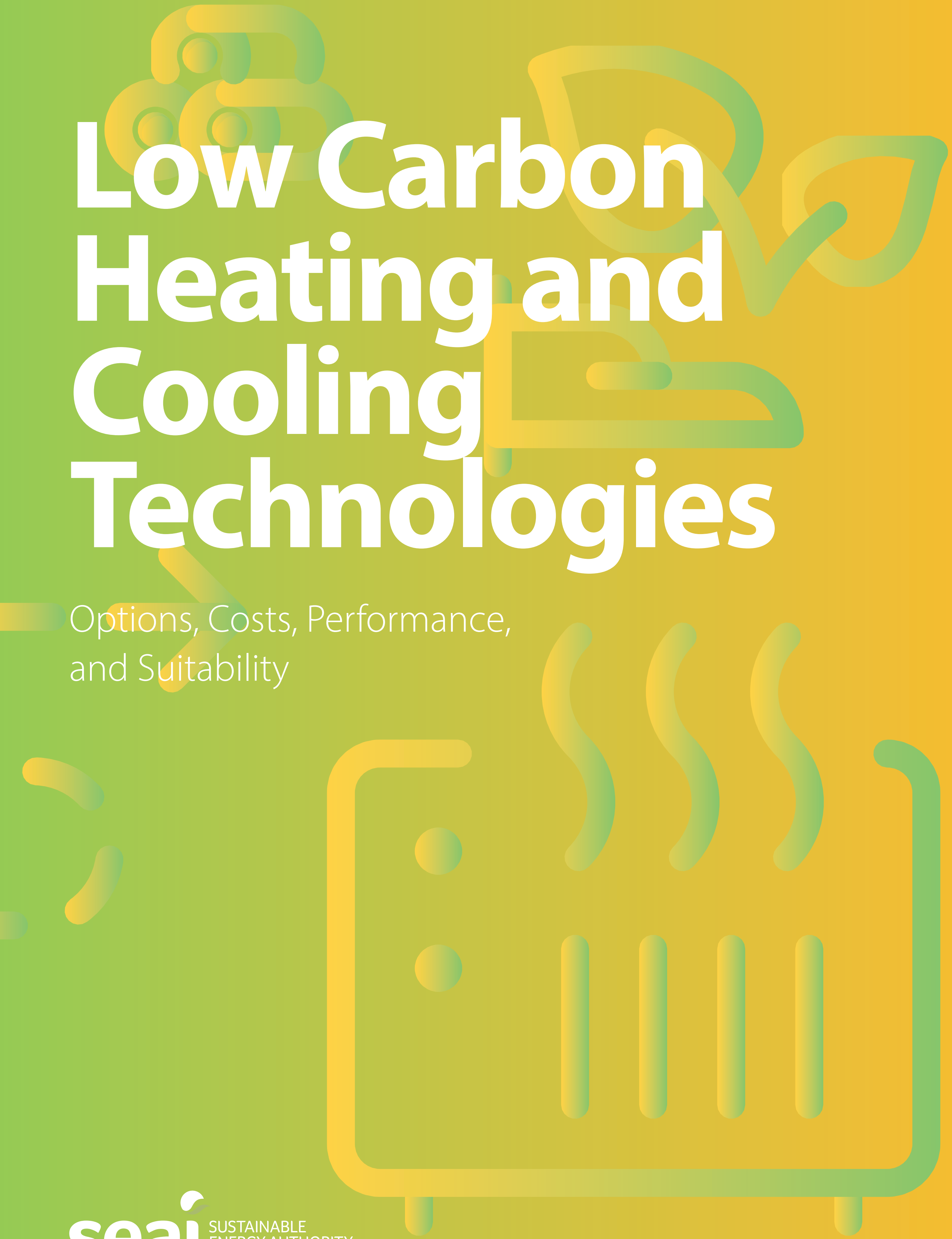
National Heat Study

Low Carbon Heating and Cooling Technologies

Options, Costs, Performance, and Suitability



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ENERGY AUTHORITY
OF IRELAND

Low Carbon Heating and Cooling Technologies

Options, Costs, Performance and Suitability

Report 4 of the National Heat Study

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The National Heat Study and associated reports were commissioned by a project team across the SEAI Research and Policy Insights Directorate and developed with the assistance of Element Energy and Ricardo Energy and Environment.

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Sustainable Energy Authority of Ireland
SEAI is Ireland's national energy authority investing in, and delivering, appropriate, effective and sustainable solutions to help Ireland's transition to a clean energy future. We work with the public, businesses, communities and the Government to achieve this, through expertise, funding, educational programmes, policy advice, research and the development of new technologies.

SEAI is funded by the Government of Ireland through the Department of the Environment, Climate and Communication.

Key insights

Data was collected to describe the cost and performance of over 90 technologies, to provide an evidence base for both current heating in Ireland and a variety of low-carbon heating pathways.
These technologies represent both the technologies that provide heat in Ireland today in the residential, commercial, public, industrial and agriculture sectors, as well a variety of low-carbon heating technologies that can be deployed to varying extent across these sectors. Technology cost and performance is described across a range of sizes, describing the entire range of heating demands and loads in all considered sectors.

The installation of each technology is considered in each building and industrial site across the entire Irish heat sector, providing a detailed description of the extent to which all technologies can help decarbonise heating in Ireland.
This assessment of installing each technology in each building or industrial site allows detailed, consumer-focused, archetype-level modelling within the National Energy Modelling Framework (NEMF). This modelling describes the consumer uptake of low-carbon heating technologies in Ireland in a range of scenarios, and provides a detailed, consumer-level and building-level breakdown of the key technologies adopted in each scenario. The additional costs of installing each technology in each building in the residential, commercial, public, industry, and agricultural sectors are considered, where building-level data allows an accurate description of which buildings would incur additional costs, such as the addition of a wet heating system or the upgrade of existing radiators within a building.

Heat pumps are technically suitable in 78% of existing residential buildings, and in 66% and 47% of existing commercial and public buildings respectively, without energy efficiency improvements.
These values are based on an assessment of the specific peak heat loss rate (W/m^2) and how this impacts required heat pump flow temperatures and therefore system efficiency. This is significantly higher in the residential sector than is considered suitable using typical Heat Loss Indicator (HLI) thresholds. The National Heat Study has used a more optimistic and ambitious threshold for technical suitability in order to explore what may be possible for decarbonisation given the scale of the challenge ahead. The analysis assumes heat emitters are upgraded where required to deliver appropriate flow temperatures and that heat pump installations follow best practice. Programmes supporting heat pump uptake in future will need to make a judgement on the acceptable balance of risk to consumers from low quality installations with the drawbacks of limiting eligibility to high efficiency dwellings.

The technical suitability of heat pumps increases to 82% of existing residential buildings, and to 97% and 98% of existing commercial and public buildings respectively, when all suitable additional fabric energy efficiency measures are deployed. Although heat pumps can achieve high efficiencies in the majority of buildings, high upfront costs for heat pumps may present a significant barrier to uptake of these technologies by consumers in buildings in Ireland. Direct electrification of heating is also considered suitable in all archetypal buildings in these sectors, although this does not utilise the high operational efficiencies of heat pumps.

Low carbon gases such as hydrogen and biomethane have the potential to decarbonise heating in over half of residential, commercial and public buildings, with solid biomass and bioliquid fuels also suitable in significant proportions of domestic and service sector buildings.
If the fuel is available, a maximum of 35% of residential buildings in Ireland can be decarbonised by using hydrogen or biomethane injected into the gas distribution grid, however this number increases to 58% of residential buildings if the gas distribution grid is expanded via the "in-fill" of buildings in close proximity to the network. Similar proportions of service sector buildings can also decarbonise using low carbon gases provided by either existing gas connections or through gas grid expansion. Biomethane is also available as a decarbonisation option to off-grid service sector buildings, providing a potential market for biomethane in future scenarios where the gas distribution grid is either decommissioned or converted to hydrogen. Biomass and bioliquid fuels are also a potential decarbonisation option in off-grid or rural buildings in these sectors, with the domestic resource potential to produce these fuels considered in this National Heat Study.

A wide range of low carbon fuels are available for heating across the Irish industry sector, and electrification of heat, hydrogen, biomethane and biomass fuels all have the potential to decarbonise key industrial sectors.
Half of industrial heating processes have the potential to use direct electrification for heat, with 9% of heating suitable for industrial heat pumps. Biomass and biomethane have the potential to decarbonise 57% and 62% of Irish industrial heating respectively, and 77% of Irish industrial processes can decarbonise using hydrogen with appropriate heating equipment. Boilers, dryers, ovens and furnaces can all decarbonise using a variety of these different fuels. Cement and lime kilns have reduced options for decarbonisation using low carbon fuels, leading to increased likelihood of carbon capture and storage being required for these sites.

A comprehensive description of upfront costs and energy savings from the installation of energy efficiency was produced for a variety of measures in each archetype in the residential, commercial, public and industrial sectors.
These are used as inputs into the archetype-level modelling of decarbonisation of the heat sector in Ireland, one of the benefits of which will be to identify in which buildings and industrial sites energy efficiency measures have the greatest impact on fuel cost and carbon emission savings and can help identify which measures have the best potential for low-cost emissions savings. The interaction between the uptake of energy efficiency and low carbon heating technology in the wider modelling in the Heat Study can also provide insight into how energy efficiency can help enable decarbonisation using certain technologies more dependent on building efficiency for optimal operation, such as heat pumps.

The energy efficiency measures in the residential sector with the lowest payback periods across the entire suitable stock are cavity wall insulation and draught proofing, which both have average payback periods less than 11 years. Average payback periods for other measures are higher than this in the residential sector, and so the fuel cost savings alone resulting from energy efficiency improvements are unlikely to drive high energy efficiency uptake across the entire stock. In commercial and public buildings, energy efficiency measures have lower payback periods on average, with most energy efficiency measures having average payback periods under 10 years in suitable buildings in these sectors, with the exception of high efficiency glazing. In the industry sector energy efficiency measures have the potential to deliver fuel and emissions savings in a cost-effective manner through improving process integration and heat recovery, however these measures are site- and process-specific.

These findings, together with other insights in this report, inform the wider National Heat Study. A final report will analyse net-zero pathways to 2050. The full suite of reports will be available at www.seai.ie/data-and-insights/national-heat-study/.

Acknowledgements

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- Irving Oil Whitegate Refinery
- OFTEC

To avoid doubt, this acknowledgement does not imply endorsement by the stakeholders listed, and this report is solely the work of Element Energy, Ricardo Energy and Environment and the Sustainable Energy Authority of Ireland.

Contents

Executive Summary

Ireland's 2021 Climate Action and Low Carbon Development (Amendment) Act commits to reducing greenhouse gas emissions by 51% by 2030 and to achieving economy-wide carbon neutrality by 2050. This requires immediate emissions reductions in every sector. Energy used for heating and cooling accounts for 24% of Ireland's greenhouse gas emissions, but the current pace of decarbonisation falls short of the cuts required. Almost every sector of Ireland's economy uses heat energy, and decarbonisation efforts will need to be implemented by industry, businesses, and households. This requires a comprehensive, robust and actionable evidence base that policymakers and other stakeholders can use to make decisions.

