the European Union (2012). https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:072:0007:0027:EN:PDF

Cooling Post. (2021, February 17). DEFRA begins UK F-gas review. Cooling Post. https://www.coolingpost.com/uk-news/defra-begins-uk-f-gas-review/

DECC. (2014). Impacts of Leakage from Refrigerants in Heat Pumps. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/303689/Eunomia_-_DECC_Refrigerants_in_Heat_Pumps_Final_Report.pdf

EFCTC. (2020). Ending the illegal trade in HFCs by enforcing the F-Gas Regulation: What can Member States do? https://www.fluorocarbons.org/wp-content/uploads/2020/08/EFCTC_Factsheet_2_EN.pdf

Element Energy. (2017). Hybrid Heat Pumps - Final report for Department for Business, Energy & Industrial Strategy. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700572/Hybrid_heat_pumps_Final_report-.pdf

Energy Saving Trust. (2019). Solar water heating systems-guidance for professionals, conventional indirect models CE131 Solar water heating systems-guidance for professionals, conventional indirect models Contents. https://mcscertified.com/wp-content/uploads/2019/08/Solar_water_heating_systems_CE131.pdf

Energy Saving Trust. (2020). Renewable Heat in Scotland, 2019. https://energysavingtrust.org.uk/wp-content/uploads/2020/10/Renewable-Heat-in-Scotland-2019_new.pdf

Environment Agency and DEFRA. (2021). Bans on F gas in new products and equipment: current and future . https://www.gov.uk/guidance/bans-on-f-gas-in-new-products-and-equipment-current-and-future#refrigerants-f-gases-banned-in-new-products

Environmental Investigation Agency. (2021). Europe’s Most Chilling Crime: The illegal trade in HFC refrigerant gases. https://eia-international.org/wp-content/uploads/EIA-Report-Europes-most-chilling-crime-Spreads.pdf

Regulation (EU) No 517/2014, Pub. L. No. 517/2014 (2014). https://www.eea.europa.eu/policy-documents/regulation-eu-no-517-2014

European FluoroCarbons Technical Committee. (2020). Heat Pumps. https://www.fluorocarbons.org/applications/heat-pumps/

Greater London Authority. (2018). Low Carbon Heat: Heat Pumps in London. https://www.london.gov.uk/sites/default/files/low_carbon_heat_-_heat_pumps_in_london_.pdf

Holland, R., Khan, M. A. H., Driscoll, I., Chhantyal-Pun, R., Derwent, R. G., Taatjes, C. A., Orr-Ewing, A. J., Percival, C. J., & Shallcross, D. E. (2021). Investigation of the Production of Trifluoroacetic Acid from Two Halocarbons, HFC-134a and HFO-1234yf and Its Fates Using a Global Three-Dimensional Chemical Transport Model. ACS Earth and Space Chemistry, 5(4), 849–857. https://doi.org/10.1021/ACSEARTHSPACECHEM.0C00355

IPCC. (2021). IPCC 6th Assessment Report; AR6 WGI Report - Chapter 7: The Earth’s energy budget, climate feedbacks, and climate sensitivity - Supplementary Material: ist of corrigenda to be implemented. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_07_Supplementary_Material.pdf

Kauffeld, M. (2016). Current long-term alternative refrigerants and their possible applications. https://seors.unfccc.int/applications/seors/attachments/get_attachment?code=743SF600720U6UXDQPNJXNFGNQXRGEIQ

Kiwa. (2018). Measurement of the in-situ performance of solid biomass boilers Summary of findings Preface. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/830905/Summary_of_findings.pdf

Lawton, A. R., & Rhodes, C. (2018). Comparison between HFCs and HFO/HFC blends in a commercial heat pump. IIR International Conference on the Application of HFO Refrigerants, Part F147651, 347–354. https://doi.org/10.18462/IIR.HFO.2018.1156

NetRegs. (n.d.). Stationary refrigeration, air conditioning and heat pumps: F-gas controls. Retrieved October 14, 2021, from https://www.netregs.org.uk/environmental-topics/air-pollution/fluorinated-gases-f-gases/stationary-refrigeration-air-conditioning-and-heat-pumps-f-gas-controls/

REAL Zero Europe. (2015). Leakage matters: The equipment owner's responsibilities. https://ior.org.uk/document-download-page?p_id=487 [access requires free registration]

Scottish Government. (2020). Low carbon heating in domestic buildings - technical feasibility: report - https://www.gov.scot/publications/technical-feasibility-low-carbon-heating-domestic-buildings-report-scottish-governments-directorate-energy-climate-change/

Scottish Government. (2021a). Heat in buildings strategy - achieving net zero emissions: consultation. https://consult.gov.scot/energy-and-climate-change-directorate/heat-in-buildings-strategy/

Scottish Government. (2021b). New Build Heat Standard: scoping consultation. https://consult.gov.scot/energy-and-climate-change-directorate/new-build-heat-standard/

Scottish Government. (2021c). Scottish Building Regulations: Proposed changes to Energy Standards and associated topics, including Ventilation, Overheating and Electric Vehicle Charging Infrastructure. https://consult.gov.scot/local-government-and-communities/building-regulations-energy-standards-review/

Scottish Government. (2021d). Building regulations - new domestic buildings - modelling of proposed energy improvements: research report. https://www.gov.scot/publications/research-report-modelling-proposed-energy-improvements-new-domestic-buildings/

Slovak Association for Cooling and AC Technology. (2019). Evaluation of Refrigerants Leakage Ratios based on Electronic Logging and Reporting System. https://www.ozonactionmeetings.org/system/files/210210_slo_refrigerant_leakage_rations_based_on_electronic_logbooks_peter_tomlein.pdf

The Ozone-Depleting Substances and Fluorinated Greenhouse Gases (Amendment etc.) (EU Exit) Regulations 2019, Pub. L. No. 583 (2019). https://www.legislation.gov.uk/uksi/2019/583/contents/made

Tsupari, E., Monni, S., & Pipatti, R. (2005). Non-CO_2 greenhouse gas emissions from boilers and industrial processes Evaluation and update of emission factors for the Finnish national greenhouse gas inventory. VTT TIEDOTTEITA ñ RESEARCH NOTES 2321. https://www.vttresearch.com/sites/default/files/pdf/tiedotteet/2005/T2321.pdf

Appendix A: Research approach

The research team – made up of key individuals within ACE Research and Energy Saving Trust - delivered a mix of desk-based research and stakeholder interviews through a four-stage methodology.

The evidence collected was analysed and synthesised to produce this report. This evidence base will support heat decarbonisation policy objectives by:

- Identifying and quantifying in-building GHG emissions from a range of low, zero and renewable heating technologies.
- Identifying building and heating system related parameters to support evaluation of in-building GHG emissions across the Scottish building stock.
- Identifying opportunities and pathways for reducing in-building GHG emissions from heating systems.

Stage 1: Identification of technologies in scope

Following on from an inception meeting with ClimateXChange and key members of Scottish Government, the team set about identifying the full range of technologies used in both domestic and non-domestic settings within the scope of this project. This included assessing the documented GHG emission factors and each technology's market technology readiness levels (TRL) including an understanding and analysis of market penetration across different sectors.

The team undertook two research activities in parallel:

- A comprehensive literature review of both white (academic) and grey (industry) literature through academic databases and targeted Google searches (the latter focussing on organisations known to be active in the sector).
- The team engaged with key organisations to gather evidence and used a semi-structured topic guide.

This parallel activity supported the identification of additional literature and stakeholders in a snow-ball approach to desk-based research.

The team also built on experience from our current work with the Scottish Renewable Heat Database and the Home Renewable Advice (HRA) service, drawing on insights from evidence used to develop these tools.

The team also developed a benchmark for comparison, focussing on natural gas combination boilers and hybrid heating systems.

Stage 2: Developing an assessment methodology

Our approach to the assessment methodologies was informed by the evidence identified through the research in stage 1.

For each technology, the research team identified the key factors that influence GHG emissions. Therefore, each technology required its own methodology to incorporate the relevant factors, which included:

- Emissions that were proportional to the amount of heat produced, subject to parameters such as operating conditions and fuel conditions (e.g. wood fuel moisture content).
- Emissions that were proportional to the installed capacity of the heating system.
- Emissions that were dependent primarily on other parameters, such as number of heating programme cycles and planned maintenance schedule for example.

Based on evidence from the research, the team then developed formulae wherever possible to calculate typical emissions for each GHG from each technology from the relevant parameters. This enabled emissions to be projected for any given situation and, by using parameters from the building archetypes (see below), for specific sectors of the building stock.

The archetypes considered were chosen in view of the influencing factors identified in Stage 1, in order to cover the full range of potential GHG emission profiles. The team engaged directly with the team at Scottish Government to understand existing data and parameters on archetypes.

- For domestic buildings we reused several characteristics from our work for the Technical Feasibility of Low Carbon Heating report (Scottish Government, 2020), such as property age, type and floor area, together with a combined “level of insulation” score.
- Non-domestic buildings archetypes are characterised by business sector, heat distribution system, and occupancy patterns, as well as property age and floor area.

Stage 3: Assessment of emissions

The formulae developed in stage 2 was then used to calculate emissions for each of the archetypes developed, for each relevant technology, based on standardised assumptions. For domestic properties, the assumptions for heating demand included Standard Assessment Procedure (SAP) default heating schedules and heat loss calculation methodologies. For non-domestic properties, heating requirements were based either on published industry benchmarks or analysis of Energy Performance Certificate (EPC) data.

Stage 4: Monitoring and mitigation recommendations

In this final stage of the research, the team developed recommendations on how:

- Emissions could be monitored over the lifetime of the system.
- The potential solutions to mitigate such emissions (or even their elimination).

This stage involved both literature reviews and additional stakeholder interviews.

Appendix B: Heat pumps – considerations around refrigerant leakage

Switching from gas boilers to heat pumps presents significant carbon emission savings potential (dependent on decarbonisation of electricity as well as heat pump efficiencies). While it is important to be aware of the risk of emissions from heat pumps due to refrigerant leakage, and increasing attention is directed at the global warming potential of refrigerants used in heat pumps, it is widely acknowledged that the GHG benefits of switching from fossil fuel heating to heat pumps far outweigh the potential emissions due to refrigerant leakage (Climate Change Committee, 2020).

This appendix discusses key considerations around refrigerant related emissions from heat pumps, including a review of commonly used refrigerants, potential climate impact and monitoring and mitigation measures.

The climate impact of refrigerant leakage varies by type of heat pump system (split systems vs monobloc systems and ground source heat pumps, where the refrigerant circuit is located within a hermetically sealed unit) and by refrigerant used (the GWP of refrigerants used in the heat pump industry range from 0 to 2088). Thus, the risk of in-building emissions from heat pumps and the climate impact thereof will vary greatly both by choice of refrigerant and by type of heat pump, as explored below.

According to expert interviews, the risk of leakage can be assumed to be negligible for heat pumps when correctly installed, pressure tested and correctly functioning. The greatest risk of leakage is likely during installation and decommissioning of split systems.

Our modelling (see Appendix C) finds that refrigerant related emissions from heat pumps, on average, correspond to between 0% and 9% of emissions from a baseline gas boiler scenario.

Regulation is driving a shift towards lower GWP refrigerants, with natural refrigerants gaining attention as ultra-low GWP alternatives. The trend towards increasing use of monobloc systems can also be expected to be beneficial in terms of direct emissions reduction, as monobloc systems are expected to have lower leakage rates than split systems, and the reclaiming of refrigerants likely easier to control, as this is likely to occur at a worksite under a potentially more controlled environment.

There are both pros and cons associated with different types of refrigerants, and while one refrigerant may appear preferable from the perspective of reducing in-building GHGs, this may come with costs in terms of heat pump performance, safety considerations and/or other environmental impacts. It is crucial that measures to reduce the climate impacts of refrigerant leakage in heat pumps are balanced against the requirement for rapid upscaling of heat pump deployment, as the introduction of new refrigerants is associated with significant time and resource requirements for R&D and could lead to higher costs of heat pumps.

Refrigerants used in heat pumps

Refrigerants are used as working fluid in heat pumps, to transfer heat from the heat source to the heat sink. Since the phase out of ozone-depleting chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), following adoption of the Montreal Protocol in 1987, hydrofluorocarbons (HFCs) have become widely used as refrigerants. While HFCs do not cause ozone depletion, these refrigerants are now regulated due to their frequently high GWP.

In the move away from high GWP refrigerants, HFC substitutes include HFOs, HFC/HFO blends and ‘natural’ refrigerants. It is important to note, however, that heat pump systems are designed to work with a particular refrigerant as working fluid and cannot be assumed to work with alternative fluids. Thus, introduction of new/alternative refrigerants occurs through the development and placement on the market of new heat pump systems specifically designed to work with an alternative refrigerant.

Table 10 shows commonly used HFCs in the heat pump industry. According to the Building Services Research and Information Association (BSRIA) (BSRIA, 2020), R410A and R134A are the most common refrigerants, with the use of lower GWP R32[10] and R290 (propane) expected to increase by 2023, in a move away from R410A.