The Sustainable Energy Authority of Ireland (SEAI) commissioned Element Energy and Ricardo Energy and Environment to work with SEAI on the National Heat Study to provide this evidence base. The study evaluates the costs and benefits of various pathways that reach net zero by 2050. We based the evaluation on a comprehensive understanding of heating and cooling demand in Ireland and the deployment costs, potential and suitability of technologies, infrastructure and fuels to reduce emissions.

We have separated the insights and analysis from the study into eight reports (outlined in *Figure 1)*. These reports provide a rigorous and comprehensive analysis of options for decarbonising heating and cooling in Ireland up to 2050. The findings support Ireland's second submission to the EU of a national comprehensive assessment of the potential for efficient heating and cooling, as required by Article 14 of the Energy Efficiency Directive.[1] There are seven major technical reports, each focusing on topics that form the overall analysis. The concluding report is called *Net-Zero by 2050: Exploring Decarbonisation Options for Heating and Cooling in Ireland*[2]. It outlines the study's key insights across scenarios that achieve net-zero emissions from heating and cooling.

This report, *Low Carbon Heating and Cooling Technologies*, provides an evidence base for the cost and performance of technologies across all sectors considered in this National Heat Study. It also includes an evidence base for the cost and savings from energy efficiency measures in all sectors. It is accompanied by a data workbook[3] with a detailed breakdown of the data describing these technologies and energy efficiency measures. The data collected for this evidence base of heating technologies and energy efficiency measures feeds into the National Energy Modelling Framework (NEMF), which is a detailed modelling framework describing the energy system in Ireland over the next 30 years as the heat sector decarbonises.

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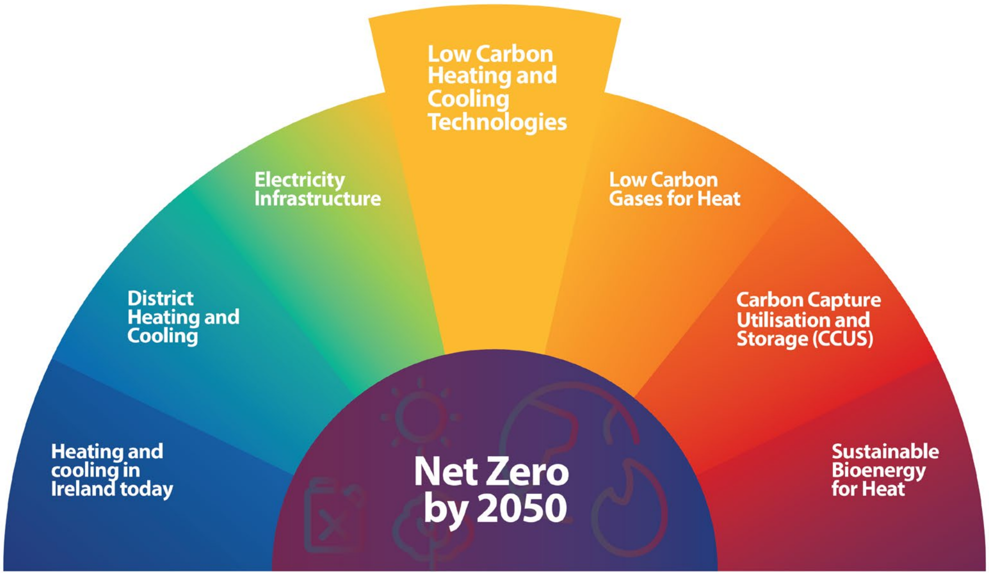
[1] SEAI, 'Comprehensive Assessment of the Potential for Efficient Heating and Cooling in Ireland, report to the European Commission'. 2021 [Online]. Available: https://www.gov.ie/en/publication/e4332-introductory-text-for-publication-of-the-national-comprehensive-assessment-on-govie/#

[2] SEAI, 'Net-Zero by 2050: Exploring Decarbonisation Pathways for Heating and Cooling in Ireland'. 2022 [Online]. Available: www.seai.ie/publications/Net-Zero-by-2050.pdf

[3] Further supporting information is available in Excel for download at https://www.seai.ie/data-and-insights/national-heat-study/Low-Carbon-Heating-And-Cooling-Technologies/

Figure 1: Framework of reports in the National Heat Study

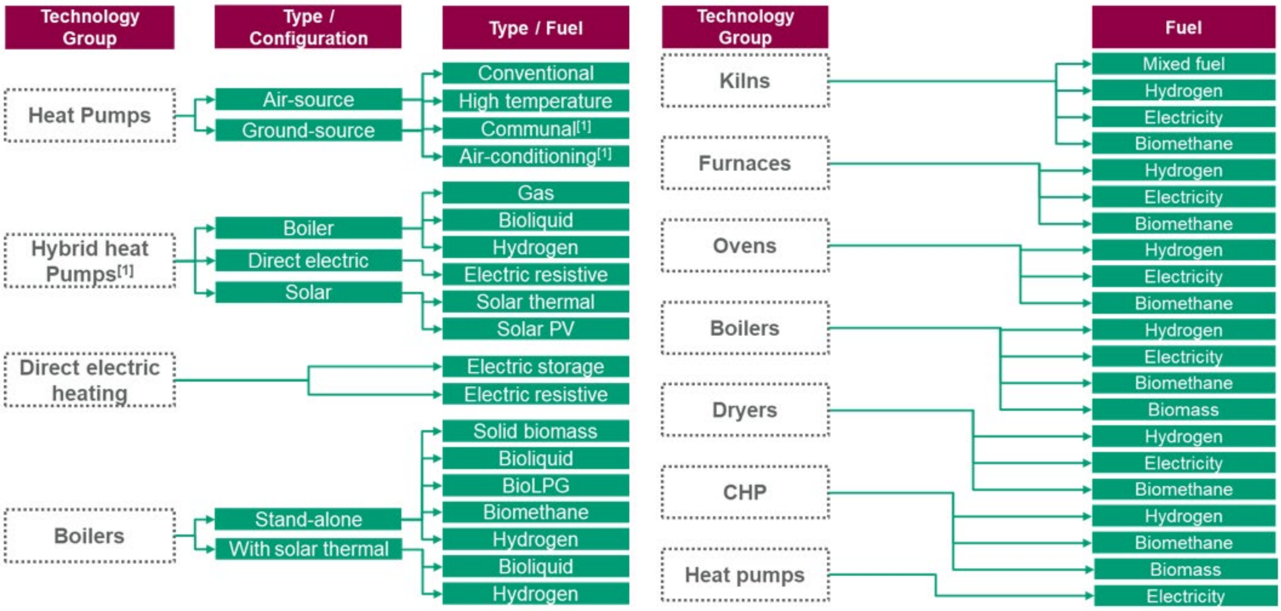


Technologies for buildings and industry

Figure 2 shows the technology groups, configurations, types and fuels considered in the residential sector, commercial, public and agriculture sectors (left), and technology groups and fuels considered for the industry sector on the right. Information on all of these technologies was collected for use in the NEMF (National Energy Modelling Framework), including upfront costs, operational and maintenance costs, fuel costs, hidden costs and performance for a range of sizes of each technology. In the non-industry sectors, a range of fuels were considered, including electricity, biogenic fuels (biogas, bioliquid and solid biomass), and hydrogen. Additional costs beyond the upfront and maintenance costs were also considered for certain technologies in specific archetypes.

In the industry sector, the technology groups cover kilns, furnaces, ovens, boilers, dryers, combined heat and power (CHP) systems, and heat pumps. The primary fuels considered for these technology groups are electricity, biomethane and hydrogen, however some technology groups require specialist fuels, such as cement kilns.

Figure 2: The technology groups, configurations, types and fuels considered in this study.



Energy efficiency

The costs, fuel savings and suitability for several energy efficiency measures in each archetype are considered in the residential, commercial, public and industry sectors. In the residential, commercial and public sectors, these measures include improvements to the fabric efficiency of buildings and improvements to the efficiency of electrical appliances. In industry, improvements to the efficiency of industrial processes were considered. Energy efficiency in the agriculture sector was not considered due to the lack of available data.

Technical potential for low carbon heating in buildings

The heat demand of most buildings is suitable for more than one low-carbon or renewable technology, and all buildings have at least one. Heat pumps are a key decarbonisation option in all sectors, with energy efficiency improvements being a key factor in allowing more buildings to become suitable. 78% of residential buildings, 66% of commercial buildings and 47% of public buildings are suitable for heat pumps without any additional energy efficiency improvements; this rises to 82%, 97% and 98% with maximum energy efficiency improvements in these three sectors. See *Figure 3* for the technical potential of a selection of key technologies in the residential sector, with *Figure 4* and *Figure 5* showing the same breakdown for the commercial and public sectors respectively. Low carbon gases such as hydrogen or biomethane have significant decarbonisation potential, especially in the residential sector; 35% of residential buildings can be decarbonised with low carbon gases, which increases to 58% when considering the potential expansion of the gas distribution network via in-fill connections. Biomass and bioliquid boilers are both suitable in over 50% of residential buildings, and in 14% of buildings in the services sector.

Figure 3: Technical potential for low carbon heating systems in Irish residential buildings.

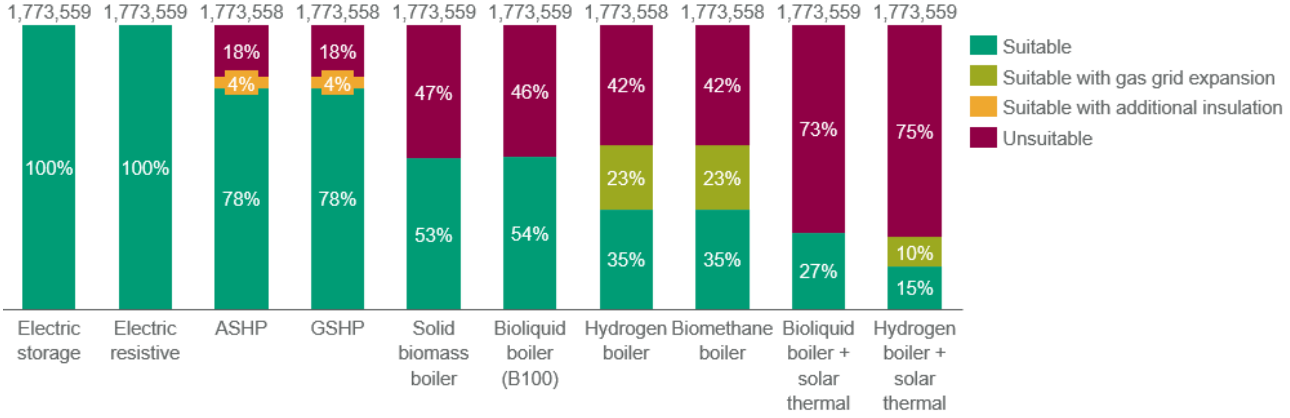


Figure 4: Technical potential for low carbon heating systems in Irish commercial buildings.