Table 10: Commonly used refrigerants in heat pumps in the UK

Refrigerant	GWP	Comments
R410A	2088	According to BSRIA, over 80% of heat pumps sold in the UK in 2019 contained R410A refrigerant.
R407C	1774	
R134A	1300	BSRIA find R134A to be the second most common refrigerant in heat pumps in the UK.
R32	675	The IPCC (2021) recently adjusted the GWP of R32 up to 771.
Propane (R290)	3	The IPCC (2021) recently adjusted the GWP of propane down to 0.072. Mildly flammable; use is regulated under safety regulations.
CO_2 (R744)	1	Requires high pressure.
Ammonia	0	Suitable for large scale installations, subject to sufficient ventilation, monitoring and maintenance.

As the F-gas quota system (detailed below) drives up the cost of high GWP refrigerants, blends of HFCs with hydrofluoro-olefins (HFOs) are also becoming increasingly common (Lawton & Rhodes, 2018). Importantly, while HFOs have a lower GWP than HFCs, HFOs are associated with other negative environmental impacts; according to recent research, widespread use of HFOs leads to significant increase in trifluoroacetate (TFA), one of the products of HFO decomposition, with negative health and environmental implications (Holland et al., 2021). Thus, it may not be desirable to encourage the heat pump industry to switch to HFO refrigerants at scale. A range of natural refrigerants (including propane, CO_2 and ammonia) are gaining attention as ultra-low GWP alternatives.

Choice of refrigerant is based on considerations around energy efficiency, reliability and technical performance, as well as safety, which is why non-flammable HFCs such as R410A and R134a continue to be widely used in heat pumps.

According to the CCC, as well as stakeholders interviewed for this research project, hydrocarbon refrigerants such as propane are a good low-GWP option, particularly for smaller systems, but high flammability limits the proportion of the market that can safely use hydrocarbon refrigerants. The CCC suggest that hydrocarbons may be suitable for up to 50% of the residential heat pump market (Climate Change Committee, 2020). Expert interviews suggest that there may be scope for reviewing safety regulations, as use of greater volumes of propane may be safe depending on ventilation and other precautions, and the benefits of the use of propane may justify relaxation of current restrictions.

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[10] Notably, a recent upward adjustment, by the IPCC (2021), of the GWP of R32 (from 675 to 771) could have implications for the future relevance of R32 as a lower-GWP alternative, as the new value brings this refrigerant above the threshold for a ban, taking effect in 2025, on the use of refrigerants with GWP above 750 in split systems with less than 3kg of refrigerant (Environment Agency and DEFRA, 2021). It is not yet clear whether these new values will be recognised within F-gas Regulations in the UK.

Refrigerant leakage: data

There may be a risk of refrigerant leakage from heat pumps during operation, at the point of decommissioning and as a result of catastrophic events (e.g. puncturing of a pipe).

However, comprehensive and reliable data on refrigerant leakage is lacking in the UK heat pump sector as well as the wider European heat pump sector. In the UK, the best available sources of leakage are a report from DECC (2014) and the default leakage rates stated in the Pol 01 Credit from BREEAM (2018).

The impacts of leakage report by DECC (2014) presents analysis of annual leakage rates from F-gas logbooks, however this included logbooks from just six organisations, and logbooks were found to be of poor quality leading to significant uncertainty in the conclusions. The findings from this report suggested average annual leakage rates of approximately 3.8% in non-domestic applications and 3.5% for domestic applications. However, these averages appear to be the result of few instances of leaks resulting in high proportions of refrigerant loss, with 9% of non-domestic installations and 10% of domestic installations found to have leaked each year, with a median loss of 42% of total refrigerant charge where leaks occurred in non-domestic installations, and 35% for domestic installations. In case of catastrophic leakage, refrigerant loss was of the magnitude of 75% for non-domestic and 92% for domestic installations. This suggests opportunities for improvement both in heat pump design and handling, to minimise the risk of leakage due to poor installation and catastrophic events.

Based on leakage rates reported in previous studies on air conditioning units, BREEAM (2018) estimate the risk of catastrophic leakage of refrigerant from heat pumps at 1% per year, while giving an estimate of 6% annual leakage overall.

Most recently, the European Heat Pump Association (EHPA) is in the process of collecting information from national heat pump associations across Europe, to understand how much oversight they have of leakage rates in their national heat pump sectors, and how leakage is dealt with in terms of monitoring, training and improvements. This survey is not yet concluded, with several countries (including the UK) yet to submit a response.

Table 12 on the next page presents a summary of available leakage data. Additionally, the International Institute for Refrigeration (IIR) published a report in 2016, citing figures from 2002 (Table 11) (Lawton & Rhodes, 2018).

Table 11: Leakage rates from IRR (2016), figures based on 2002 study of air conditioning units

	Annual leakage rate (%)[11]	**End of life leakage (%)**	**Lifetime (years)**
Residential packaged units	2.5	15	15
Residential split units	4	15	15
Commercial packaged units	5	15	10
Commercial split units	5	15	10

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[11] "Average unit lifetimes, unit annual refrigerant leakage rates and end-of-life leakage rates are taken from AR4, AR5 reports and United Nations Environment Programme (UNEP) Technical Options Committee 2002 report, given as averages for developed countries."

Table 12: Leakage preliminary data summary (dash (-) indicates no available data)

Application/ Refrigerant	**UK**						**Italy**[12]			**Slovakia**[13]
	DECC[14]	**BREEAM**[15]								
	Annual leakage rate	Annual leakage rate	Annual purge release (zero if no purge required)	Annual service release (only for systems requiring opening up for servicing)	Probability of catastrophic failure (%/yr)	Refrigerant loss at system retirement	Average loss from heat pumps (%)			Average weighted leakage (%) to 2018
							2013	2014	[Calculated Average]	
Heat pumps (general)	-	6%	0.5%	0.25%	1%	5%	3.3%	0.87%	2.09%	-
Domestic	3.5%	-	-	-	-	-	1.4%	2%	1.70%	-
Non-domestic	3.8%	-	-	-	-	-	-	-	-	-
Commercial	-	-	-	-	-	-	5.2%	2%	3.60%	-
Industrial	-	-	-	-	-	-	4.9%	6%	5.45%	-
R134a	-	-	-	-	-	-	-	-	-	3.1%
R410A	-	-	-	-	-	-	-	-	-	4.7%

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[12] Gagna, A.; Gonella, B.; Scaramella, A. (ISPRA), 2018. Dichiarazione F-gas: analisi dei dati.
[13] Slovak Association for Cooling and AC Technology (2019). Evaluation of Refrigerants Leakage Ratios based on Electronic Logging and Reporting System.
[14] DECC 2014. Impacts of Leakage from Refrigerants in Heat Pumps.
[15] BREEAM UK New Construction, Non-domestic buildings (Scotland), Technical Manual. https://www.breeam.com/discover/technical-standards/newconstruction/

Leakage rates: differences between monobloc and split systems

Risk of refrigerant leakage depends, in part, on the type of system used, with differences between ‘split systems’ and ‘monobloc systems’.

Refrigerant is used as heat transfer fluid in heat pumps, where a compressor circulates the refrigerant through a refrigerant circuit, transferring heat from a heat source via a heat exchanger to the heating system (radiators/underfloor heating).

Split system - The refrigerant circuit sits between an external compressor on the outside of the building and a separate internal unit housing the other components of the heat pump. There are thus several joints where leakage could occur.

Monobloc heat pump - All the components of the heat pump are in a single hermetically sealed unit.

Ground Source Heat Pumps (GSHPs) are always a monobloc-style system (although they are not typically referred to in these terms). Air Source Heat Pumps (ASHPs) can be either monobloc or split, with monobloc ASHP units situated outdoors.

Monobloc systems have the advantage that the refrigerant circuit sits within a single hermetically sealed unit, meaning no/lower risk of operational refrigerant leakage, as opposed to the split system, where several joints formed on site create a potential for leakage of refrigerant. Moreover, monobloc systems come with the refrigerant pre-charged, with no filling of refrigerants on-site at the point of installation. Similarly, according to expert interviews, monobloc systems are likely to be transported off-site before being de-gassed (refrigerant reclaimed from the sealed unit), meaning less likelihood of refrigerant leakage at the point of decommissioning, and reclaiming of refrigerant occurring in potentially more controlled environment.

The relative simplicity of the installation of monobloc heat pumps means that engineers do not have to be F-gas certified to install monobloc systems. In many ways, this simplicity is beneficial, and availability of qualified engineers is less of an issue than for split systems requiring F-gas certified engineers to carry out installation work[16]. F-gas certification is required for servicing and decommissioning of heat pumps, regardless of type.

Monobloc systems are becoming increasingly popular in the UK market (69% market share (BEIS, 2020a)), with the added benefit that they require less space inside a building.

The benefits of split systems include greater flexibility in terms of location of the external unit for out of sight and hearing location, and greater applicability in cold climates, as the fluid passing through outdoor pipes is a refrigerant, which does not freeze. In contrast, monobloc systems have water passing through outdoor pipes to the outdoor unit, requiring use of antifreeze (typically glycol), which adds to costs and may impact efficiency.

Leakage rates: variations by refrigerant

The refrigerant used as working fluid in a system also impacts on leakage rates, primarily due to different pressures required for different refrigerants, with higher pressures most likely leading to higher leakage rates.

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[16] Stakeholder feedback.

Most available data on leakage rates does not differentiate by refrigerant, with the exception of a report from the national heat pump association in Slovakia, as set out in Table 12.

Heat pump efficiency

Heat pump efficiency - frequently referred to in terms of Seasonal Performance Factors (SPFs[17]) - impacts on the sizing of a system for a given building (with further implications for amount of refrigerant required by the system). Thus, higher efficiencies may require a smaller system with a smaller charge and as a result lead to lower potential emissions from refrigerant leakage.

Different refrigerants can achieve different levels of heat pump performance, i.e. there may be a trade-off, in terms of performance, in choosing a lower GWP refrigerant (although this is not necessarily the case; R-32, for example, has a higher efficiency than R-410A, and a lower GWP, and some natural refrigerants achieve higher efficiencies than HFCs (Kauffeld, 2016)). The difference in efficiency achievable with different refrigerants is typically in the range of +/-5% (European FluoroCarbons Technical Committee, 2020).

Market penetration

In 2017, heat pumps made up less than 1% of new heating systems in the UK (Greater London Authority, 2018). The majority of heat pump installations in the UK are in domestic properties (89% in 2019), dominated by low temperature air-to-water monobloc systems (69% in 2019) (BEIS, 2020).

Air source heat pumps dominate, in particular, the retrofit market. Ground source heat pumps fare better in new builds than in the retrofit market. In 2019, split systems accounted for 12% of sales of heat pumps in the UK (BEIS, 2020).

According to data from BSRIA (2021) air-to-water systems account for over 95% of UK heat pump market share, based on sales figures between 2019 and 2021, with ground/water source heat pumps making up less than 5% of sales. Air-to-water source heat pumps are relatively evenly distributed over small and medium-to-large (10-15kW) domestic applications, while large domestic (>10kW) and large commercial (>50kw) applications account for the majority of ground source heat pump sales.

Averaged over 2019-2021, air-to-water heat pumps made up 96.8% of domestic heat pump sales and ground or water source heat pumps 3.2%, whereas the opposite was the case for commercial applications, where ground/water source heat pumps accounted for 61.3% of heat pump sales and ASHP 38.7%.

Monitoring and mitigation

There are two aspects to mitigating the risk of refrigerant related GHG emissions from heat pumps: 1) using low to zero GWP refrigerants and 2) take action to eliminate leakage.

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[17] Seasonal performance factor (SPF) is the average coefficient of performance (CoP) of a heat pump over the heating season. CoP is the ratio of heat output (kW) to electrical input (kW) at any one time.

In the UK and the European Union (EU), refrigerant usage is regulated under F-gas Regulations (FGR)[18]. Following the UK's departure from the EU, the EU FGR (Regulation (EU) No 517/2014, 2014) has been retained and amended for operability in the UK; the new GB F-Gas Regulations (The Ozone-Depleting Substances and Fluorinated Greenhouse Gases (Amendment Etc.) (EU Exit) Regulations 2019, 2019) came into effect on 1st Jan. 2021 across Great Britain.

Low/zero GWP refrigerants

The FGR include a ban on specific refrigerants for specific purposes, as well as F-gas phase down. F-gas phase down under the FGR is a quota system, aiming to gradually increase the cost of high GWP F-gases, by reducing the amount (measured in CO_2eq) of F-gases that producers and importers can place on the market. The UK has a target to phase down F-gases, including mixtures, by 79% by 2030, from 2015 levels.

In 2020, a service ban came into force on the use of refrigerants with a GWP above 2,500 for refill/servicing of equipment with charge above 40 tonnes CO_2 equivalent. Recycled/reclaimed gases can be used for servicing/maintenance until 2030.