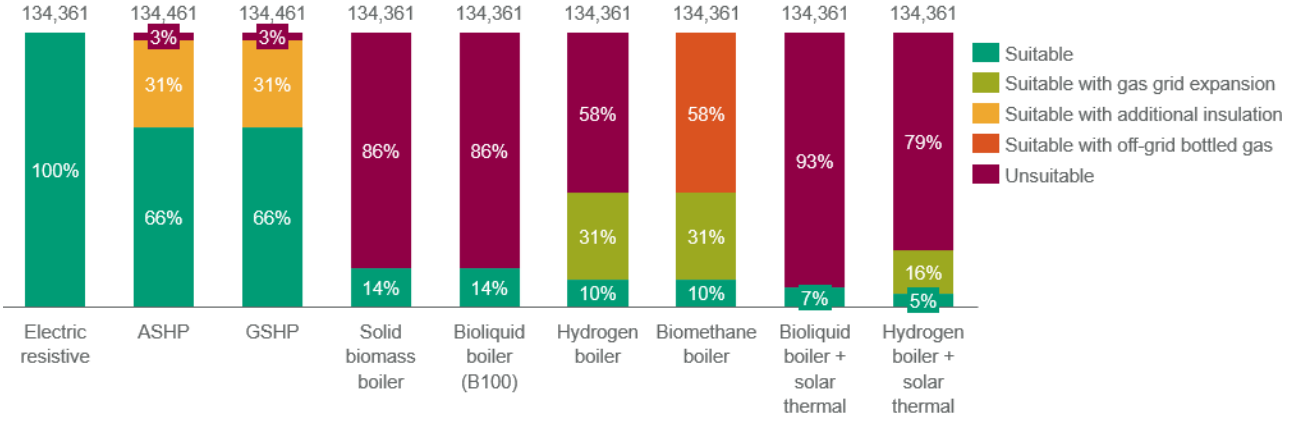
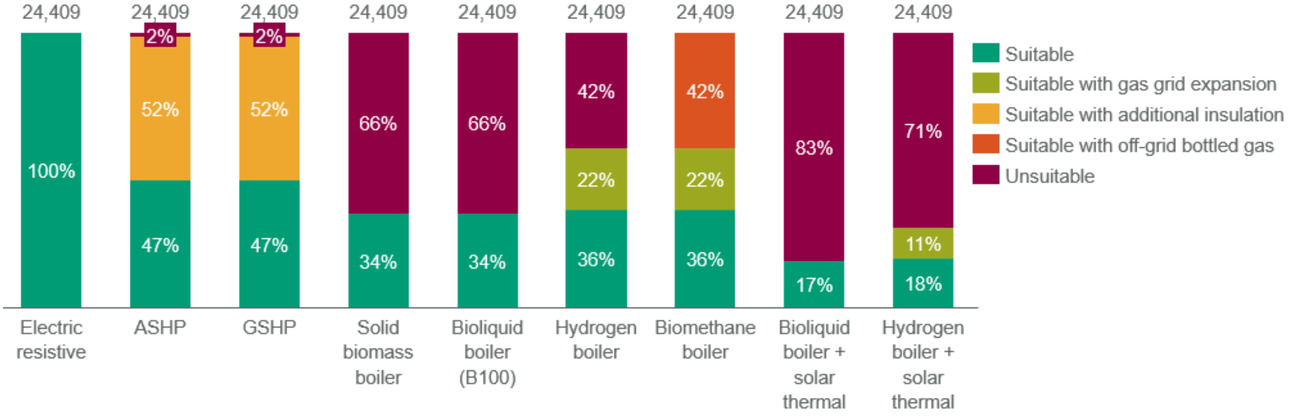


Figure 5: Technical potential for low carbon heating systems in Irish public buildings.



Technical potential for low carbon heating in industry

Most of the industry sector heat demand in Ireland can be decarbonised through technology changes or fuel switching. Various technologies currently serve industry heat demand, including boilers, CHP systems, furnaces, and ovens. This variation reflects the range of processes and temperature requirements of the sector. A range of low-carbon and renewable fuel options are available to decarbonise these technologies, with the suitability of different fuels in each technology type shown in *Table 1* below. These include electricity, hydrogen and biomethane. Over 50% of industrial heat demand in Ireland can be decarbonised via electrification of industrial heating processes, either heat pumps or direct electrification, and over 50% of Irish industrial heating demand can decarbonise using biomass. Over 75% of industrial processes can decarbonise by fuel switching to low carbon gases (either hydrogen or biomethane). The final total uptake of biological fuels (solid, liquid and gaseous) may be limited by resource constraints rather than technology suitability. Some technologies and processes have fewer decarbonisation options because of their temperature requirements or the characteristics of the manufacturing processes. For example, cement or lime kilns emit greenhouse gases from the processing of cement in addition to their energy consumption. Therefore, CCS is key in decarbonising cement manufacture to mitigate both of these emissions sources.

Table 1: Technical potential (GWh) for low carbon fuels in the Irish industry sector for each technology type

Technology Type	Biomass	Biomethane	Electricity	Heat Pump (High temp)	Heat Pump (Med temp)	Hydrogen	Mixed Fuel	Bio and non-bio waste	Total heat demand (GWh)
Boiler	6,499	4,656	6,499	532	1,031	5,875	-	-	**6,499**
CHP	3,498	3,275	-	-	-	3,390	-	-	**3,498**
Cement/lime kiln/calciner	-	-	-	-	-	276 (lime only)	3,079	982	**3,079**
Furnace	-	2,025	-	-	-	2,136	-	-	**2,136**
Dryer	-	338	1,509	-	-	1,294	-	31	**1,509**
Oven	-	488	631	-	-	538	-	-	**631**
Kiln (other)	-	20	133	-	-	67	-	-	**133**
Heat demand potential served by each fuel	9,997	10,802	8,772	532	1,031	13,524	3,079	1,013	**17,486**

1 Introduction

Ireland's 2021 Climate Action and Low Carbon Development (Amendment) Act commits Ireland to reducing greenhouse gas emissions by 51% by 2030 and to achieving economy-wide carbon neutrality by 2050. This requires immediate emissions reductions in every sector. Energy used for heating and cooling accounts for 24% of Ireland's greenhouse gas emissions, but the current pace of decarbonisation falls short of the cuts required. Almost every sector of Ireland's economy uses heat energy, and decarbonisation efforts will need to be implemented by industry, businesses, and households. This requires a comprehensive, robust and actionable evidence base that policymakers and other stakeholders can use to make decisions.

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We have separated the insights and analysis from the study into eight reports (outlined in *Figure 1*). These reports provide a rigorous and comprehensive analysis of options for decarbonising heating and cooling in Ireland up to 2050. The findings support Ireland's second submission to the EU of a national comprehensive assessment of the potential for efficient heating and cooling, as required by Article 14 of the Energy Efficiency Directive [1]. There are seven major technical reports, each focusing on topics that form the overall analysis. The concluding report is called *Net-Zero by 2050: Exploring Decarbonisation Options for Heating and Cooling in Ireland* [2]. It outlines the study's key insights across scenarios that achieve net-zero emissions from heating and cooling.

This report serves as a standalone document detailing the low carbon heating and cooling technologies analysed within the National Heat Study and the key characteristics of the systems used as inputs to the modelling analysis. We present data on the costs, performance, and technical potential of 21 low carbon heating systems suitable for use in the residential, commercial, public, and agriculture sectors. We also present data on a further 21 systems for industry. The report also includes information on each system's technical potential or maximum technically feasible deployment and a discussion of the relationship between a building’s heat loss indicator (HLI) and its suitability for a heat pump. We also discuss the costs, energy savings, and building suitability criteria for the energy efficiency measures analysed.

This report is part of a series of eight reports produced as outputs from the National Heat Study.

1.1 Objectives and scope of this report

The objectives of the work done on heating and cooling technologies described in this report are:

1. Develop a shortlist of low and zero-carbon heating and cooling systems and energy efficiency measures suitable for use in Irish buildings and industry between today and 2050.
2. Gather up-to-date information on the costs, performance, technical suitability, and constraints of these systems, as well as the latest informed views on how these may evolve over time and with increased deployment.
3. Provide a detailed data set including the above data on the technology options considered that may be used for other research in future.
4. Determine the maximum technical potential for individual heating and cooling systems uptake in the Irish building and industry stock.

The results of this work are also essential inputs to the overall National Heat Study. The goals of the overall study are to:

1. Develop a detailed understanding of heating and cooling demand in the residential, services and industrial sectors and the opportunities to reduce this.
2. Assess the potential and costs of the low-carbon technologies and fuels that can decarbonise heat generation.
3. Explore pathways for technology and fuel deployment to reach net zero by 2050.
4. Understand the perspectives of various stakeholders and seek to include data and information from a wide range of sources in the analysis.
5. Provide detailed analysis and useful insights to policymakers, stakeholders, and the public.
6. Build modelling capacity to support further work on policy development.

An overview of the low carbon technologies analysed for individual building and industry sites is provided in Chapter 2 of this report, including data on system performance and costs. Chapter 3 presents details of the energy efficiency measures analysed in the National Heat Study. These cover the potential savings from different measures, their costs, and an assessment of their cost-effectiveness. The technical potential for each low carbon heating system is discussed in Chapter 4. Chapter 5 compares heat pump technical suitability across the Irish building stock using the peak heat loss rate and the heat loss indicator.

In the interest of clarity and brevity, a detailed data set on the low carbon heating and cooling technologies analysed in the National Heat Study is available as an Excel workbook[4], This includes information on the costs, performance, and technical suitability of the low carbon technologies discussed here. The latest costs for technologies and energy efficiency measures were included to ensure the findings of this study are as up-to-date as possible. All prices in the accompanying data workbook are given in units of €$_{2019}$, with the Consumer Price Index used to adjust costs when 2019 costs were not available.

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[4] Further supporting information is available in Excel for download at https://www.seai.ie/data-and-insights/national-heat-study/Low-Carbon-Heating-And-Cooling-Technologies/

2 Low Carbon Heating and Cooling Technologies

A wide variety of technologies and fuels at various stages of development can be used to decarbonise heating, in both buildings and industrial processes. It is important to understand the full range of technology options that will be available in Ireland to decarbonise the heat sector in the next 30 years. This National Heat Study aims to model the cost-effective uptake of different heating and cooling technologies across all sectors in Ireland in a range of scenarios; this report and the accompanying data workbook provide an evidence base for the cost, performance and technical potential of a wide variety of technologies that could play a role in the decarbonisation of heating in Ireland.

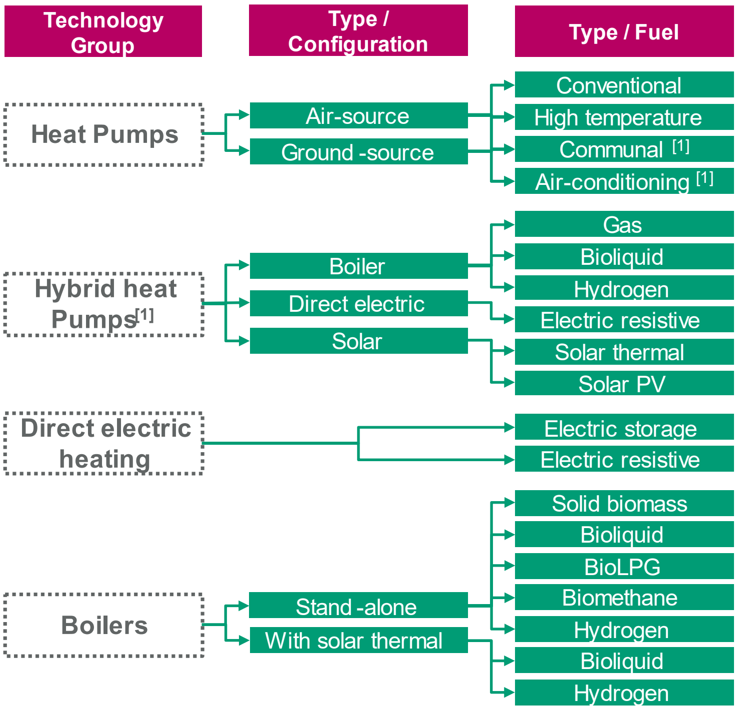
Some of these technologies are ready for deployment in buildings or in industrial processes in Ireland today, whereas some are still at various stages of development. Technology Readiness Levels (TRL) are a standardised description of how ready a technology is for commercialisation from a score of 1 (starting lab development) to a score of 9 (full commercial development). TRLs are defined in further detail below, and scores are also given for each technology. Note there are many interpretations of the TRL scale, with different organisations using different versions. Here we have estimated TRLs according to the Horizon 2020 TRL scale [3].

2.1 Technologies for Buildings

The majority of heating technologies in buildings in Ireland do not currently provide low-carbon heating, and so will need to be replaced with new technologies to decarbonise the heating sector. There is currently significant uncertainty regarding the best technology to decarbonise heating in each building type, with upfront and annual costs seen by the consumers, emissions from use, and impacts from the use of each technology on the wider energy system in Ireland all important considerations. A wide variety of renewable heating technologies for buildings have been considered in this report, across four main groups, as shown in *Figure 6*. The study considers a wide basis of candidate technologies to develop a comprehensive picture of heating in Ireland in 2050 in all types of buildings and industry. Some options may be used to decarbonise relatively few buildings but will nevertheless be critical to decarbonising certain buildings segments and reaching net zero emissions.

Technologies for buildings were modelled as applicable for the residential, commercial, public and agriculture sectors. While buildings across these sectors vary significantly in size, they require similar temperatures for space heating and hot water and hence can be served by the same types of systems. In total, 21 different technologies were modelled. These are discussed in further detail in the sections below. The lifetime of heating technologies for buildings is assumed to be 15 years [4], with the exception of GSHPs (20 year lifetime, [4] [5]) and solar thermal systems (25 year lifetime, [6]).

Figure 6: Heating technologies for buildings, categorised by technology group and type/configuration. [1] indicates technologies modelled only as air-source heat pumps.



2.1.1 Heat pumps

Heat pumps use electrical energy to move heat from the environment into buildings to provide space heating and hot water. Heat pumps are at Technology Readiness Level (TRL) 9. Heat pumps have been at TRL 9 for many years and are readily available for purchase and installation today. We consider air- and ground-source heat pumps for all building subsectors, including conventional (low-temperature) and high-temperature heat pumps. While water-source and exhaust heat pumps are also available, these are not explicitly considered as they are used relatively rarely, and their performance and costs are likely to be between those of air- and ground-source heat pumps. For buildings, high-temperature heat pumps are those producing flow temperatures above 60 degrees Celsius. Heat pumps serving communal heating systems are included for flats in the residential sector. Many already host communal pipework and thermal plant. Communal heat pumps are not considered within the commercial, public, and agricultural sectors as the communal infrastructure is less common. In the commercial and public sectors, reversible heat pumps may be used to provide air conditioning as well as heating.

Several factors can make buildings unsuitable for heat pumps. Space-constrained residential and commercial buildings may not be able to accommodate the internal and external components of a heat pump. A storage cylinder is required for hot water provision, which can be challenging in buildings where one is not already present. However, Irish data shows that most buildings in Ireland already have hot water storage. We have used data on cylinder presence and space constraints from the BER database, as described in the *Heating and cooling in Ireland today* report [7] as part of this National Heat Study.

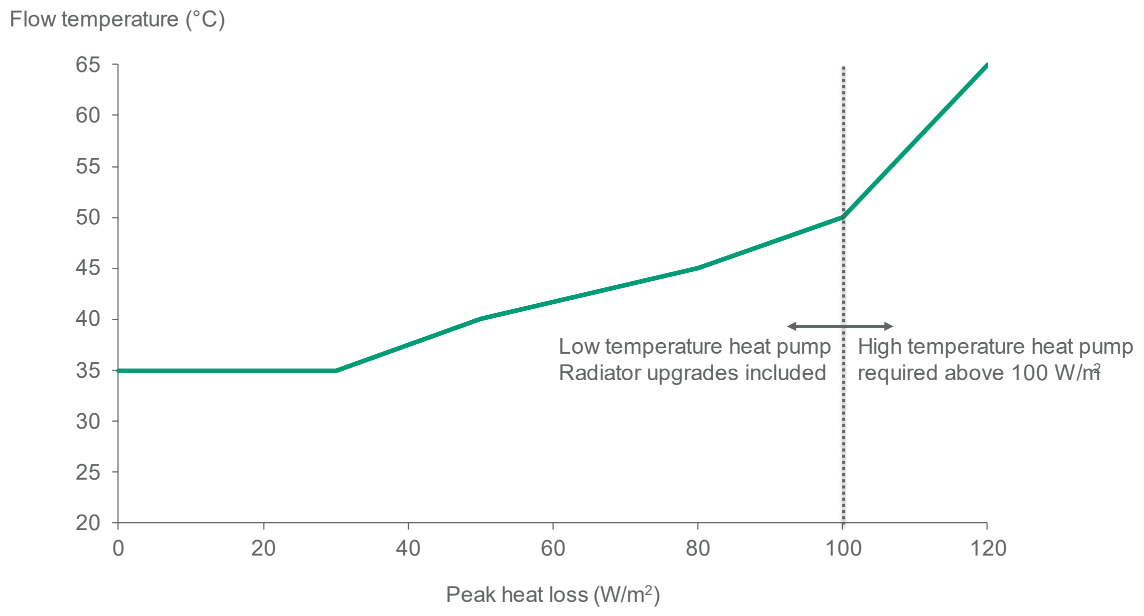
The level of building fabric efficiency required for heat pump installation is a current topic of debate. Our approach in the National Heat Study is to explore what may be possible for decarbonisation of homes and other buildings; we have therefore taken a less conservative approach to heat pump suitability than has been done elsewhere. This introduces a greater need for high quality design of the entire building heating system (beyond selection and installation of the heat pump itself, including upgrading of radiators and pipework where needed), and may place a greater risk of poor system design and resulting performance on the end consumer. However, this more optimistic approach is justified given the scale of ambition required to meet net zero emissions and the technical evidence presented below. Also note that this only relates to technical suitability, not economic suitability; some archetypes with heating demand per unit floor area close to but below this 100 W/m^2 threshold are considered technically suitable, but the resulting cost from this high fuel use to meet this high heating demand could lead to other technologies being preferred when consumer decision making is considered. The NEMF considers heat pumps in competition with other renewable and counterfactual technologies; heat pumps will not be selected for installation within a building unless they are the most cost-effective amongst the technically suitable options.

For all wet heating systems, no matter the heat source, heat is delivered to the building through the radiators. To maintain a constant indoor temperature, the heat delivered by the radiators must match the heat loss to the environment through the building fabric and from air turnover. There are two ways to increase the amount of heat that can be delivered through a wet heating system: increasing the radiator surface area and increasing the flow temperature of the water within the radiators. Therefore, a building with poor fabric efficiency will require either or both of larger heat emitter surface area and higher flow temperature than an otherwise similar building with high fabric efficiency.

Heat pumps operate by moving heat rather than generating it. Electricity is used to move heat against a thermal gradient (i.e. removing heat from the cold environment into a warm building). This enables heat pumps to achieve efficiencies significantly greater than 100% as several units of useful heat energy can be moved using a single unit of electricity. Heat pumps are most efficient moving heat across as small a temperature difference as possible. Because the outside temperature is fixed by weather conditions, the key metric for heat pump operational efficiency is the flow temperature to the radiators. This creates a relationship between building fabric efficiency, the heat distribution system including pipework and radiators, and heat pump operational efficiency. This relationship means that a building with poor fabric efficiency heated with a heat pump has not only a higher demand for heating but will also have a lower heat pump efficiency due to requiring a higher flow temperature.

The UK's Microgeneration Certification Scheme (MCS) creates and maintains standards for low carbon energy products and their installation and certifies installers who adhere to these standards. MCS guidance on domestic heat pump installation and heat emitters recommends an achievable flow temperature based on a building's peak specific heat demand, as shown in *Figure 7* [8]. The NEMF limits uptake of heat pumps in buildings with peak heat loss above 100 W/m^2 (high temperature heat pumps remain an option for these buildings). The MCS guidance on heat emitter sizing indicates that radiators can be upsized to meet a building's peak heat demand using the flow temperatures shown in the figure. The cost of upgrading radiators is included with the cost of heat pump installation (see Section 2.4.3 below).

Figure 7: Relationship between peak heat loss rate and recommended flow temperature *[8]*.



More information on this limit is provided in Sections 0 and 5 below, including how this threshold relates to the heat loss indicator (HLI). Note that the threshold stated here is a purely technical suitability limit, in that a heat pump could heat the building to a comfortable temperature. These same buildings may however be economically unsuitable for heat pumps in that the fuel costs required to provide this level of comfort may be higher than the amount consumers are generally willing or able to pay for heating. The modelling analysis conducted as part of the National Heat Study [9] considers energy efficiency measures combined with renewable heating technologies. When energy efficiency measures are adopted as well, more buildings are both technically suitable and economically suitable for heat pumps. Following the maximum available energy efficiency improvements, only a minority of buildings remain unsuitable for heat pumps due to poor fabric efficiency.

The annual run hours (and daily run hours within the heating season) of a heat pump are typically much higher than those of a boiler. Many consumers will be used to operating their heating systems in a certain way: allowing their building to cool off overnight and during the day while they are away, and then using the high capacity of the boiler to rapidly heat up the building when heat is desired in the morning and evening. This results in a high peak heat output and low total run hours. Heat pumps operate most efficiently when they are run for a higher number of hours each day at a lower heat output. This is because heat pumps are generally sized to meet the peak winter heating demand and are not oversized as is common with boiler installations. Heat pumps therefore steadily replace heat as it is lost to the environment, rather than rapidly raising a building's temperature when heat is desired by the occupants.

The operational profiles assumed for heat pumps in the National Heat Study are based on data collected during a 2015 heat pump trial in the north of England [10]. This gives an expected annual load factor of 23% for domestic heat pumps, compared with less than 10% for boilers. Measured data operational performance of heat pumps unfortunately remains scarce.

2.1.2 Boilers

Fossil gas and oil boilers are the predominant heat generation technologies used in Ireland today. A smaller number of solid fuel boilers are also used[5]. There are a number of low carbon fuels currently available and under development for use with combustion boilers. Five low carbon alternative fuel boilers are analysed here, including biomethane, hydrogen, solid biomass, bioliquid, and bioLPG[6].

Biomethane is chemically identical to fossil gas and can be blended into the gas network at any fraction. In July 2020, biomethane produced via anaerobic digestion was injected into the Irish gas network for the first time [11]. Biomethane is therefore judged to be at TRL 8 because it is not yet fully commercialised in Ireland. In this report, biomethane boilers refer to boilers that use fuel composed of 100% biomethane. This fuel supply could be via a gas grid consisting of 100% biomethane or bottled biomethane transported to the site where the boiler is located. No changes are required to existing fossil gas boilers or pipework to accommodate biomethane.