From 2025, all F-gases with a GWP>750 will be banned in single split systems containing less than 3kg of refrigerant (no limit for split systems above 3kg charge) (Environment Agency and DEFRA, 2021). NOTE: if the updated values from the recently published IPCC report are 'upheld' under F-Gas regulation, this would mean R32 would now be subject to this ban, whereas the previous GWP value for R32 was below 750. This is important, as R32 has been considered an important low-GWP alternative

In addition to the formal requirements around F-gases under the FGR, provisions under the EU Eco-design Directive seek to steer the market towards the use of lower GWP refrigerants (Commission Regulation (EU) No 206/2012, 2012). This involves a bonus applied to air conditioning appliances using low-GWP refrigerants, leading to lower minimum energy efficiency requirements for such appliances. Air-conditioning appliances up to 12 kW receive a 10% bonus on their performance data if they use refrigerants with a GWP of less than 150, leading to lower minimum energy efficiency requirements for appliances using low-GWP refrigerants.

Preventing leakage

FGR also includes requirements around leak checks and leak detection (depending on the charge size and refrigerant's GWP, certification of persons carrying out leak checks and servicing, and record keeping (see NetRegs for further detail)). This includes ensuring:

- Leak testing of the system (the frequency of which depends on the charge size and refrigerant's GWP (see below)). Persons carrying out leak checks and servicing of heat pumps must possess an F-Gas certificate.
- Repair of leaks without undue delay, with re-check within 1 month.
- Permanent leak detection fitted to large systems (charge > 500 tonnes CO_2e).
- Maintaining records of leak testing and refrigerant usage.

Other considerations in relation to leakage prevention include:

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[18] Both the European Commission and the UK Government are currently reviewing the respective F-gas Regulations; the impact of these reviews is not yet known, with the UK Government expected to publish the results of their review by December 2022.

- **Heat pump type**: increasing use of packaged systems/monobloc systems, which are hermetically sealed, is a positive development in terms of emissions from heat pumps due to reduced leakage rates from such systems; monobloc systems are commonly used in domestic settings, and increasingly also in commercial (small and large) applications.
- **Manufacturing:** potential to improve mechanical joints to make more leak tight[19].
- **Role of installers:** installers play an important role in ensuring correct installation, and thereby minimising risk of leakage and in ensuring correct handling of refrigerants when (re)filling and reclaiming refrigerants. As such, training of heat pump installers is an important consideration; F-gas Regulations mandate that engineers working with split systems are F-gas certified. Due to the simpler installation process for monobloc systems, no F-gas certification is required for the installation of these systems.

Implementation and effectiveness

Overall, the EU FGR is found to have successfully driven (and continues to drive) a shift from very high GWP gases to lower-GWP options such as R32, which is expected to be the dominant HFC refrigerant in 2040; progress towards even lower-GWP alternatives is slower, however (Climate Change Committee, 2020).

One of the challenges facing the FGR is a lack of enforcement and problems with illegal trade. In response, the European Fluorocarbons Technical Committee (EFCTC) (2020) have published guidance for EU Member States on addressing illegal F-gas trade and have started an initiative ‘Stop Illegal Cooling’, to encourage improved enforcement of FGR across Europe[20].

The European Heat Pump Association (EHPA) is currently conducting a survey of national associations of their levels of oversight with refrigerant use and leakage in the heat pump industry in their respective countries. Based on unpublished interim findings, very few national associations have such overview, with the exception of Slovakia, where leakage data is collected under an industry led initiative, and Italy (and to an extent Norway). Eight out of seventeen countries, who have responded to the survey to date, undertake activities related to leakage reduction, ranging from reporting requirements to training provision.

Activities to control collection, reclaim, reuse and recycling of refrigerants in heat pumps varies greatly across Europe, including initiatives led by individual companies, schemes coordinated by the industry or heat pump associations and government led programmes. Interim findings suggest that very few national authorities have activities in place for effective implementation and enforcement of F-gas Regulations. Training on handling of refrigerants is found to exist almost everywhere, but it is not clear how well leakage prevention and reclaim, reuse and recycling of refrigerants are covered.

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[19] Stakeholder feedback.

[20] EFCTC. Stop Illegal Cooling. https://stopillegalcooling.eu

Appendix C: Heat pumps – modelling of refrigerant related emissions

As outlined in Appendix B, there is a risk of emissions caused by refrigerant leakage from heat pumps. While this can be assumed to be negligible for correctly installed, pressure tested and correctly functioning systems, we conducted an assessment of the potential implications hereof, presented below for illustrative purposes.

For non-domestic applications, heat pump leakage emissions are likely to correspond to between 0% and 6% of the baseline scenario (gas boiler) emissions (Tables 13-14). For domestic applications, this is likely to be in the range of 0% and 9% of the baseline (gas boiler) emissions (Tables 15-16).

These figures are based on estimates and assumptions and should be interpreted with care. Note: for systems using ammonia (GWP=0) as a refrigerant, emissions are always zero CO_2e.

We expect that these results present a relatively pessimistic view. The key assumptions underpinning these findings include:

- 10% 'oversizing' of heat pump system (to allow for unlikelihood of exact capacity match).
- 6% leakage rate: this average does not differentiate based on split/monobloc/ground source, and masks large deviations, from negligible leakage from correctly installed and functioning heat pumps to catastrophic leakage due to accidental damage leading to rapid loss of full refrigerant charge. As such, for a majority of cases, we would expect to be well below the top end of the estimated range of emissions as percent of baseline scenario).

Results

Results presented here are based on estimates and assumptions, and should be interpreted with care.

Risk of emissions due to refrigerant leakage varies substantially from case to case, due in particular to the large differences in GWP between heat pumps using different refrigerants. For illustrative purposes, potential refrigerant related emissions from heat pumps are estimated for three different refrigerants for each of the defined archetypes (detailed tables 13-16):

- High GWP example (R410a): between 0.6 % and 8.1% of gas boiler baseline
- Lower GWP example (R32): between 0.2% and 2.6% of gas boiler baseline
- Ultra-low GWP example (R290; Propane): <0.01% of gas boiler baseline

Note: for systems using ammonia (GWP=0) as refrigerant, emissions are always zero CO_2e.

Domestic archetypes

Table 13: Refrigerant related emissions from heat pumps for refrigerant R290, in domestic archetypes with comparison to gas boiler benchmark, assuming a **6%** annual refrigerant leakage rate

					R290 (propane)				**R290, new IPCC GWP**	
Archetype		***Benchmark gas boiler emissions (kgCO_2e /year)***	***Req. capacity (kW) heat pump***	***Heat pump sizing 'extra allowance'***	**Estimated refrigerant charge (kg**	**Refrigerant leakage (kg/yr) (assuming 6%)**	**Direct emissions (kgCO_2e /year)**	**% of baseline**	**Direct emissions (kgCO_2e /year)**	**% of baseline**
SG New Build Advanced	4 bed detached	*1248*	***3***	*3.3*	0.40	0.024	0.071	**0.006**	0.000	**0.00004**
	3 bed semi	*866*	***3***	*3.3*	0.40	0.024	0.071	**0.008**	0.000	**0.00005**
	2 bed flat	*761*	***3***	*3.3*	0.40	0.024	0.071	**0.009**	0.000	**0.00006**
Current well insulated	4 bed detached	*3487*	***6***	*6.6*	0.79	0.048	0.143	**0.004**	0.001	**0.00003**
	3 bed semi	*2331*	***5***	*5.5*	0.66	0.040	0.119	**0.005**	0.001	**0.00003**
	2 bed flat	*1821*	***4***	*4.4*	0.53	0.032	0.095	**0.005**	0.001	**0.00003**
Current average insulated	4 bed detached	*6845*	***13***	*14.3*	1.72	0.103	0.309	**0.005**	0.002	**0.00003**
	3 bed semi	*4274*	***9***	*9.9*	1.19	0.071	0.214	**0.005**	0.001	**0.00003**
	2 bed flat	*2203*	***5***	*5.5*	0.66	0.040	0.119	**0.005**	0.001	**0.00004**

Table 14: Refrigerant-related emissions from heat pumps for refrigerants R32 and R410a, in domestic archetypes with comparison to gas boiler benchmark, assuming **6%** annual refrigerant leakage rate

		R32				**R32, new IPCC GWP**		**R410a**			
Archetype		**Estimated refrigerant charge (kg)**	**Refrigerant leakage (kg/yr) (assuming 6%)**	**Direct emissions ($kgCO_2e$ /year)**	**% of baseline**	**Direct emissions ($kgCO_2e$ /year)**	**% of baseline**	**Estimated refrigerant charge (kg)**	**Refrigerant leakage (kg/yr) (assuming 6%)**	**Direct emissions ($kgCO_2e$ /year)**	**% of baseline**
SG New Build Advanced	4 bed detached	0.50	0.030	20	**1.6**	23	**1.8**	0.50	0.030	62	**5.0**
	3 bed semi	0.50	0.030	20	**2.3**	23	**2.6**	0.50	0.030	62	**7.2**
	2 bed flat	0.50	0.030	20	**2.6**	23	**3.0**	0.50	0.030	62	**8.1**
Current well insulated	4 bed detached	0.99	0.059	40	**1.1**	46	**1.3**	0.99	0.059	124	**3.6**
	3 bed semi	0.83	0.050	33	**1.4**	38	**1.6**	0.83	0.050	103	**4.4**
	2 bed flat	0.66	0.040	27	**1.5**	31	**1.7**	0.66	0.040	83	**4.5**
Current average insulated	4 bed detached	2.15	0.129	87	**1.3**	99	**1.4**	2.15	0.129	269	**3.9**
	3 bed semi	1.49	0.089	60	**1.4**	69	**1.6**	1.49	0.089	186	**4.4**
	2 bed flat	0.83	0.050	33	1.5	38	1.7	0.83	0.050	103	4.7

Non-domestic archetypes

Table 15: Direct emissions from heat pumps for refrigerant R290, in non-domestic archetypes with comparison to gas boiler benchmark, assuming 6% annual refrigerant leakage rate, showing results for R290 (propane)

					R290 (propane)				**R290, new IPCC GWP**	
Archetype		***Benchmark gas boiler emissions (kgCO₂e /yr)***	***Req. capacity (kW) heat pump***	***Heat pump sizing 'extra allowance'***	**Estimated refrigerant charge (kg)**	**Refrigerant leakage (kg/yr) (assuming 6%)**	**Direct emissions (kgCO₂e /yr)**	**% of baseline**	**Direct emissions (kgCO₂e /year)**	**% of baseline**
SG New Build Advanced	Hospital	*469,479*	*510*	*561*	67	4	12	**0.003**	0.08	**0.00002**
	Care home	*29,904*	*32*	*35*	4	0	1	**0.003**	0.01	**0.00002**
	Leisure centre	*267,957*	*360*	*396*	48	3	9	**0.003**	0.06	**0.00002**
	Hotel	*87,948*	*110*	*121*	15	1	3	**0.003**	0.02	**0.00002**
	Office	*27,678*	*67*	*74*	9	1	2	**0.006**	0.01	**0.00004**
	School	*15,175*	*37*	*41*	5	0	1	**0.006**	0.01	**0.00004**
	Community centre	*3,736*	*9*	*10*	1	0	0	**0.006**	0.00	**0.00004**
	DIY store	*45,179*	*12*	*13*	2	0	0	**0.001**	0.00	**0.00000**
	Light industrial unit	*26,810*	*67*	*74*	9	1	2	**0.006**	0.01	**0.00004**
	Warehouse	*4,518*	*8*	*9*	1	0	0	**0.004**	0.00	**0.00003**
Current well insulated	Hospital	*1,989,497*	*2130*	*2343*	281	17	51	**0.003**	0.34	**0.00002**
	Care home	*135,581*	*140*	*154*	18	1	3	**0.002**	0.02	**0.00002**
	Leisure centre	*814,959*	*1110*	*1221*	147	9	26	**0.003**	0.18	**0.00002**
	Hotel	*78,051*	*100*	*110*	13	1	2	**0.003**	0.02	**0.00002**
	Office	*321,548*	*800*	*880*	106	6	19	**0.006**	0.13	**0.00004**
	School	*54,095*	*130*	*143*	17	1	3	**0.006**	0.02	**0.00004**
	Community centre	*13,158*	*32*	*35.2*	4	0	1	**0.006**	0.01	**0.00004**
	DIY store	*151,616*	*210*	*231*	28	2	5	**0.003**	0.03	**0.00002**
	Light industrial unit	*27,776*	*70*	*77*	9	1	2	**0.006**	0.01	**0.00004**
	Warehouse	*5,800*	*10*	*11*	1	0	0	**0.004**	0.00	**0.00003**

					R290 (propane)				**R290, new IPCC GWP**	
Archetype		***Benchmark gas boiler emissions (kgCO$_2$e /yr)***	***Req. capacity (kW) heat pump***	***Heat pump sizing 'extra allowance'***	**Estimated refrigerant charge (kg)**	**Refrigerant leakage (kg/yr) (assuming 6%)**	**Direct emissions (kgCO$_2$e /yr)**	**% of baseline**	**Direct emissions (kgCO$_2$e /year)**	**% of baseline**
Current average insulated	Hospital	*2,810,559*	*3010*	*3311*	397	24	72	**0.003**	0.48	**0.00002**
	Care home	*186,107*	*200*	*220*	26	2	5	**0.003**	0.03	**0.00002**
	Leisure centre	*1,846,006*	*2510*	*2761*	331	20	60	**0.003**	0.40	**0.00002**
	Hotel	*121,760*	*150*	*165*	20	1	4	**0.003**	0.02	**0.00002**
	Office	*321,548*	*800*	*880*	106	6	19	**0.006**	0.13	**0.00004**
	School	*78,509*	*190*	*209*	25	2	5	**0.006**	0.03	**0.00004**
	Community centre	*19,684*	*47*	*52*	6	0	1	**0.006**	0.01	**0.00004**
	DIY store	*195,371*	*270*	*297*	36	2	6	**0.003**	0.04	**0.00002**
	Light industrial unit	*32,305*	*80*	*88*	11	1	2	**0.006**	0.01	**0.00004**
	Warehouse	*8,904*	*16*	*18*	2	0	0	**0.004**	0.00	**0.00003**

Table 16: Direct emissions from heat pumps for refrigerants R32 and R410a, in non-domestic archetypes with comparison to gas boiler benchmark, assuming **6%** annual refrigerant leakage rate, showing results for R32 and R410a.

		R32				**R32, new IPCC GWP**		**R410a**			
Archetype		**Estimated refrigerant charge (kg)**	**Refrigerant leakage (kg/yr) (assuming 3%)**	**Direct emissions (kgCO$_2$e /year)**	**% of baseline**	**Direct emissions (kgCO$_2$e /year)**	**% of baseline**	**Estimated refrigerant charge (kg)**	**Refrigerant leakage (kg/yr) (assuming 6%)**	**Direct emissions (kgCO$_2$e /year)**	**% of baseline**
SG New Build Advanced	Hospital	84	5	3408	**0.73**	3893	**0.83**	84	5	10542	**2.25**
	Care home	5	0	214	**0.72**	244	**0.82**	5	0	661	**2.21**
	Leisure centre	59	4	2406	**0.90**	2748	**1.03**	59	4	7442	**2.78**
	Hotel	18	1	735	**0.84**	840	**0.95**	18	1	2274	**2.59**
	Office	11	1	448	**1.62**	511	**1.85**	11	1	1385	**5.00**
	School	6	0	247	**1.63**	282	**1.86**	6	0	765	**5.04**
	Community centre	1	0	60	**1.61**	69	**1.84**	1	0	186	**4.98**
	DIY store	2	0	80	**0.18**	92	**0.20**	2	0	248	**0.55**
	Light industrial unit	11	1	448	**1.67**	511	**1.91**	11	1	1385	**5.17**
	Warehouse	1	0	53	**1.18**	61	**1.35**	1	0	165	**3.66**
Current well insulated	Hospital	351	21	14234	**0.72**	16258	**0.82**	351	21	44030	**2.21**
	Care home	23	1	936	**0.69**	1069	**0.79**	23	1	2894	**2.13**
	Leisure centre	183	11	7418	**0.91**	8473	**1.04**	183	11	22945	**2.82**
	Hotel	17	1	668	**0.86**	763	**0.98**	17	1	2067	**2.65**
	Office	132	8	5346	**1.66**	6106	**1.90**	132	8	16537	**5.14**
	School	21	1	869	**1.61**	992	**1.83**	21	1	2687	**4.97**
	Community centre	5	0	214	**1.63**	244	**1.86**	5	0	661	**5.03**
	DIY store	35	2	1403	**0.93**	1603	**1.06**	35	2	4341	**2.86**
	Light industrial unit	12	1	468	**1.68**	534	**1.92**	12	1	1447	**5.21**
	Warehouse	2	0	67	**1.15**	76	**1.32**	2	0	207	**3.56**

		R32				R32, new IPCC GWP		R410a			
Archetype		**Estimated refrigerant charge (kg)**	**Refrigerant leakage (kg/yr) (assuming 3%)**	**Direct emissions (kgCO₂e /year)**	**% of baseline**	**Direct emissions (kgCO₂e /year)**	**% of baseline**	**Estimated refrigerant charge (kg)**	**Refrigerant leakage (kg/yr) (assuming 6%)**	**Direct emissions (kgCO₂e /year)**	**% of baseline**
Current average insulated	Hospital	497	30	20114	**0.72**	22975	**0.82**	497	30	62220	**2.21**
	Care home	33	2	1337	**0.72**	1527	**0.82**	33	2	4134	**2.22**
	Leisure centre	414	25	16773	**0.91**	19159	**1.04**	414	25	51885	**2.81**
	Hotel	25	1	1002	**0.82**	1145	**0.94**	25	1	3101	**2.55**
	Office	132	8	5346	**1.66**	6106	**1.90**	132	8	16537	**5.14**
	School	31	2	1270	**1.62**	1450	**1.85**	31	2	3928	**5.00**
	Community centre	8	0	314	**1.60**	359	**1.82**	8	0	972	**4.94**
	DIY store	45	3	1804	**0.92**	2061	**1.05**	45	3	5581	**2.86**
	Light industrial unit	13	1	535	**1.65**	611	**1.89**	13	1	1654	**5.12**
	Warehouse	3	0	107	**1.20**	122	**1.37**	3	0	331	**3.71**

Modelling and assumptions

Emissions due to refrigerant leakage depend on 1) The GWP of the refrigerant used, 2) Refrigerant charge and 3) Leakage rate (which varies by type of heat pump and refrigerant). All three factors vary greatly between different heat pump systems. Types of heat pump system cannot be easily mapped onto property archetypes, as the choice of heat pump depends on a wide range of considerations, from the heating requirements of the property to heat source and space limitations, safety considerations, possibility of ventilation and considerations around noise. We, therefore, present ranges of the possible climate impact of emissions from refrigerant leakage, based on various scenarios for each property archetype. This is based on estimates and assumptions drawn from a review of actual heat pump models.

Emissions were estimated for each property archetype for three different refrigerants, to illustrate the range of GHG emissions across low to high GWP refrigerants, for illustrative purposes, we include:

1. R290 (Propane): ultra-low GWP
2. R32: moderate GWP
3. R410A: high GWP

Annual emissions from heat pumps are calculated as the product of total refrigerant charge (c_{ref}), annual leakage rate (lr) and the GWP of the refrigerant used (GWP):

$$\mathrm{E}(CO_2eq) = c_{ref(kg)} \times lr(\%) \times GWP$$

Data on refrigerant leakage from heat pumps is limited, and leakage rates vary by type of system and refrigerant used. A summary of existing leakage data is provided in Appendix B. Due to the uncertainties around leakage rates, we base our assessment on what is likely a worst-case scenario of a 6% leakage rate. This does not take into account:

- The difference between split systems and monobloc systems, with monobloc systems, theoretically and anecdotally, associated with substantially lower leakage rates compared to split systems, both in terms of leakage at point of installation and leakage during operation. Moreover, leakage at point of decommissioning of a monobloc heat pump is likely to occur offsite, and arguably does not contribute to direct in-building emissions.
- The difference between refrigerants, with R134a and R407C, for example, shown to be associated with lower leakage rates compared to R410a (Slovak Association for Cooling and AC Technology, 2019).

While the appropriate refrigerant charge is specified for any particular heat pump, for the purposes of this report, in order to calculate hypothetical scenarios for different property archetypes, we estimate refrigerant charge as follows:

$$\text{Refrigerant charge } (kg) = \text{ charge per kW x heat pump capacity (kW)}$$

The following sections provide further detail on our approach to estimating refrigerant charge and heat pump capacity.

Refrigerant charge per kW capacity

We reviewed several heat pumps from a range of manufacturers that used a variety of refrigerants, to determine the relationship between the refrigerant charge and the kW capacity. This relationship is found to vary depending on refrigerant, with some refrigerants requiring far more charge than others (for example, a heat pump using R410a or R32 will need more than double the charge compared to a heat pump using R407c). This review was not exhaustive.

A summary of the relationships for R290, R32, R410s and R407c are given in Table 17. Graphs, showing how these relationships were identified, are presented in Figure 1 to Figure 4. All heat pumps used in this exercise are given in Table 18.

Table 17: Summary of relationship between charge (kg) and capacity (kW) for a variety of refrigerants

Refrigerant	**Relationship**
R290 (Propane)	Charge (kg) = 0.12 x capacity (kW)
R32	Charge (kg) = 0.15 x capacity (kW)
R410a	Charge (kg) = 0.15 x capacity (kW)
R407c	Charge (kg) = 0.05 x capacity (kW) + 1.30

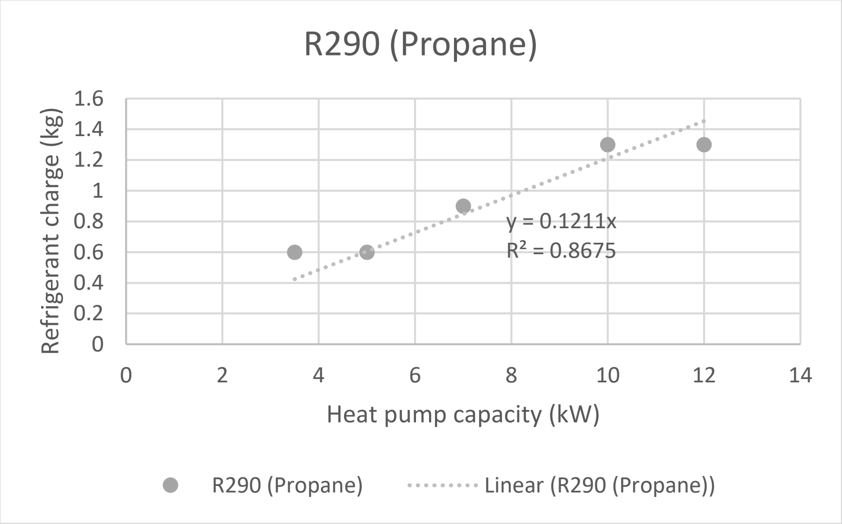

Figure 1: Heat pump capacity against refrigerant chare for a variety of heat pumps using R290

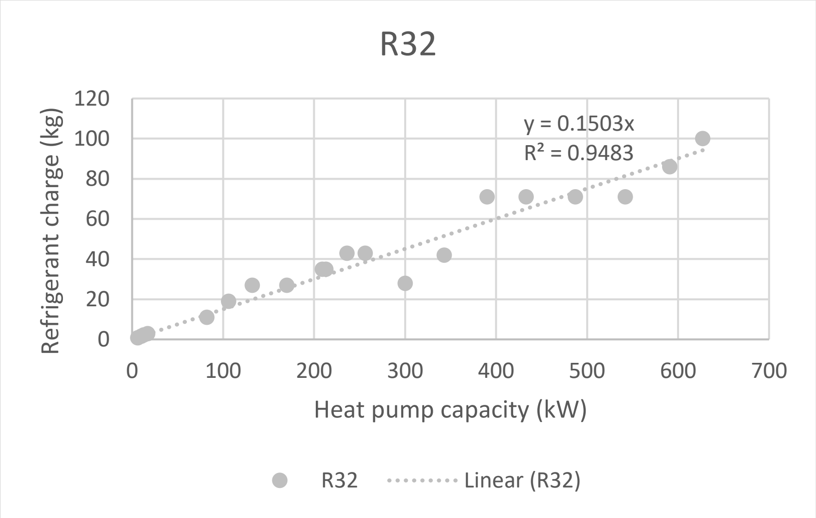

Figure 2: Heat pump capacity against refrigerant chare for a variety of heat pumps using R32

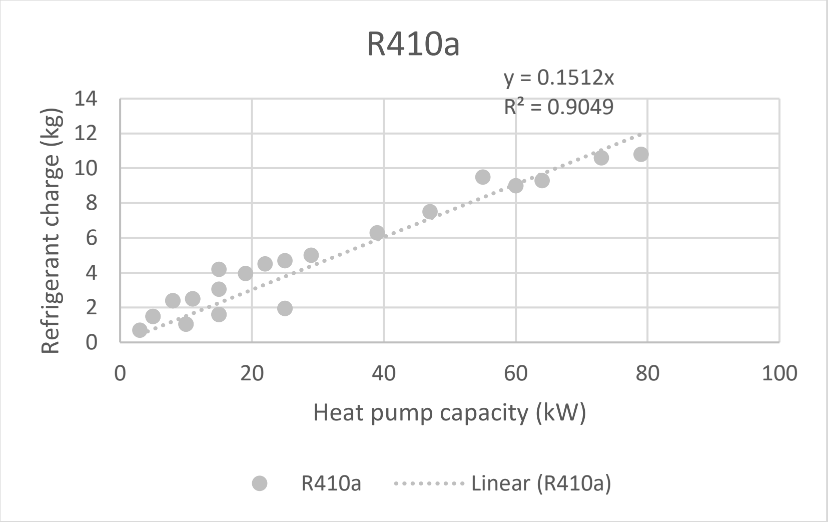

Figure 3: Heat pump capacity against refrigerant chare for a variety of heat pumps using R410a