There are several routes to hydrogen production which are discussed in the *Low Carbon Gases for Heat* report [12] of the National Heat Study. Hydrogen is not currently used for space heating or transported via the gas networks, although trials are underway in several locations across Europe [13], [14]. For biomethane and hydrogen, the primary limitation on building suitability is proximity to the gas distribution network. These fuels are therefore not considered for the agricultural sector. Larger commercial and public sites off of

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[5] Note that the National Heat Study considers only primary heating technologies. Solid fuel stoves are more commonly used for secondary heating which is outside the scope of the study.

[6] Bioliquid refers to B100 biodiesel. BioLPG available in the UK and Ireland is generally HVO, hydrogenated vegetable oil. [50]

the gas network may import bottled biomethane, but this option is not expected to be widespread within the residential sector.

Bioliquid boilers using fuels such as B100 and HVO are currently available (TRL 9) although less widely used than conventional fuels. These are primarily seen as replacements for oil boilers and are stored in tanks on-site in the same way as kerosene, and other fuel oils are currently stored. Similarly, solid biomass boilers use chips or pellets delivered by trucks and stored on-site. These fuels are therefore more suitable for larger homes and buildings with sufficient outside space for fuel storage.

Electric boilers have been excluded from the analysis due to their high operating cost and low efficiency relative to heat pumps and their low prevalence in Ireland to date.

2.1.3 Hybrid heat pumps

Hybrid heat pumps combine a heat pump with a boiler type. We analyse fossil gas, biomethane, hydrogen, and B100 boilers in combination with air source heat pumps. The space required is an important limitation on building suitability for hybrid systems. Proximity to the gas network is also a limitation for fossil gas, biomethane, and hydrogen systems. Hybrid heat pumps are not limited to buildings with low heat loss rate. While the heat pump contributes 80% of a building's annual heat and hot water demand [15], the boiler is able to cover peak winter demand periods, providing top-up heat beyond what can be provided by the heat pump.

We also consider a hybrid system combining a heat pump for hot water provision with direct electric resistive space heating. This is only considered in the residential sector and is primarily used in flats with low space heating demand.

2.1.4 Direct electric heating

Two types of direct electric heating are considered: storage and resistive (both TRL 9). Electric resistive heating here refers to the direct consumption of electricity to produce heat via resistance to electrical flow within wires and heating elements. Electric storage heating involves the same process but then stores the heat (typically in ceramic materials that can absorb lots of heat) to be released later. Based on historical usage and lack of more granular data, storage heating is included only in the residential sector. Resistive heating is an option in all buildings sectors. Currently, it makes up a high fraction of heating in the commercial sector. A hot water storage cylinder, i.e. an immersion heater, is required with all direct electric heating systems.

In the residential sector, the rating of the dwelling's fuse determines how much incoming electrical capacity from the grid it has. This quantity can place a constraint on the installation of electric heating. We assume a typical domestic fuse limit of 80 Amps, corresponding to a power draw of about 19 kW. In practice, some margin must be reserved for lighting and appliances within the home, resulting in a maximum power available for heating of between 13 and 15 kW. Note that this limit is not explicitly considered for heat pumps because their peak electrical demand will be 2 to 3 times lower due to their high efficiency.

Electric vehicles further contribute to dwelling electricity demand and will become more common in future. However, it is expected that smart charging will allow electric vehicle loads to be managed overnight without limiting the power available for other uses. Therefore, we have assumed that the margin reserved for lighting and appliances is also sufficient to cover future demand from electric vehicles. The incoming electrical capacity limit is not present in other sectors which are more likely to have a three-phase electricity connection.

In this study, direct electric heating technologies are considered renewable as they provide low-carbon heat when the electricity used is low-carbon. The renewable energy mix of grid-supplied electricity modelled in this study is modelled to align with the EirGrid TES electricity scenarios [16]. These scenarios outline scenarios with > 70% renewable energy share for electricity by 2030. The Climate Action Plan published in 2021 sets a target of 80% for the share of power generation that comes from renewable sources [17]. If these technologies were installed today, these technologies would be providing heat with much lower associated carbon emissions than fossil fuel combustion technologies by the end of the system lifetimes.

2.1.5 Solar technologies

The model considers solar thermal and solar PV installations (both TRL 9) in combination with other low carbon heating technologies. Solar thermal is analysed as a supplement to hydrogen and biomethane boilers and to air source heat pumps. Solar PV is considered in combination with air source heat pumps, where the electricity generated by the PV can offset electricity consumption by the heat pump. These options apply to all buildings sectors. Flats and apartments are excluded on the basis that dedicated roof space is required for solar installations. In the absence of detailed information on building and roof orientation, we assume that 50% of buildings are suitable for solar thermal or solar PV.

2.1.6 Heat pumps for cooling

Cooling for commercial and public buildings is considered at a high level within the National Heat Study. Heat pumps are already the typical source of cooling in these subsectors, and this is not expected to change as the energy system is decarbonised although design for passive cooling may reduce cooling demand in new construction [18]. Cooling in residential dwellings has not been considered in this study due to the low existing cooling demand for residential properties in Ireland. Future projections for the Irish climate suggest that the requirement is unlikely to rise significantly by 2050 or beyond. For more information, please see the *Heating and cooling in Ireland today* report in the National Heat Study [7].

2.1.7 Systems covered elsewhere in the National Heat Study

Further detail on several technologies discussed in this report is provided elsewhere in the National Heat Study. District heating is discussed in greater detail in the *District Heating and Cooling* report [19] in the National Heat Study. Geothermal heat for use across the heat sector is discussed in greater detail in the *Heating and cooling in Ireland today* [7] and *District Heating and Cooling* [19] reports. The treatment of decarbonisation in the industry sector by CCUS (carbon capture, utilisation and storage) is discussed in greater detail in the *Carbon Capture Utilisation and Storage (CCUS)* report [20]. Considerations surrounding resource availability and production routes of various biomass fuels is discussed in the *Sustainable Bioenergy for Heat* report [21].

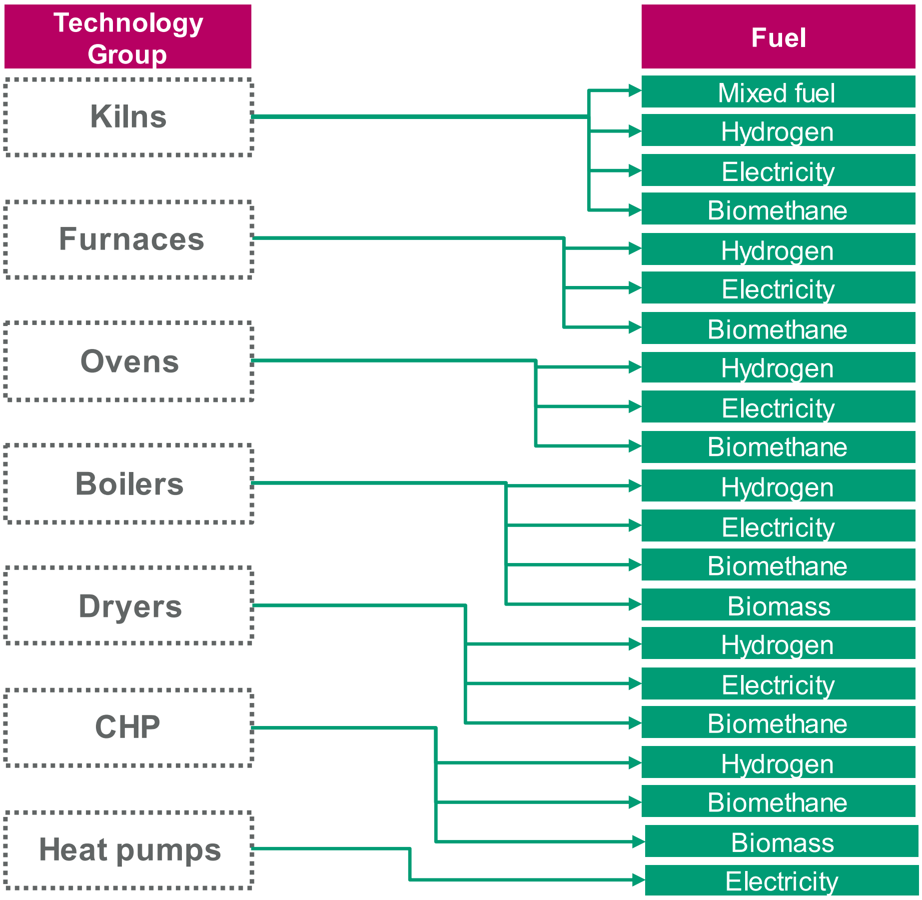
This study does not consider an exhaustive list of technologies that could decarbonise the heat sector in Ireland. For example, geothermal energy is used in other countries to power district heating networks, although it is not considered in this study. The Geological Survey Ireland (GSI) has carried out several detailed evaluations of geothermal energy potential. These data and recent studies, provided by Geological Survey Ireland (GSI), were key inputs to our analysis. High resolution and robust data is available in Ireland to depths of 400m. Beyond this depth significant further potential may exist but there is significant uncertainty about the potential and realisably. Ongoing research funded by GSI and SEAI is seeking to put a suitability framework in place for depths below 400 m but a robust data set does not as yet exist. Hence, the focus for this report is on geothermal potential for up to 400 m. However, it should be noted that using geothermal for heat for depths up to 400 m would require heat pump technology, so it is considered under GSHP and no separate category is included for geothermal energy. Water source heat pumps are also not considered for uptake in the heat sector. Their suitability is highly site-specific as they require a nearby body of water as a heat source. This data is not readily available at an archetype level, so these were not considered.

2.2 Technologies for Industry

A wide variety of renewable heating technologies for the industry were considered in combinations of technology group and renewable fuel, as shown in *Figure 8* below. These technology groups include the range of existing technologies used for heat in the industry sector today (boilers, kilns, furnaces, ovens, dryers, and combined heat and power systems), as well as heat pumps. A total of 21 technologies were modelled. The technologies are generally suitable in both ETS (Emissions Trading Scheme) and non-ETS sites with the exception of Cement/Lime Kilns in Ireland; all existing Cement/Lime Kilns in Ireland are currently included within the ETS scheme, and so these technologies are only considered suitable for the relevant sites (which are all ETS sites).

The primary fuels considered are hydrogen, electricity, and biomethane. These are suitable for most industrial technology groups considered. In addition to this, solid biomass is suitable for a number of technology groups. Mixed fuel (a combination of biomass, solid mineral fuel, and both biogenic and non-biogenic wastes) is also considered for use in kilns.

Figure 8: Heating technologies considered in the industrial sector.



2.2.1 Cement/lime kiln

Cement and lime kilns require very high temperatures (above 900 deg C) to produce materials used in construction and other industries. Cement kilns in particular, require fuel with a high carbon content, and they typically use coal, coke, and heavy oils as fuels. Therefore, low carbon fuel options must also provide the carbon needed for the manufacturing process. Biological and non-biological wastes (i.e. bio and non-bio MSW), which are between TRL 4 and 7, can meet these needs. Hydrogen is an additional suitable option for lime kilns, which is currently between TRL 6 and 9.