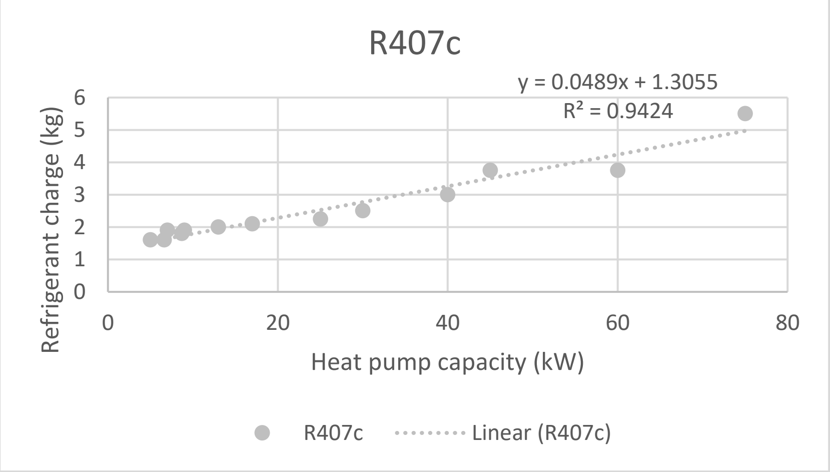

Figure 4: Heat pump capacity against refrigerant chare for a variety of heat pumps using R407c

Table 18: Capacities and refrigerant charges for a variety of heat pump models

Refrigerant	GWP	Manufacturer name and model	Capacity (kW)	Charge (kg)
R290	3	Vaillant - aroTHERM Plus 3.5kW VWL 35 / 6	3.5	0.6
R290	3	Vaillant - aroTHERM Plus 5kW VWL 55 / 6	5	0.6
R290	3	Vaillant - aroTHERM Plus 7kW VWL 75 / 6	7	0.9
R290	3	Vaillant - aroTHERM Plus 10kW VWL 105 / 6	10	1.3
R290	3	Vaillant - aroTHERM Plus 12kW VWL 125 / 6	12	1.3
R32	675	Daikin - Multi scroll heat pumps P750X	82	11
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 85	106	19
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 105	132	27
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 136	170	27
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 175	213	35

Refrigerant	GWP	Manufacturer name and model	Capacity (kW)	Charge (kg)
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 215	209	35
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 235	236	43
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 255	256	43
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 300	300	28
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 340	343	42
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 390	390	71
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 430	433	71
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 490	487	71
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 540	542	71
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 590	591	86
R32	675	Daikin - Multi scroll heat pumps EWYT-B-SS/SL 630	627	100
R32	675	Grant - Aerona3 HPID6R32	6	0.8
R32	675	Grant - Aerona3 HPID10R32	10	1.55
R32	675	Grant - Aerona3 HPID13R32	13	2.2
R32	675	Grant - Aerona3 HPID17R32	17	2.8
R410a	2088	Vaillant - geoTHERM mini ground source heat pump 3kW 230 V	3	0.7
R410a	2088	Vaillant - geoTHERM mini ground source heat pump 5kW 230 V	5	1.5
R410a	2088	Vaillant - geoTHERM mini ground source heat pump 8kW 230 V	8	2.4
R410a	2088	Vaillant - geoTHERM mini ground source heat pump 11kW 230 V	11	2.5
R410a	2088	Vaillant - geoTHERM mini ground source heat pump 5kW 400 V	5	1.5
R410a	2088	Vaillant - geoTHERM mini ground source heat pump 8kW 400 V	8	2.4
R410a	2088	Vaillant - geoTHERM mini ground source heat pump 11kW 400 V	11	2.5
R410a	2088	Vaillant - geoTHERM mini ground source heat pump 15kW 400 V	15	3.05
R410a	2088	Vaillant - geoTHERM mini ground source heat pump 19kW 400 V	19	3.95
R410a	2088	BOSCH / IVT GEO G222	22	4.5

Refrigerant	GWP	Manufacturer name and model	Capacity (kW)	Charge (kg)
R410a	2088	BOSCH / IVT GEO G228	29	5
R410a	2088	BOSCH / IVT GEO G238	39	6.3
R410a	2088	BOSCH / IVT GEO G248	47	7.5
R410a	2088	BOSCH / IVT GEO G254	55	9.5
R410a	2088	BOSCH / IVT GEO G264	64	9.3
R410a	2088	BOSCH / IVT GEO G272	73	10.6
R410a	2088	BOSCH / IVT GEO G280	79	10.8
R410a	2088	Clausius - H1-10 (Classic / Elite)	10	1.05
R410a	2088	Clausius - HC1-10 (Classic / Elite)	10	1.05
R410a	2088	Clausius - H3-15 (Classic / Elite)	15	1.6
R410a	2088	Clausius - HC3-15 (Classic / Elite)	15	1.6
R410a	2088	Clausius - H5-25 (Classic / Elite)	25	1.95
R410a	2088	Clausius - HC5-25 (Classic / Elite)	25	1.95
R410a	2088	Stiebel Eltron - WPL 15 AS	15	4.2
R410a	2088	Stiebel Eltron - WPL 25 AS	25	4.7
R410a	2088	Mitsubishi - Ecodan CRHV Monobloc Ground / Water Source Heat Pump System	60	9
R407c	1774	BOSCH / Greenline HE C6	5	1.6
R407c	1774	BOSCH / Greenline HE C7/E7	6.6	1.6
R407c	1774	BOSCH / Greenline HE C9/E9	8.7	1.8
R407c	1774	Kensa - Evo Ground Source Heat Pump K070-S1H	7	1.9
R407c	1774	Kensa - Evo Ground Source Heat Pump K090-S1H	9	1.9
R407c	1774	Kensa - Evo Ground Source Heat Pump K130-S1H	13	2
R407c	1774	Kensa - Evo Ground Source Heat Pump K170-S1H	17	2.1
R407c	1774	Kensa - Commercial Plant Room Ground Source Heat Pump P250X	25	2.25
R407c	1774	Kensa - Commercial Plant Room Ground Source Heat Pump P300X	30	2.5
R407c	1774	Kensa - Commercial Plant Room Ground Source Heat Pump P400X	40	3
R407c	1774	Kensa - Commercial Plant Room Ground Source Heat Pump P500X	45	3.75
R407c	1774	Kensa - Commercial Plant Room Ground Source Heat Pump P600X	60	3.75
R407c	1774	Kensa - Commercial Plant Room Ground Source Heat Pump P750X	75	5.5

Heat pump oversizing estimation

Once the heat demand of a building has been estimated, the heat pump engineer then needs to find a heat pump which *at least* meets the load. We have been told by installers that this usually leads to a small amount of oversizing as it is rare to find a heat pump with the exact capacity required by a building.

An exercise was undertaken to pick a heat pump from the range of heat pumps that we had identified that would meet the loads for our non-domestic archetypes. We limited ourselves to ground source heat pumps using R410a. The Bosch models that can be cascaded were limited to 8, thus there were a few archetypes for which we haven't been able to include in this exercise.

Table 19 shows the heat pump models assigned to each archetype and the total capacity of the system (some of which are single heat pumps, others are cascaded up to a maximum of 8, which was the recommended limit for the heat pump in question). The percentage oversizing is given in the final column of the table. The average oversizing was 9.5% but it varied from 0% (exact capacity match) to over 20%. For the purposes of this study, we use an estimate of 10% oversizing.

Table 19: Real-life heat pump capacities for the non-domestic archetypes

Archetype		**Heat pump capacity required (kW)**	**Model**	**Capacity of individual heat pump (kW)**	**No. needed in cascade**	**No. needed (rounded)**	**Cascaded system total capacity**	**% oversized**
New build	Hospital	510	BOSCH / IVT GEO G264	64	7.97	8	512	0.4%
	Care home	32	BOSCH / IVT GEO G238	39	0.82	1	39	21.9%
	Leisure centre	360	BOSCH / IVT GEO G264	64	5.63	6	384	6.7%
	Hotel	110	BOSCH / IVT GEO G254	55	2.00	2	110	0.0%
	Office	67	BOSCH / IVT GEO G272	73	0.92	1	73	9.0%
	School	37	BOSCH / IVT GEO G238	39	0.95	1	39	5.4%
	Community centre	9	Vaillant - geoTHERM mini ground source heat pump 11kW	11	0.82	1	11	22.2%
	DIY store	12	Vaillant - geoTHERM mini ground source heat pump 15kW	15	0.80	1	15	25.0%
	Light industrial unit	67	BOSCH / IVT GEO G272	73	0.92	1	73	9.0%
	Warehouse	8	Vaillant - geoTHERM mini ground source heat pump 8kW	8	1.00	1	8	0.0%

Archetype		Heat pump capacity required (kW)	Model	Capacity of individual heat pump (kW)	No. needed in cascade	No. needed (rounded)	Cascaded system total capacity	% oversized
Existing well insulated	Hospital	2130	Demand exceeds single heat pump unit	-	-	-	-	-
	Care home	140	BOSCH / IVT GEO G272	73	1.92	2	146	4.3%
	Leisure centre	1110	Demand exceeds single heat pump unit	-	-	-	-	-
	Hotel	100	BOSCH / IVT GEO G254	55	1.82	2	110	10.0%
	Office	800	Demand exceeds single heat pump unit		-	-	-	-
	School	130	BOSCH / IVT GEO G272	73	1.78	2	146	12.3%
	Community centre	32	BOSCH / IVT GEO G238	39	0.82	1	39	21.9%
	DIY store	210	BOSCH / IVT GEO G254	55	3.82	4	220	4.8%
	Light industrial unit	70	BOSCH / IVT GEO G272	73	0.96	1	73	4.3%
	Warehouse	10	Vaillant - geoTHERM mini ground source heat pump 11kW	11	0.91	1	11	10.0%
Existing poorly insulated	Hospital	3010	Demand exceeds single heat pump unit	-	-	-	-	-
	Care home	200	BOSCH / IVT GEO G272	73	2.74	3	219	9.5%
	Leisure centre	2510	Demand exceeds single heat pump unit	-	-	-	-	-
	Hotel	150	BOSCH / IVT GEO G280	79	1.90	2	158	5.3%
	Office	800	Demand exceeds single heat pump unit	-	-	-	-	-
	School	190	BOSCH / IVT GEO G264	64	2.97	3	192	1.1%
	Community centre	47	BOSCH / IVT GEO G248	47	1.00	1	47	0.0%
	DIY store	270	BOSCH / IVT GEO G272	73	3.70	4	292	8.1%
	Light industrial unit	80	BOSCH / IVT GEO G248	47	1.70	2	94	17.5%
	Warehouse	16	Vaillant - geoTHERM mini ground source heat pump 19kW	19	0.84	1	19	18.8%
							Average	9.5%

Appendix D: Solid biomass emissions modelling

We have developed indicative GHG factors for a range of wood-burning systems, based on the limited data available. Due to the above shortcomings in the data, individual results are not rigorous enough to support policy decisions that differentiate between technologies, and are presented here to indicate the potential scale of the issues and whether further research is justified.

The data for solid biomass emissions came from the following two key sources:

Bhattu et al. (2019) reported on CH_4 emissions in g/kg of wood at a range of Modified Combustion Efficiencies[21] (MCE) for 7 different technologies. In our analysis, the MCE is used to determine in-use vs. start-up emissions for various biomass technologies; operational emissions use an average from high MCE values, while start-up uses low MCE values.

To account for N_2O emissions we incorporated research by Tsupari *et al.* (2005), who investigated CH_4 and N_2O emissions from large boiler systems (typically MWs in size). Table 20 shows the emissions at various system sizes. They add that there is not enough information to provide N_2O emission factors for smaller boilers, but some studies have shown that they should be larger due to shorter residence time in furnaces and less advanced technology.

Table 20: CH_4 and N_20 emissions for other wood/bark fuelled furnaces. The fuel is noted as comprising of at least 80% of the indicated fuel stock. Range of values where applicable are shown in brackets

		Size (MW)		
Greenhouse gas	**Fuel**	**<5 MW**	**5-50 MW**	**>50 MW**
CH_4	Wood & Bark	50 mg/MJ	30 (15-50) mg/MJ	5 (0.5-50) mg/MJ
N_2O	Wood	Data not available	3 mg/MJ	3 mg/MJ

CH_4 emissions for all systems apart from the chip boiler are calculated using the data provided by Bhattu. Due to the higher CH_4 emissions during start-up and shutdown, we have derived emission factors for this stage as well as normal operation. For each technology a combustion efficiency cut-off was estimated based on the graphical data. Averages were taken for the data above and below this cut-off to give the ignition/ shutdown and operational emission factors. The results are summarised in Table 21 together with the boiler efficiency and net calorific value for each system.