2.2.2 Ceramic kiln

Kilns used for ceramics also require high temperatures (up to 1500 deg C) but are somewhat more flexible in terms of fuel use. Electricity (TRL 4-7), biomethane (TRL 6-9), and hydrogen (TRL 6-9) are low carbon options for ceramic kilns. As with all gas systems, proximity to the gas network is a key requirement for the use of hydrogen and biomethane kilns. While small and medium industrial facilities may use fuels delivered in pressurised containers, this is less practical for larger sites due to the scale of demand.

2.2.3 Steam boilers

Boilers are one of the most common heating systems in the industry sector. They are used to produce steam for process use at temperatures up to 1,000 deg Celsius. As with boilers for space heating, steam boilers can be designed to use many different fuels. Low carbon options include electricity, solid biomass, liquid biofuels, biomethane, and hydrogen. The suitability considerations for industrial boilers are similar to those for buildings, including proximity to the gas network for gaseous fuels and the requirement to have storage space for liquid biofuels and solid biomass on site. While storage volumes for industrial sites can be considerable, this is generally less of a barrier to uptake than in the buildings sectors. Issues around air quality with biomass are generally less of a concern for industrial sites than in other sectors as they are typically outside of urban areas and have a greater ability to filter particulates from flue gases.

2.2.4 Combined Heat and Power (CHP)

Industrial CHP facilities have similar decarbonisation options to boilers. They can be decarbonised through conversion to biomethane, liquid biofuels, solid biomass, or hydrogen. Liquid biofuels are likely to be a niche application for sites without connection to the gas network that may convert from oil and LPG fuelled CHP. Note that the CHP systems considered here are exclusively for on-site use by industry. CHP systems for district heating are considered in the *District Heating and Cooling* report [19] of the National Heat Study. An alternative is to replace fossil CHP systems with electricity supplied from the grid and a low carbon heat source, either a boiler or heat pump depending on the temperatures required.

2.2.5 Ovens, furnaces, and dryers

Ovens, furnaces, and dryers provide process heating in a range of industries. Furnaces typically deliver temperatures over 400 deg C, while the temperatures produced in ovens and dryers vary from 100 deg C to 400 deg C depending on the application. Electricity, biomethane, and hydrogen are suitable for ovens, furnaces, and dryers, subject to similar suitability considerations as faced by boilers and CHP systems.

2.2.6 Heat pumps

Heat pumps are suitable replacements for industrial applications requiring both hot water and process steam. We consider both medium temperature heat pumps (producing hot water up to 100 deg C) and high-temperature heat pumps (producing steam at up to 200 deg C). Both of which are currently commercially available (TRL 9). Higher temperature heat pumps are also under development (TRL 4-7) but are not analysed within the National Heat Study due to uncertainty in costs and timeline for commercial availability. Absorption heat pumps are not explicitly considered as replacement technologies within the study. These are heat pumps powered by a heat source other than electricity and are likely to be used for industrial energy efficiency via improved process integration, as outlined in Section 3.1.3 below.

2.2.7 Refrigeration

Industrial cooling is considered only at a high level within the National Heat Study. Heat pumps are already the typical cooling source in industry, and this is not expected to change as the energy system is decarbonised.

2.3 System performance

2.3.1 Efficiency of building heating technologies

Figure 9 shows the assumed efficiency of the various heating systems considered for use in the residential, commercial public and agricultural sectors. Heat pump efficiency is shown further below in *Figure 10*. These efficiencies range from 100% for direct electric technologies to 80% for hydrogen boilers. The gas boiler efficiency represents the typical operational efficiency of boilers. Condensing boilers can perform at efficiencies above 90%. This requires low flow and return temperatures which are not always achieved in practice, particularly in older or less efficient properties. Hydrogen boilers have the same efficiencies as gas boilers using the lower heating values of the fuels considered, and it is the conversion to using the higher heating values of the fuels that gives the difference in the two efficiencies. These efficiencies are taken from the Committee for Climate Change's 6th Carbon Budget Assumptions Log [15], updated in line with Ireland-specific data collected via stakeholder engagement with industry groups. The accompanying data workbook[7] provides further detail on these efficiency assumptions and how they may improve over time. These efficiencies are for newly installed technologies. The efficiency of the technologies already installed in existing buildings is calculated for each archetype using data in the domestic and non-domestic BER databases, capturing the reduced efficiency observed in older systems which are less likely to be condensing boilers.

Figure 9: Efficiency of heating systems for the residential, commercial, public, and agriculture sectors, excluding heat pumps.

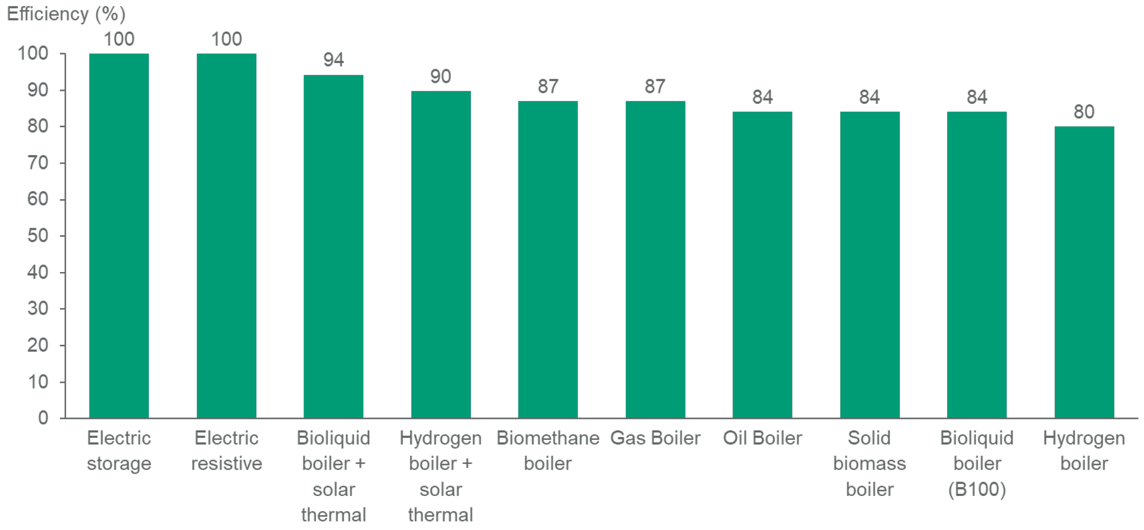


Figure 10 shows the assumed efficiencies of ground source heat pumps (GSHPs) and air source heat pumps (ASHPs), as a function of flow temperature. The efficiency is calculated in terms of heat energy provided divided by fuel energy consumed. As heat pumps consume electricity to transfer heat rather than to produce it, their coefficient of performance ('efficiency') is greater than 100%. Heat pumps require less electricity per unit of supplied heat when operating at lower flow temperatures. Heat pump efficiency also depends on the external temperature, which of course varies daily and seasonally. The seasonal coefficient of performance (SCOP) is calculated by dividing the total annual heat provided by the total annual electricity consumed. The efficiencies shown in *Figure 10* reflect the annual efficiency of space heating given the flow temperature on the X-axis.

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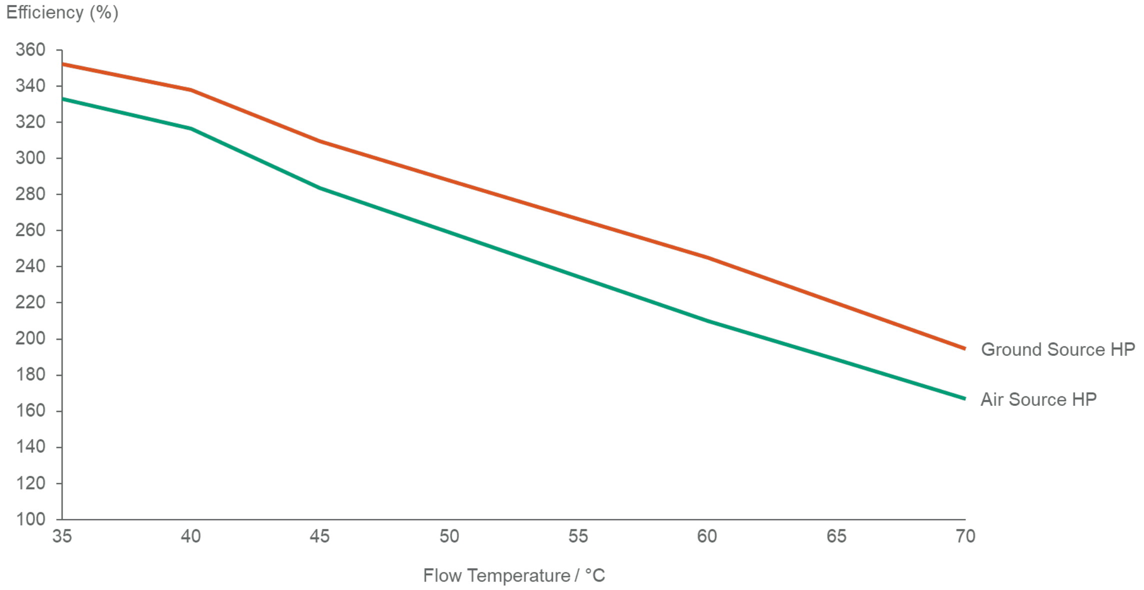
[7] Further supporting information is available in Excel for download at https://www.seai.ie/data-and-insights/national-heat-study/Low-Carbon-Heating-And-Cooling-Technologies/

Even at the highest flow temperatures, the heat energy supplied per unit of fuel consumed is significantly higher than even the most efficient fuel combustion technologies or direct electric heating technologies (shown in *Figure 9* above). The flow temperature and resulting SCOP are determined individually for each archetype within the model. This process is discussed further in Section 5 below.

Figure 10: Ground- and air-source heat pump seasonal efficiency as a function of flow temperature.

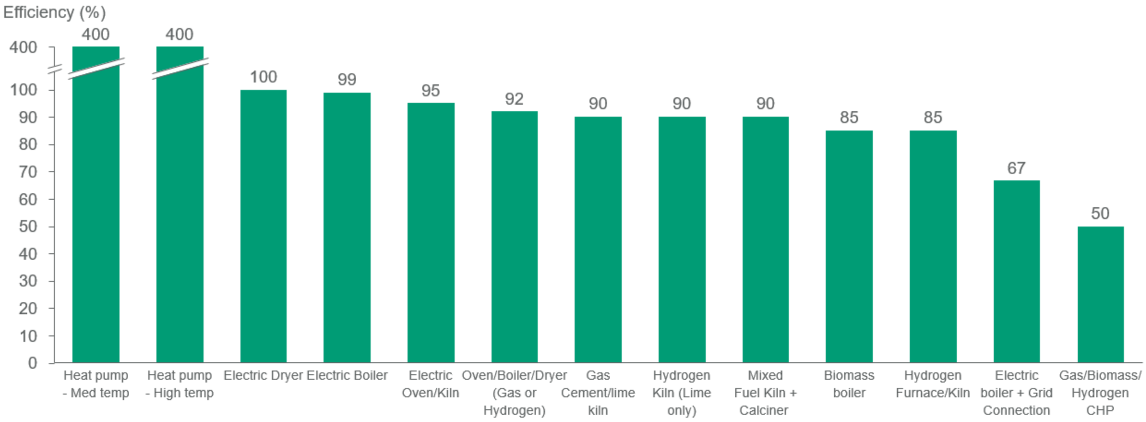


Hybrid technologies consist of a heat pump providing a base heating load and another technology (e.g. a gas boiler) providing the remaining heating demand. The heat pumps in hybrid technologies supply heat at a flow temperature of 40 °C (and therefore operate with an efficiency of 320%), with any increase in flow temperature required provided by the other component of the hybrid technology. The heat pump component of a hybrid is assumed to provide 80% of the heating demand, with the remainder supplied by the other technology component.

2.3.2 Efficiency of industrial heating technologies

Figure 11 gives the modelled efficiency for a selection of industrial heating technologies and for various fuels (both fossil and renewable). These are the assumptions for both existing technologies and technologies that are considered for installation in the modelling. For the CHP (combined heat and power) systems, the assumed heating efficiency of 50% is shown below.

Figure 11: Efficiency of heating systems for the industrial sector. For CHP systems, only the heating efficiency is shown.



2.4 System costs

The costs of all counterfactual and renewable systems include both a fixed capex (€) and marginal capex (€ / $kW_{thermal}$) to describe the costs of these systems at the range of sizes necessary to be considered in the range of sizes of buildings considered in these sectors. The operational costs have also been considered on both a fixed and marginal basis where relevant. As with the efficiencies, these were updated using a range of sources and via stakeholder engagement with various Irish industrial groups. This section presents the costs of a selection of heating technologies across the various sectors. To allow all technology costs to be fully comparable and transparent, a base year of 2019 was selected. Cost data from other years was converted to real 2019 € using the Irish Consumer Price Index (CPI). Any costs in other currencies were first converted to € and then inflated to their 2019 real values using the CPI.

2.4.1 Cost of residential heating technologies

Figure 12 shows the total upfront cost of a range of thermal combustion heating technologies and electrical heating technologies in the residential sector, at a range of different sizes [22] [23] [24] [25] [26] [27]. The total cost of the combustion technologies generally scales less with increasing size as these systems are typically oversized to meet hot water demands and allow short heat-up times if heating is used intermittently. For example, a gas boiler may deliver 12 kW or more to when charging a hot water tank although the building peak heat demand is less than 6 kW. The upfront cost of heat pump systems is also generally higher than for boilers.

Figure 12: Upfront cost of heating systems for the residential sector. Left: boilers. Right: other systems.

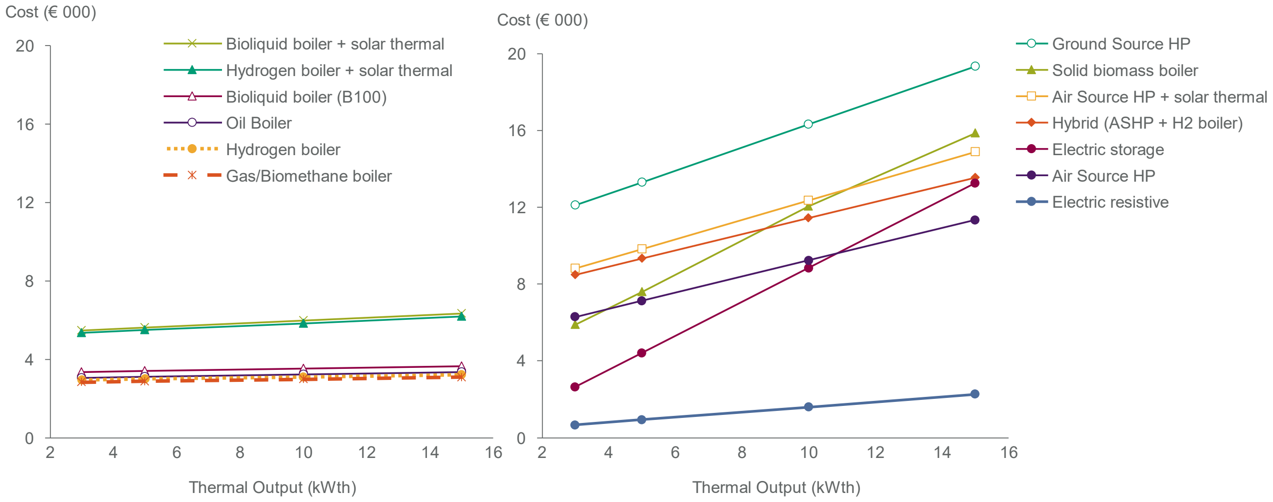
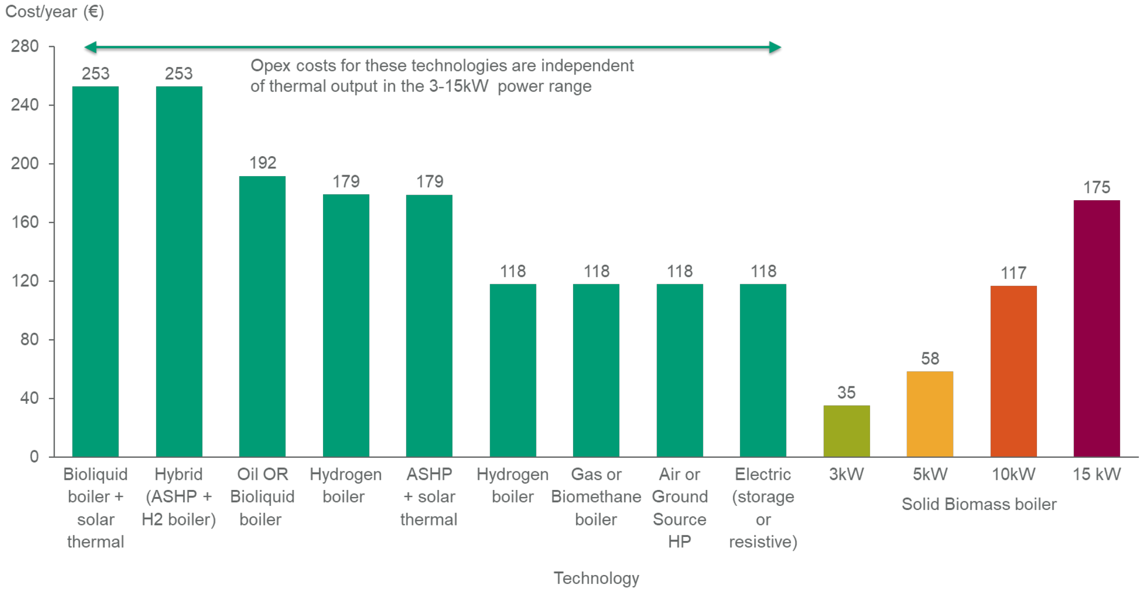


Figure 13 shows the annual operational costs of these systems in units of € / year. Combustion technologies have higher maintenance costs than electrical technologies due to the additional damage caused by high combustion temperatures, thermal cycling, and the emissions generated in the combustion process. Note that these only include typical operational and maintenance costs, and do not include the typical annual fuel costs of these technologies. These fuel costs are covered in Section 6 below.

Figure 13: Annual maintenance costs for heating systems in the residential sector.



2.4.2 Cost of heating technologies for the commercial, public, and agriculture sectors

The range of sizes of technologies required by buildings in the commercial, public and agricultural sectors is generally much larger than for the equivalent technologies in the residential sector. The heating demands in services sector archetypes also vary more widely, from small retail Commercial archetypes to large healthcare and education archetypes.

Figure 14 below shows the upfront cost of heating systems in the commercial, public and agricultural sectors [22] [23] [24] [25] [26] [27]. This graph shows that boiler technologies vary in upfront cost less than heat pump technologies. The sizing of boilers to meet peak heating demands more flexibly is also a feature in heating system design for service sector buildings. The electric resistive technology has the lowest upfront cost of all electrical technologies as it is the simplest electrical technology in terms of the number and complexity of components.

Figure 14: Upfront cost of heating systems in the commercial, public, and agricultural sectors.

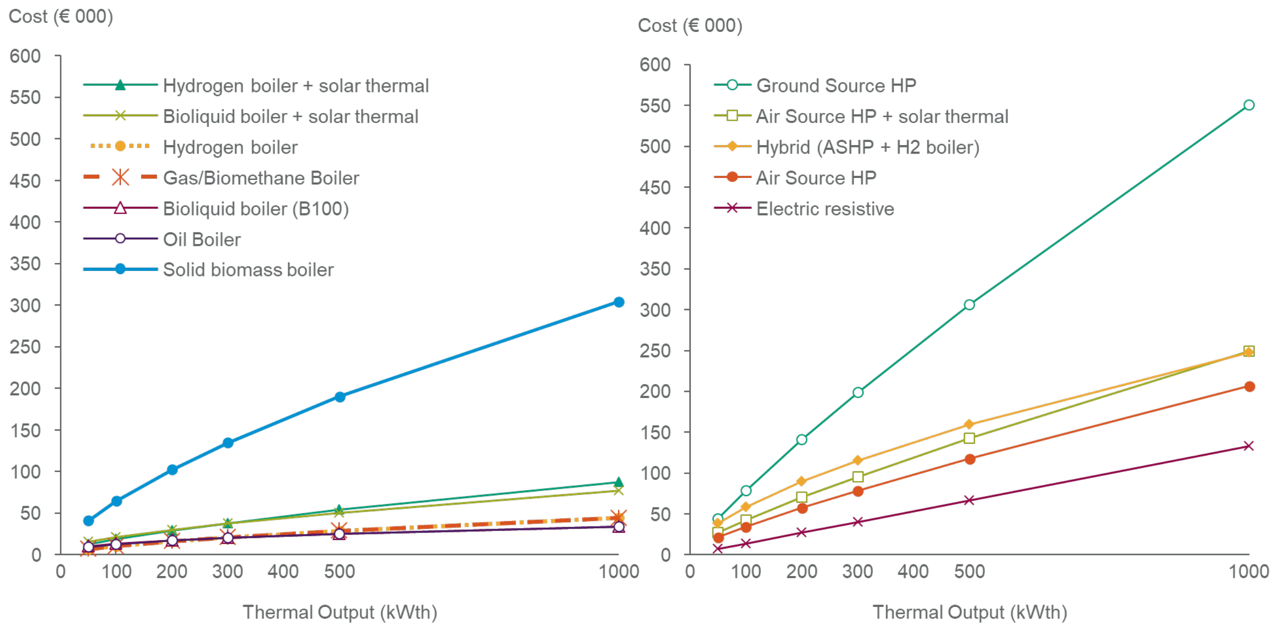
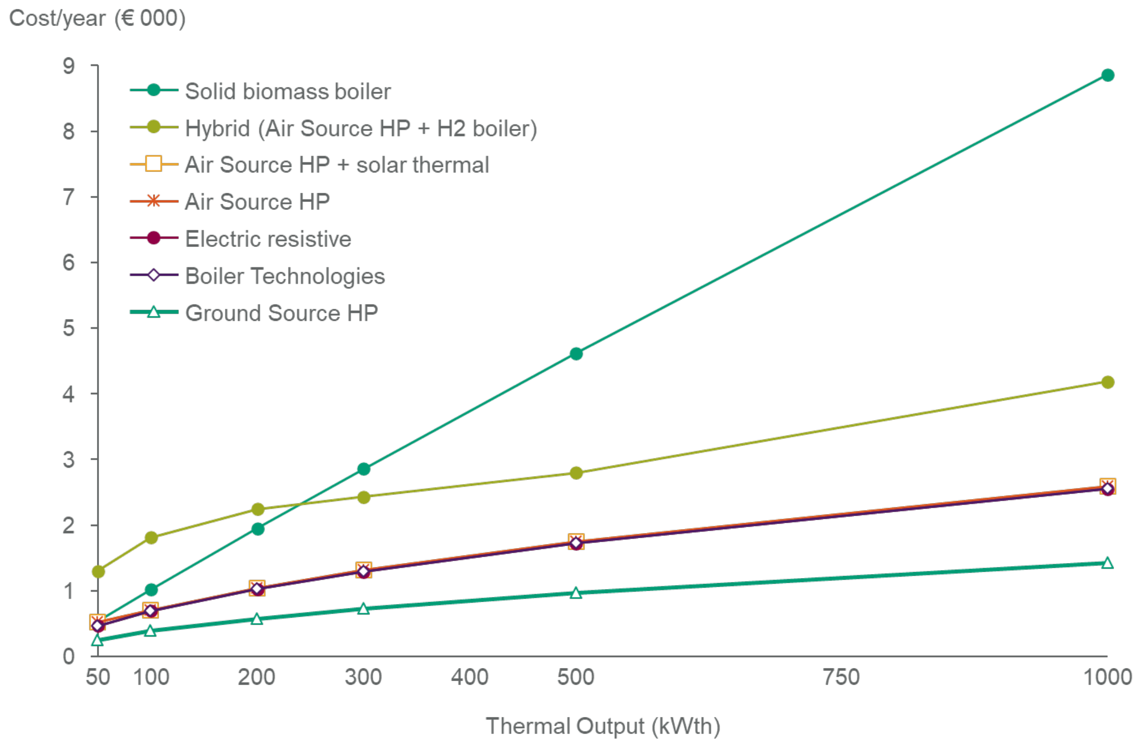