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[21] Modified combustion efficiency is effectively a measurement of how close the combustion process is to complete combustion. 100% MCE would mean that all the carbon in the fuel was oxidised to carbon dioxide and all the hydrogen oxidised to water.

Table 21: Ignition and operational methane emissions for wood-fuelled heating systems

Technology	**Ignition / Operational MCE cut-off**	**Methane emissions (g/kg wood)**		**Net boiler efficiency**	**Net calorific value (kWh/kg)**
		Ignition/ shutdown	**Operation**		
15kW pellet boiler	97%	0.47	0.18	0.79	4.84
6kW pellet stove	98%	0.50	0.05	0.79	4.84
30kW log boiler	98%	2.72	0.16	0.8	4.38
4.6kW adv log stove	97%	1.18	0.29	0.75	4.38
8kW adv log stove	95%	6.66	2.38	0.75	4.38
6kW simple log stove	97%	3.28	0.59	0.75	4.38

The emission factor is converted into $kgCO_2e/kWh$ using the equation below where EF_{CH4} is the emission factor in g/kg wood (given in Table 21), *GWP* is the global warming potential of Methane (= 25), η is the efficiency of the biomass system and *NCV* is the net calorific value of the fuel:

$$\mathrm{EF}_{\mathrm{CO2}} = \frac{EF_{CH4}(g/kg)\cdot GWP_{CH4}}{\eta(\%)\cdot NCV(kW)}$$

Emissions for the chip boiler are taken directly from Tsupiri's et al. (2005) data from Finland, and have been added to Table 22. We have not used the chip boiler from Bhattu *et al.* as the emissions were significantly smaller than the other technologies and were not considered to be realistic.

Table 22: Total emissions per kWh from biomass heating systems

Technology	**Ignition proportion**	**Methane emissions ($kgCO_2e/kWh$)**			**Nitrous oxide emissions ($kgCO_2e/kWh$)**	**Total emissions ($kgCO_2e/kWh$)**
		Ignition	**Operation**	**Combined**		
15kW pellet boiler	5%	3.1×10^{-3}	1.2×10^{-3}	1.3×10^{-3}	$0.2\text{-}0.9\times10^{-3}$	$1.5\text{-}2.2\times10^{-3}$
6kW pellet stove	8%	3.3×10^{-3}	0.3×10^{-3}	0.5×10^{-3}	$0.2\text{-}0.4\times10^{-3}$	$0.8\text{-}0.9\times10^{-3}$
30kW log boiler	5%	19.4×10^{-3}	1.1×10^{-3}	2.0×10^{-3}	$0.2\text{-}1.5\times10^{-3}$	$2.3\text{-}3.5\times10^{-3}$
4.6kW adv log stove	12%	9.0×10^{-3}	2.2×10^{-3}	3.0×10^{-3}	$0.2\text{-}2.2\times10^{-3}$	$3.3\text{-}5.2\times10^{-3}$
8kW adv log stove	12%	50.7×10^{-3}	18.1×10^{-3}	22.0×10^{-3}	$0.2\text{-}15.7\times10^{-3}$	$22.2\text{-}37.7\times10^{-3}$
6kW simple log stove	12%	24.9×10^{-3}	4.5×10^{-3}	7.0×10^{-3}	$0.2\text{-}5.0\times10^{-3}$	$7.2\text{-}11.9\times10^{-3}$
Chip boiler	-	-	-	0.3×10^{-3}	0.2×10^{-3}	0.6×10^{-3}

Combining the relative proportions of ignition and operation stages of various biomass systems gives the total methane emissions presented in Table 22.

N_2O emissions are calculated using the information in Table 20. In the absence of other data, we have used two methods to calculate N_2O emissions: a constant value from the Finnish data (0.00025 $kgCO_2e/kWh$) and a ratio between emissions for CH_4 and N_2O given by the equation below:

$$EF_{N2O} = EF_{CH4} \times \frac{3 \cdot GWP_{N2O}}{50 \cdot GWP_{CH4}}$$

The two emission factors were combined to give the overall value and ranges are presented in Table 22:

$$EF_{combined} = EF_{CH4} + EF_{N2O}$$

For these cases we have assumed a CO_2 GWP of 0 in line with the UK methodology. Technically this is ignoring significant in-building emissions of a GHG but is in line with the established approach of assuming that these emissions make no net contribution to global warming. For completeness we have included figures in Appendix G using a GWP of 1 for biomass CO_2, effectively treating these emissions in the same way as fossil carbon. It should be stressed that these figures do not represent any real assessment of the possible impact of biomass emissions – they are included simply to demonstrate the impact of different approaches to CO_2 accounting in this context. In principle, it would be possible to establish appropriate GWP factors for some common biofuel supply chains, but that is outside the scope for this project.

Appendix E: Archetype assumptions and definitions

Domestic archetype assumptions

The following assumptions were used to determine the domestic archetypes used in this report.

Table 23: Key modelling assumptions in the development of domestic archetypes

Key modelling assumptions	
Heating hours weekday	9
Heating hours weekend	16
Living areas set point temperature	21°C
Other areas set point temperature	18°C
Climate Region	East Scotland

Table 24: Domestic archetype assumptions: U-values

Domestic archetype assumptions					
Scenario Name	U-values				
	Wall	Loft	Glazing	Floor	Doors
SG New Build Advanced	Not applicable. Energy requirements not modelled and are based on the latest Scottish Government (2021d) energy standards for new builds (advanced case)				
Current insulated	0.3	0.11	2.1	0.33	2
Current poorly insulated	1.5	0.4	4.8	0.64	3

Non-domestic archetype definitions

The following tables detail the full definitions for the non-domestic archetypes. This covers the three insulation scenarios: new build, existing insulated and existing poorly insulated.

Table 25: Non-domestic archetype definitions for new build properties. “HW” abbreviates Hot Water.

Archetype	Characteristics	Total floor area (m^2)	Annual space heating load (MWh)	Typical flow temperature (°C)	Annual water heating load (MWh)	Typical load factor (gas)	Assumed system capacity (kW) (gas)
Hospital	High temp, high HW, 24/7	25000	1207.5	75	1022.5	45%	566
Care home	High temp, med HW, 24/7	2000	96.6	75	45.4	45%	36
Leisure centre	Med temp, high HW, long hours	15000	1109.2	55	192.8	35%	425
Hotel	Med temp, med HW, 24/7	1500	129.2	65	293.4	40%	121
Office	Low temp, low HW, short hours	20000	84.0	45	52.0	15%	104
School	Med temp, low HW, short hours	2300	43.9	60	29.0	15%	55
Community centre	High temp, low HW, v short hrs	500	10.6	75	7.2	15%	14
DIY store	Low temp, v low HW, long hours	5000	34.5	45	8.0	35%	14
Light industrial	V low temp, low HW, short hours	1500	109.1	35	24.2	15%	101
Warehouse	Low temp, no HW, long hours	250	18.2	45	4.0	25%	10

Table 26: Non-domestic archetype definitions for insulated existing properties. “HW” abbreviates Hot Water

Archetype	Characteristics	Total floor area (m^2)	Annual space heating load (MWh)	Typical flow temperature (°C)	Annual water heating load (MWh)	Typical load factor (gas)	Assumed system capacity (kW) (gas)
Hospital	High temp, high HW, 24/7	25,000	6,300	75	3,150	45%	2,397
Care home	High temp, med HW, 24/7	2,000	504	75	1,400	45%	163
Leisure centre	Med temp, high HW, long hours	15,000	3,366	55	594	35%	1,292
Hotel	Med temp, med HW, 24/7	1,500	270	65	105	40%	107
Office	Low temp, low HW, short hours	20,000	1,422	45	158	15%	1,202
School	Med temp, low HW, short hours	2,300	234	60	26.0	15%	198
Community centre	High temp, low HW, v short hrs	500	56.3	75	6.25	15%	48
DIY store	Low temp, v low HW, long hours	5,000	708	45	37.3	35%	243
Light industrial	V low temp, low HW, short hours	1,500	131	35	6.90	15%	105
Warehouse	Low temp, no HW, long hours	250	27.1	45	1.43	25%	13

Table 27: Non-domestic archetype definitions for poorly insulated existing properties. "HW" abbreviates Hot Water

Archetype	**Characteristics**	**Floor area (m^2)**	**Annual space heating load (MWh)**	**Typical flow temperature (°C)**	**Annual water heating load (MWh)**	**Typical load factor (gas)**	**Assumed system capacity (kW) (gas)**
Hospital	High temp, high HW, 24/7	25000	8300	75	5050	45%	3387
Care home	High temp, med HW, 24/7	2000	664	75	220	45%	224
Leisure centre	Med temp, high HW, long hours	15000	7624.5	55	1345.5	35%	2926
Hotel	Med temp, med HW, 24/7	1500	420	65	165	40%	167
Office	Low temp, low HW, short hrs	20000	1422	45	158	15%	1202
School	Med temp, low HW, short hrs	2300	339.5	60	37.7	15%	287
Community centre	High temp, low HW, v short hrs	500	84.2	75	9.4	15%	71
DIY store	Low temp, v low HW, long hours	5000	912	45	48	35%	313
Light industrial	V low temp, low HW, short hrs	1500	152.5	35	8.0	15%	122
Warehouse	Low temp, no HW, long hours	250	41.6	45	2.2	25%	20

Appendix F: Assumptions and calculation of gas baseline emissions

Gas combi system

Emissions for a gas combi system were calculated using the information in Table 6 (Section 4.1). Using efficiency factors of 88% and 78% (calculated from average SEDBUK 2009 efficiencies for new boilers) for space heating and hot water respectively, the amount of fuel used is calculated. This is converted to GHG emissions using the UK emissions factor of 0.18316 kgCO_2e/kWh (Gross CV). Table 28 shows the domestic emissions for the 9 archetypes.

Table 28: Direct emissions from the gas boiler baseline for domestic archetypes

Scenario Name	**House type**	**Annual Space Heating Energy (kWh)**	**Annual Hot Water Energy (kWh)**	**Annual Nat Gas used (kWh)**	**Annual CO_2e emissions (kgCO_2e)**
SG New Build Advanced	4 bed detached	2,378	2,688	6,134	1,124
SG New Build Advanced	3 bed semi	935	2,498	4,258	780
SG New Build Advanced	2 bed flat	562	2,426	3,744	686
Current well insulated	4 bed detached	10,330	4,231	17,107	3,133
Current well insulated	3 bed semi	5,455	4,115	11,443	2,096
Current well insulated	2 bed flat	5,573	2,050	8,931	1,636
Current average insulated	4 bed detached	24,859	4,231	33,542	6,144
Current average insulated	3 bed semi	13,866	4,115	20,958	3,839
Current average insulated	2 bed flat	7,228	2,050	10,803	1,979

For non-domestic properties a combined efficiency was used as it was unlikely that combination boilers would be used for the majority of these. Instead, a variable efficiency was obtained based on non-domestic assumptions. Space heating and hot water demand can be seen in Appendix E.

Table 29 shows the emissions for gas systems for all archetypes and insulation levels.

Table 29: Direct emissions from the gas boiler benchmark for all non-domestic archetypes and insulation levels.

Archetype	**Efficiency**	**New build emissions ($kgCO_2e/year$)**	**Existing well insulated emissions ($kgCO_2e/year$)**	**Existing poorly insulated emissions ($kgCO_2e/year$)**
Hospital	87%	469,479	1,989,497	2,810,559
Care home	87%	29,904	135,581	186,107
Leisure centre	89%	267,957	814,959	1,846,006
Hotel	88%	87,948	78,051	121,760
Office	90%	27,678	321,548	321,548
School	88%	15,175	54,095	78,509
Community centre	87%	3,736	13,158	19,684
DIY store	90%	45,179	151,616	195,371
Light industrial unit	91%	26,810	27,776	32,305
Warehouse	90%	4,518	5,800	8,904

Hybrid heat pump

Emissions for hybrid heat pumps (HHPs) are presented in Table 30 for domestic properties. To illustrate HHP emissions we use an illustrative example of a heat pump using the moderate-GWP refrigerant R32. As discussed in the heat pump sections, the change in refrigerant will greatly affect the emissions. This scenario is, therefore,illustrative of potential emissions. For the hybrid heat pump benchmark, we assumed a 3% refrigerant leakage rate, reflecting the lower leakages associated with monobloc systems.

A range is shown to account for the varying use of heat pumps in a HHP set up. This varies between 48% and 89% of the space heating demand. All hot water is met with the combi boiler. The results show a 14-66% reduction in emissions for the minimum emissions case and a 7-40% reduction for the maximum emissions case. The majority of emissions come from the gas boiler, with less than 1% in almost all cases coming from the heat pump. This variation is due to the changing use of hot water, with the new build total energy predominantly made up of hot water use. In reality it is highly unlikely new builds would use a HHP, but are presented here for completeness.

Table 30: Direct emissions from the hybrid heat pump benchmark system for domestic archetypes

Archetype		**Natural gas emissions min ($kgCO_2e$/ kWh)**	**Natural gas emissions max ($kgCO_2e$/ kWh)**	**Heat pump emissions ($kgCO_2e$/ kWh)**	**Total min ($kgCO_2e$/ kWh)**	**Total max ($kgCO_2e$/ kWh)**
SG New Build	4 bed detached	685	887	6.8	692	894
	3 bed semi	608	687	6.8	614	694
	2 bed flat	582	630	6.8	589	637
Current well insulated	4 bed detached	1,228	2,106	13.6	1,242	2,119
	3 bed semi	1,090	1,553	11.3	1,101	1565
	2 bed flat	608	1,082	9.0	617	1,091
Current average insulated	4 bed detached	1,560	3,671	29.4	1,589	3,701
	3 bed semi	1,282	2,460	20.4	1,302	2,480
	2 bed flat	646	1,260	11.3	657	1,271

Emissions from HHP are presented for non-domestic properties in Table 31. Again, a range is shown for varying rates of use. However, in this case the proportion is based on the total heat demand. The minimum case shows an 88-89% reduction in emissions compared to the baseline and the maximum shows a 47% reduction for all archetypes. Again, heat pumps make up a small proportion of the total emissions (less than 5% in this case).

Table 31: Direct emissions from the hybrid heat pump benchmark system for non-domestic archetypes

Archetype		**Natural gas emissions min ($kgCO_2e$/ kWh)**	**Natural gas emissions max ($kgCO_2e$/ kWh)**	**Heat pump emissions ($kgCO_2e$/ kWh)**	**Total min ($kgCO_2e$/ kWh)**	**Total max ($kgCO_2e$/ kWh)**
SG New Build Advanced	Hospital	51,643	244,129	1,131	52,774	245,260
	Care home	3,289	15,550	72	3,362	15,623
	Leisure centre	29,475	139,338	814	30,290	140,152
	Hotel	9,674	45,733	249	9,923	45,982
	Office	3,045	14,392	158	3,203	14,551
	School	1,669	7,891	84	1,753	7,975
	Community centre	411	1,943	20	431	1,963

Archetype		Natural gas emissions min (kgCO$_2$e/ kWh)	Natural gas emissions max (kgCO$_2$e/ kWh)	Heat pump emissions (kgCO$_2$e/ kWh)	Total min (kgCO$_2$e/ kWh)	Total max (kgCO$_2$e/ kWh)
	DIY store	4,970	23,493	140	5,110	23,634
	Light industrial unit	2,949	13,941	158	3,107	14,099
	Warehouse	497	2,349	18	515	2,367
Existing well Insulated	Hospital	218,845	1,034,538	4,818	223,663	1,039,357
	Care home	14,914	70,502	317	15,231	70,819
	Leisure centre	89,646	423,779	2,511	92,156	426,290
	Hotel	8,586	40,587	204	8,789	40,790
	Office	35,370	167,205	1,810	37,180	169,014
	School	5,950	28,129	294	6,244	28,423
	Community centre	1,447	6,842	72	1,520	6,915
	DIY store	16,678	78,840	475	17,153	79,315
	Light industrial unit	3,055	14,443	158	3,214	14,602
	Warehouse	638	3,016	23	661	3,039
Existing poorly insulated	Hospital	309,161	1,461,490	6,809	315,970	1,468,300
	Care home	20,472	96,776	452	20,924	97,228
	Leisure centre	203,061	959,923	5,678	208,739	965,601
	Hotel	13,394	63,315	339	13,733	63,654
	Office	35,370	167,205	1,810	37,180	169,014
	School	8,636	40,825	430	9,066	41,255
	Community centre	2,165	10,236	106	2,272	10,342
	DIY store	21,491	101,593	611	22,102	102,204
	Light industrial unit	3,554	16,798	181	3,734	16,979
	Warehouse	979	4,630	36	1,016	4,666

Appendix G: Biomass and hydrogen - detailed results tables

Biomass

This section presents the detailed results of our assessment of direct emissions from biomass combustion.

There is a level of uncertainty in all these results; therefore, results are presented as ranges of likely emissions. Further in situ measurement of CH_4 and N_2O emissions will be needed to determine actual GHG emissions of different systems and operating practices with certainty. Nevertheless, all the biomass systems appear to provide significant GHG reductions compared to a gas boiler, with most systems offering a 98% reduction or more. This is assuming CO_2 emissions are effectively excluded by giving them a GWP of zero. If CO_2 emissions are included with a GWP of 1 then all biomass systems have higher GHG emissions than a gas boiler.

When considering the direct CH_4 and N_2O emissions from the pure biomass systems, it is clear they produce significantly fewer emissions than the gas baseline total emissions. Even if the least efficient technology was used (log stoves), the emissions are less than 10% of those of gas boilers. It should be noted that the quality and condition of the fuel can play a significant factor in emissions, however there is limited data to present on this at this stage. Biomass systems would benefit from significant and extensive laboratory testing which would give further confidence in the results presented here. Currently, these numbers should not be considered statistically significant as they are based on limited data and reasonably large assumptions. However, with proper testing, these types of results could be used to provide a limit at which biomass systems could be considered ‘low carbon’ (or low emissions).

Domestic archetypes

Annual emissions for domestic biomass systems are presented in Table 32 with the relative emissions to the gas baseline in Table 33. Table 34 and Table 35 show the same data but with CO_2 with a GWP of 1 included. Please note that including CO_2 in this way does not reflect the climate impact of biomass systems.

Table 32: Annual emissions for domestic biomass systems for the 9 archetypes. Note: GWP for CO_2 = 0 for biomass.

Archetype		**Annual emissions (kgCO$_2$e/year)**							
		Pellet boiler	**Log stove High**	**Log stove Low**	**Pellet stove**	**Bio-diesel (HVO)**	**40% Bio LPG**	**100% Bio LPG**	**Biomethane**
New Build	4 bed detached	9.2 - 13.3	134.2 - 227.6	19.7 - 31.3	4.7 - 5.6	25.5	586.6	2.0	2.6
	3 bed semi	6.3 - 9	90.9 - 154.2	13.4 - 21.2	3.2 - 3.8	17.3	397.5	1.4	1.8
	2 bed flat	5.4 - 7.8	79.1 - 134.2	11.6 - 18.4	2.8 - 3.3	15.0	346.0	1.2	1.5
Current insulated	4 bed detached	26.5 - 38.1	385.7 - 654.1	56.7 - 89.9	13.6 - 16	73.2	1,685.9	5.9	7.5
	3 bed semi	17.4 - 25.1	253.5 - 429.9	37.3 - 59.1	9 - 10.5	48.1	1,108.0	3.9	4.9
	2 bed flat	13.9 - 20	201.9 - 342.5	29.7 - 47	7.1 - 8.4	38.3	882.6	3.1	3.9
Current average	4 bed detached	53 - 76.2	770.5 - 1306.8	113.3 - 179.5	27.3 - 32	146.2	3,368.1	11.8	15.0
	3 bed semi	32.8 - 47.1	476.3 - 807.8	70 - 111	16.8 - 19.8	90.4	2,081.9	7.3	9.3
	2 bed flat	16.9 - 24.3	245.8 - 416.8	36.1 - 57.3	8.7 - 10.2	46.6	1,074.2	3.7	4.8

Table 33: Comparison of biomass emissions to the gas baseline (gas baseline includes CO_2 emissions). GWP for CO_2 = 0 for biomass.

Archetype		**Comparison to gas baseline emissions**							
		Pellet boiler	**Log stove High**	**Log stove Low**	**Pellet stove**	**Bio-diesel (HVO)**	**40% Bio LPG**	**100% Bio LPG**	**Biomethane**
New Build	4 bed detached	1.2%	11.9% - 20.3%	1.8% - 2.8%	0.4% - 0.5%	2.3%	52.2%	0.2%	0.2%
	3 bed semi	1.2%	11.7% - 19.8%	1.7% - 2.7%	0.4% - 0.5%	2.2%	51.0%	0.2%	0.2%
	2 bed flat	1.1%	11.5% - 19.6%	1.7% - 2.7%	0.4% - 0.5%	2.2%	50.4%	0.2%	0.2%
Current insulated	4 bed detached	1.2%	12.3% - 20.9%	1.8% - 2.9%	0.4% - 0.5%	2.3%	53.8%	0.2%	0.2%
	3 bed semi	1.2%	12.1% - 20.5%	1.8% - 2.8%	0.4% - 0.5%	2.3%	52.9%	0.2%	0.2%
	2 bed flat	1.2%	12.3% - 20.9%	1.8% - 2.9%	0.4% - 0.5%	2.3%	54.0%	0.2%	0.2%
Current average	4 bed detached	1.2%	12.5% - 21.3%	1.8% - 2.9%	0.4% - 0.5%	2.4%	54.8%	0.2%	0.2%
	3 bed semi	1.2%	12.4% - 21%	1.8% - 2.9%	0.4% - 0.5%	2.4%	54.2%	0.2%	0.2%
	2 bed flat	1.2%	12.4% - 21.1%	1.8% - 2.9%	0.4% - 0.5%	2.4%	54.3%	0.2%	0.2%

Table 34: Annual emissions for domestic biomass systems for the 9 archetypes including CO2 emissions. Note: GWP for CO2 = 1 for biomass. Please note that including CO_2 in this way does not reflect the climate impact of biomass systems.

Archetype		**Annual emissions (kgCO$_2$e/year)**							
		Pellet boiler	**Log stove High**	**Log stove Low**	**Pellet stove**	**Bio-diesel (HVO)**	**40% Bio LPG**	**100% Bio LPG**	**Biomethane**
New Build	4 bed detached	2248 - 2252	2487 - 2565	2391 - 2400	2245 - 2245	1483	1229	1229	1143
	3 bed semi	1524 - 1526	1685 - 1738	1620 - 1627	1521 - 1522	1005	833	833	774
	2 bed flat	1326 - 1328	1467 - 1513	1410 - 1416	1324 - 1324	874	725	725	674
Current insulated	4 bed detached	6462 - 6472	7148 - 7374	6872 - 6900	6452 - 6454	4262	3533	3533	3284
	3 bed semi	4247 - 4254	4698 - 4846	4516 - 4535	4240 - 4242	2801	2322	2322	2159
	2 bed flat	3383 - 3388	3742 - 3860	3597 - 3612	3378 - 3379	2231	1850	1850	1719
Current average	4 bed detached	12911 - 12930	14280 - 14731	13728 - 13784	12889 - 12893	8514	7058	7058	6561
	3 bed semi	7980 - 7992	8827 - 9105	8486 - 8520	7967 - 7969	5262	4363	4363	4056
	2 bed flat	4118 - 4124	4555 - 4698	4379 - 4396	4111 - 4112	2715	2251	2251	2093

Table 35: Comparison of biomass emissions to the gas baseline including CO_2 emission for biomass (gas baseline includes CO_2 emissions). Includes CO2 emission with GWP = 1. Please note that including CO2 in this way does not reflect the climate impact of biomass systems.

Archetype		**Comparison to gas baseline emissions**							
		Pellet boiler	**Log stove High**	**Log stove Low**	**Pellet stove**	**Bio-diesel (HVO)**	**40% Bio LPG**	**100% Bio LPG**	**Biomethane**
New Build	4 bed detached	200%	221% - 228%	213% - 214%	200% - 200%	132%	109%	109%	102%
	3 bed semi	196%	216% - 223%	208% - 209%	195% - 195%	129%	107%	107%	99%
	2 bed flat	194%	214% - 221%	206% - 206%	193% - 193%	128%	106%	106%	98%
Current insulated	4 bed detached	207%	228% - 235%	219% - 220%	206% - 206%	136%	113%	113%	105%
	3 bed semi	203%	224% - 231%	215% - 216%	202% - 202%	134%	111%	111%	103%
	2 bed flat	207%	229% - 236%	220% - 221%	206% - 207%	136%	113%	113%	105%
Current average	4 bed detached	210%	232% - 240%	223% - 224%	210% - 210%	139%	115%	115%	107%
	3 bed semi	208%	230% - 237%	221% - 222%	208% - 208%	137%	114%	114%	106%
	2 bed flat	208%	230% - 237%	221% - 222%	208% - 208%	137%	114%	114%	106%

Non-domestic archetypes

Emissions per unit of floor area are presented in Table 36 for all non-domestic archetypes. Table 37 shows the emissions relative to a gas baseline. Tables 38 and 39 show the same data but with CO$_2$ with a GWP of 1 included. Please note that including CO$_2$ in this way does not reflect the climate impact of biomass systems.

Table 36: Emissions from biomass systems per unit of floor area (gCO$_2$e/m^2 floor area). Only emissions from CH$_4$ and N$_2$O are included for biomass.

Archetype		Chip boiler	Pellet boiler	HVO	40% BioLPG	100% BioLPG	Bio methane
SG New Build Advanced	Hospital	53.1	136.6 - 196.3	382.7	8815.0	30.8	39.2
	Care home	-	108.7 - 156.3	304.7	7018.6	24.5	31.2
	Leisure centre	51.7	132.9 - 191	364.0	8385.3	29.3	37.3
	Hotel	167.8	431.3 - 619.8	1194.8	27522.1	96.0	122.4
	Office	4.0	10.4 - 15	28.2	649.6	2.3	2.9
	School	-	48.5 - 69.7	134.5	3097.1	10.8	13.8
	Community centre	-	54.3 - 78.1	152.3	3507.8	12.2	15.6
	DIY store	-	68 - 97.7	184.1	4241.5	14.8	18.9
	Light industrial unit	52.9	136 - 195.4	364.2	8389.7	29.3	37.3
	Warehouse	-	0 - 0	368.3	8483.0	29.6	37.7
Current well insulated	Hospital	225.1	-	1621.7	37355.1	130.3	166.2
	Care home	191.8	493 - 708.5	1381.4	31821.0	111.0	141.6
	Leisure centre	157.2	404.2 - 580.9	1107.1	25503.0	89.0	113.5
	Hotel	148.9	382.8 - 550.1	1060.3	24425.0	85.2	108.7
	Office	47.0	121 - 173.8	327.6	7546.8	26.3	33.6
	School	67.3	173 - 248.6	479.3	11040.1	38.5	49.1
	Community centre	-	191.4 - 275	536.3	12352.9	43.1	55.0
	DIY store	88.7	228.1 - 327.8	617.9	14233.8	49.7	63.3
	Light industrial unit	54.8	140.9 - 202.4	377.3	8692.1	30.3	38.7
	Warehouse	-	-	472.8	10890.3	38.0	48.5

Archetype		Chip boiler	Pellet boiler	HVO	40% BioLPG	100% BioLPG	Bio methane
Current average insulated	Hospital	318.0	-	2290.9	52771.5	184.1	234.8
	Care home	263.2	168.4 - 242	1896.2	43679.8	152.4	194.3
	Leisure centre	356.1	0 - 0	2507.8	57768.1	201.6	257.0
	Hotel	232.3	168.4 - 242	1654.1	38103.0	133.0	169.5
	Office	47.0	12.1 - 17.4	327.6	7546.8	26.3	33.6
	School	97.7	25.1 - 36.1	695.6	16022.8	55.9	71.3
	Community centre	111.4	28.6 - 41.1	802.2	18479.9	64.5	82.2
	DIY store	114.3	14.7 - 21.1	796.2	18341.5	64.0	81.6
	Light industrial unit	63.7	8.2 - 11.8	438.9	10109.3	35.3	45.0
	Warehouse	-	-	725.7	16717.6	58.3	74.4

Table 37: Relative emissions of biomass compared to gas baseline (gas baseline includes CO_2 emissions). Only emissions from CH_4 and N_2O are included for biomass.

Archetype		Chip boiler	Pellet boiler	HVO	40% BioLPG	100% BioLPG	Bio methane
SG New Build Advanced	Hospital	0.28%	0.7% - 1%	2.04%	46.94%	0.16%	0.21%
	Care home	-	0.7% - 1%	2.04%	46.94%	0.16%	0.21%
	Leisure centre	0.29%	0.7% - 1.1%	2.04%	46.94%	0.16%	0.21%
	Hotel	0.29%	0.7% - 1.1%	2.04%	46.94%	0.16%	0.21%
	Office	0.29%	0.8% - 1.1%	2.04%	46.94%	0.16%	0.21%
	School	-	0.7% - 1.1%	2.04%	46.94%	0.16%	0.21%
	Community centre	-	0.7% - 1%	2.04%	46.94%	0.16%	0.21%
	DIY store	-	0.8% - 1.1%	2.04%	46.94%	0.16%	0.21%
	Light industrial unit	0.30%	0.8% - 1.1%	2.04%	46.94%	0.16%	0.21%
	Warehouse	-	0% - 0%	2.04%	46.94%	0.16%	0.21%
Curren	Hospital	0.28%	-	2.04%	46.94%	0.16%	0.21%

Archetype		Chip boiler	Pellet boiler	HVO	40% BioLPG	100% BioLPG	Bio methane
	Care home	-	0.7% - 1%	2.04%	46.94%	0.16%	0.21%
	Leisure centre	0.29%	0.7% - 1.1%	2.04%	46.94%	0.16%	0.21%
	Hotel	0.29%	0.7% - 1.1%	2.04%	46.94%	0.16%	0.21%
	Office	0.29%	0.8% - 1.1%	2.04%	46.94%	0.16%	0.21%
	School	0.29%	0.7% - 1.1%	2.04%	46.94%	0.16%	0.21%
	Community centre	-	0.7% - 1%	2.04%	46.94%	0.16%	0.21%
	DIY store	-	0.8% - 1.1%	2.04%	46.94%	0.16%	0.21%
	Light industrial unit	0.30%	0.8% - 1.1%	2.04%	46.94%	0.16%	0.21%
	Warehouse	-	-	2.04%	46.94%	0.16%	0.21%
Current average insulated	Hospital	0.28%	-	2.04%	46.94%	0.16%	0.21%
	Care home	0.28%	0.7% - 1%	2.04%	46.94%	0.16%	0.21%
	Leisure centre	0.29%	0% - 0%	2.04%	46.94%	0.16%	0.21%
	Hotel	0.29%	0.7% - 1.1%	2.04%	46.94%	0.16%	0.21%
	Office	0.29%	0.8% - 1.1%	2.04%	46.94%	0.16%	0.21%
	School	0.29%	0.7% - 1.1%	2.04%	46.94%	0.16%	0.21%
	Community centre	0.28%	0.7% - 1%	2.04%	46.94%	0.16%	0.21%
	DIY store	0.29%	0.8% - 1.1%	2.04%	46.94%	0.16%	0.21%
	Light industrial unit	0.30%	0.8% - 1.1%	2.04%	46.94%	0.16%	0.21%
	Warehouse	-	-	2.04%	46.94%	0.16%	0.21%

Table 38: Emissions from biomass systems per unit of floor area (kgCO2e/m2 floor area). Emissions from CH_4, N_2O and CO_2 (GWP = 1) are included. NOTE: units are different from Table 36 (in kg rather than g). Please note that including CO_2 in this way does not reflect the climate impact of biomass systems.

Archetype		Chip boiler	Pellet boiler	HVO	40% BioLPG	100% BioLPG	Bio methane
SG New Build Advanced	Hospital	43	40	27	22	22	20
	Care home	-	32	21	18	18	16
	Leisure centre	42	39	25	21	21	19
	Hotel	137	125	83	69	69	64
	Office	3	3	2	2	2	2
	School	-	14	9	8	8	7
	Community centre	-	16	11	9	9	8
	DIY store	-	20	13	11	11	10
	Light industrial unit	43	39	25	21	21	19
	Warehouse	-	-	26	21	21	20
Current well insulated	Hospital	183	-	112	93	93	87
	Care home	156	143	96	79	79	74
	Leisure centre	128	117	77	64	64	59
	Hotel	121	111	74	61	61	57
	Office	38	35	23	19	19	18
	School	55	50	33	28	28	26
	Community centre	-	56	37	31	31	29
	DIY store	72	66	43	36	36	33
	Light industrial unit	45	41	26	22	22	20
	Warehouse	-	-	33	27	27	25

Archetype		Chip boiler	Pellet boiler	HVO	40% BioLPG	100% BioLPG	Bio methane
Current average insulated	Hospital	259	-	159	132	132	122
	Care home	214	49	131	109	109	101
	Leisure centre	290	-	174	144	144	134
	Hotel	189	49	115	95	95	88
	Office	38	4	23	19	19	18
	School	80	7	48	40	40	37
	Community centre	91	8	56	46	46	43
	DIY store	93	4	55	46	46	43
	Light industrial unit	51888	2374 - 2378	30421	25220	25220	23445
	Warehouse	-	-	50307	41706	41706	38770

Table 39: Relative emissions of biomass compared to gas baseline (gas baseline includes CO_2 emissions). Emissions from CH_4, N_2O and CO_2 (GWP = 1) are all included for biomass. Please note that including CO_2 in this way does not reflect the climate impact of biomass systems.

Archetype		Chip boiler	Pellet boiler	HVO	40% BioLPG	100% BioLPG	Bio methane
SG New Build Advanced	Hospital	230%	211% - 211%	141%	117%	117%	109%
	Care home		211% - 211%	141%	117%	117%	109%
	Leisure centre	236%	216% - 216%	141%	117%	117%	109%
	Hotel	233%	213% - 214%	141%	117%	117%	109%
	Office	238%	218% - 218%	141%	117%	117%	109%
	School		213% - 214%	141%	117%	117%	109%
	Community centre		211% - 211%	141%	117%	117%	109%
	DIY store		218% - 218%	141%	117%	117%	109%
	Light industrial unit	241%	221% - 221%	141%	117%	117%	109%
	Warehouse		0% - 0%	141%	117%	117%	109%

Archetype		Chip boiler	Pellet boiler	HVO	40% BioLPG	100% BioLPG	Bio methane
Current well insulated	Hospital	230%		141%	117%	117%	109%
	Care home		211% - 211%	141%	117%	117%	109%
	Leisure centre	236%	216% - 216%	141%	117%	117%	109%
	Hotel	233%	213% - 214%	141%	117%	117%	109%
	Office	238%	218% - 218%	141%	117%	117%	109%
	School	233%	213% - 214%	141%	117%	117%	109%
	Community centre		211% - 211%	141%	117%	117%	109%
	DIY store		218% - 218%	141%	117%	117%	109%
	Light industrial unit	241%	221% - 221%	141%	117%	117%	109%
	Warehouse			141%	117%	117%	109%
Current average insulated	Hospital	230%		141%	117%	117%	109%
	Care home	230%	211% - 211%	141%	117%	117%	109%
	Leisure centre	236%	0% - 0%	141%	117%	117%	109%
	Hotel	233%	213% - 214%	141%	117%	117%	109%
	Office	238%	218% - 218%	141%	117%	117%	109%
	School	233%	213% - 214%	141%	117%	117%	109%
	Community centre	230%	211% - 211%	141%	117%	117%	109%
	DIY store	238%	218% - 218%	141%	117%	117%	109%
	Light industrial unit	241%	221% - 221%	141%	117%	117%	109%
	Warehouse			141%	117%	117%	109%

Hydrogen

This section presents the detailed results of our assessment of direct emissions from hydrogen combustion. The figures presented here must be interpreted with care, due to the lack of data on N_2O emissions. As elaborated in Section 3.4.4, these results are based on an assumption that the same ratio of N_2O to NO_x for natural gas combustion applies to hydrogen combustion. Further research is required to confirm whether this is an appropriate assumption, or to provide data N_2O emissions.

Domestic archetypes

Table 40 presents the annual emissions for hydrogen boilers for the nine domestic archetypes. Table 41 provides a comparison to the gas baseline.

Table 40: Annual emissions (from N_2O) for domestic hydrogen systems for the 9 archetypes

Archetype		**Annual emissions from hydrogen boiler ($kgCO_2e$)**
New Build	4 bed detached	0.3
	3 bed semi	0.2
	2 bed flat	0.2
Current insulated	4 bed detached	1.0
	3 bed semi	0.6
	2 bed flat	0.5
Current average	4 bed detached	1.9
	3 bed semi	1.2
	2 bed flat	0.6

Table 41: Comparison of hydrogen emissions to the gas baseline.

Archetype		**Comparison to gas baseline gas boiler emissions**
New Build	4 bed detached	<0.1%
	3 bed semi	<0.1%
	2 bed flat	<0.1%
Current insulated	4 bed detached	<0.1%
	3 bed semi	<0.1%
	2 bed flat	<0.1%
Current average	4 bed detached	<0.1%
	3 bed semi	<0.1%
	2 bed flat	<0.1%

Non-domestic archetypes

Table 42 presents the annual emissions for hydrogen boilers for the nine domestic archetypes. Table 43 provides a comparison to the gas baseline.

Table 42: Nitrous Oxide emissions from hydrogen systems per unit of floor area (gCO_2e/m^2 floor area)

Archetype	New build	Existing well insulated	Existing poorly insulated
Hospital	4.9	20.8	29.4
Care home	3.9	17.7	24.3
Leisure centre	4.8	14.5	32.9
Hotel	15.5	13.8	21.5
Office	0.4	4.3	4.3
School	1.7	6.2	9.0
Community centre	2.0	6.9	10.3
DIY store	2.4	8.2	10.6
Light ind. unit	4.9	5.1	5.9
Warehouse	4.9	6.3	9.6

Table 43: Comparison of emissions from hydrogen boilers compared to gas baseline

Archetype	New build	Existing well insulated	Existing poorly insulated
Hospital	0.03%	0.03%	0.03%
Care home	0.03%	0.03%	0.03%
Leisure centre	0.03%	0.03%	0.03%
Hotel	0.03%	0.03%	0.03%
Office	0.03%	0.03%	0.03%
School	0.03%	0.03%	0.03%
Community centre	0.03%	0.03%	0.03%
DIY store	0.03%	0.03%	0.03%
Light ind. unit	0.03%	0.03%	0.03%
Warehouse	0.03%	0.03%	0.03%

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