Figure 15 below shows the annual maintenance costs of technologies in the commercial, public and agriculture sectors as a function of technology size. Again, these costs do not include the annual fuel costs, which are covered in Section 6 below.

Figure 15: Annual maintenance costs of heating systems in the commercial, public, and agricultural sectors. Boiler technologies include gas, biomethane, oil, hydrogen, and bioliquid systems.



2.4.3 Additional costs for technologies in the residential, commercial, public and agriculture sectors

Some technologies require costs in addition to the upfront cost of the technology before installation. These cover the costs of additional components required for the effective use of a given technology. These include additional wiring required by direct electric technologies, upgrading existing radiators for more effective heat distribution that heat pumps may require in some homes, and adding a gas distribution network connection for properties without an existing connection. *Table 2* below gives the additional costs included for consideration in this study and the relevant systems for which these additional costs apply [23] [28] [29] [15] [30] . *Table 3* gives a breakdown of the costs included, in terms of upfront costs (€), marginal costs that scale with the system size (€ / $kW_{thermal}$), or area dependent costs (€ / m^2). For more information, please see the accompanying data workbook, where further sources are provided.

Table 2: Source of additional costs when installing low carbon heating systems for the first time. These costs apply to the residential, commercial and public sectors.

Additional cost	Relevant systems
Resistive electrical wiring	Electric resistive heating
Storage electrical wiring	Electric storage heating
Wet heating system removal	Electric resistive or storage heating
Wet heating system addition	Electric resistive or storage heating
Radiator upgrades	Conversion from a CF boiler to air- or ground-source heat pump
Hydrogen in-building pipework and hy-ready boiler switchover	Hydrogen boiler
Gas network connection	Biomethane or hydrogen boiler, if not already connected to gas
Buffer tank	Air- or ground-source heat pump, including hybrid systems
Hot water cylinder (180 L)	Heat pumps and electric heating, if cylinder not already present
Communal distribution system – terraces (per dwelling)	Communal air source heat pump, if communal heating not already present
Communal distribution system – flats (per dwelling)	Communal air source heat pump if communal heating not already present

Table 3: Additional costs incurred when converting to a low carbon heating system for the first time. These costs apply to the residential, commercial, and public sectors.

Investment Required	Fixed capex (€)	Marginal capex (€/kWth)	Area dependent capex (€/m^2)
Resistive electrical wiring		157	3
Storage electrical wiring		206	16
Wet heating system removal	236		6
Wet heating system addition	1473		6
Radiator upgrades	1429		3
Hydrogen in-building pipework and hy-ready boiler switchover		12	
Gas network connection	289		
Buffer tank	170		
Hot water cylinder (180 L)	1225		

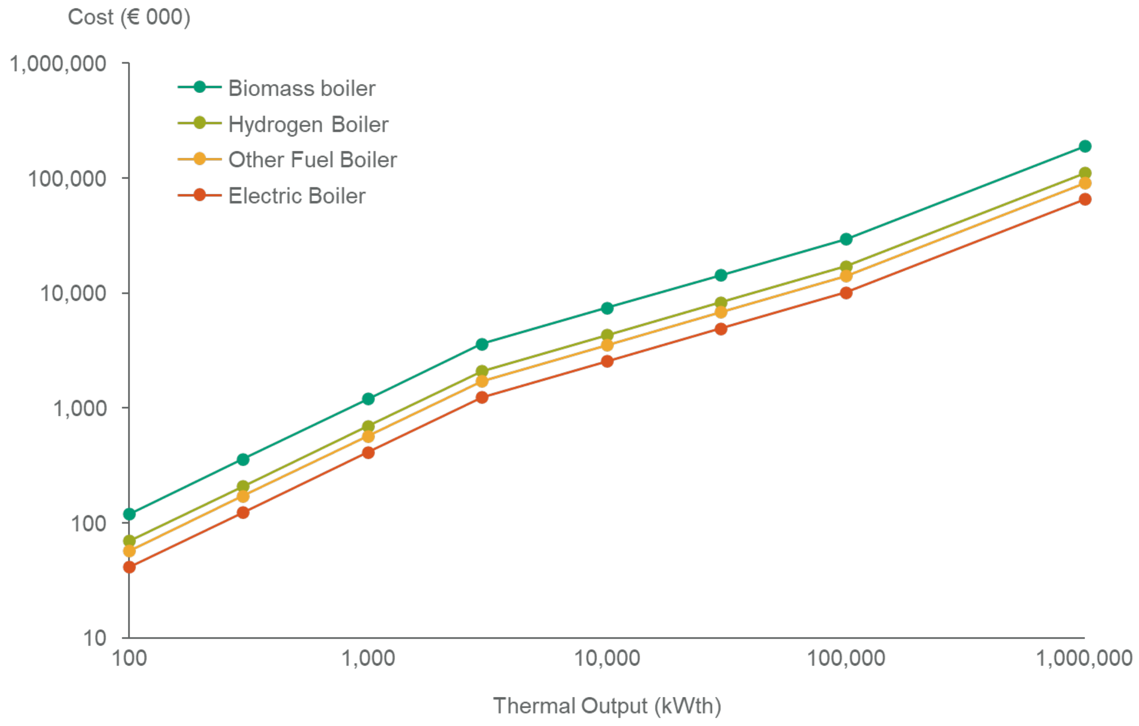
Communal distribution system – terraces (per dwelling)	7122		
Communal distribution system – flats (per dwelling)	3230		

One or more of these costs in *Table 3* may apply in the case of a change of heating technology, and except where indicated, they are independent of property type. Wiring costs are associated with the introduction of electrical heating, a wet heating system is required with any heat pump or boiler-based system and radiator upgrades are associated with heat pump technology adoption.

2.4.4 Cost of heating technologies for the industrial sector

The upfront costs for a selection of industrial technologies and both fossil and renewable fuels is given below in *Figure 16* (boilers), *Figure 17* (CHP plants), and *Figure 18* (kilns) [31] [32] [33] [34]. Note that due to the large range of sizes and costs for these technologies, these industrial costs are presented on a log scale on both the cost and thermal output axes. The operational and maintenance costs are assumed to be 2%[8] of the upfront capex for all industrial technologies at all sizes.

Figure 16: Capital cost of industrial boilers. Other fuel boilers include biomethane, gas, and oil boilers. Please note log scale.



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[8] Based on Element Energy internal estimates.

Figure 17: Capital cost of industrial CHP systems and heat pumps. Other fuel CHP systems include biomethane, gas, and oil. Please note log scale.

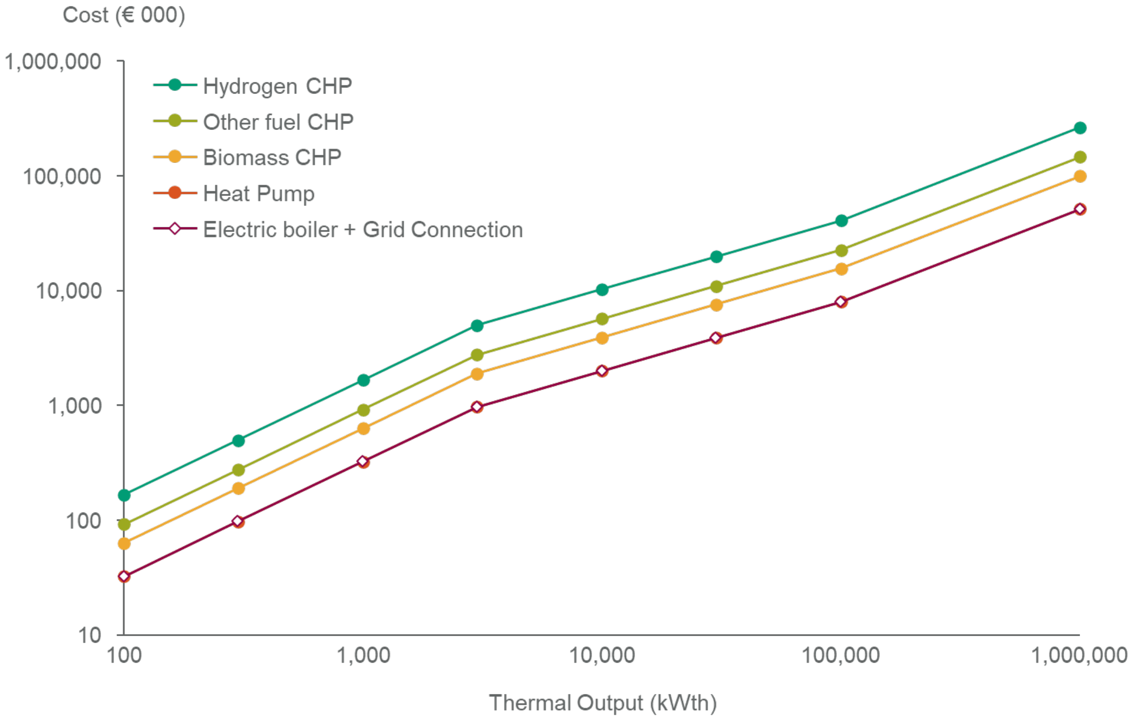
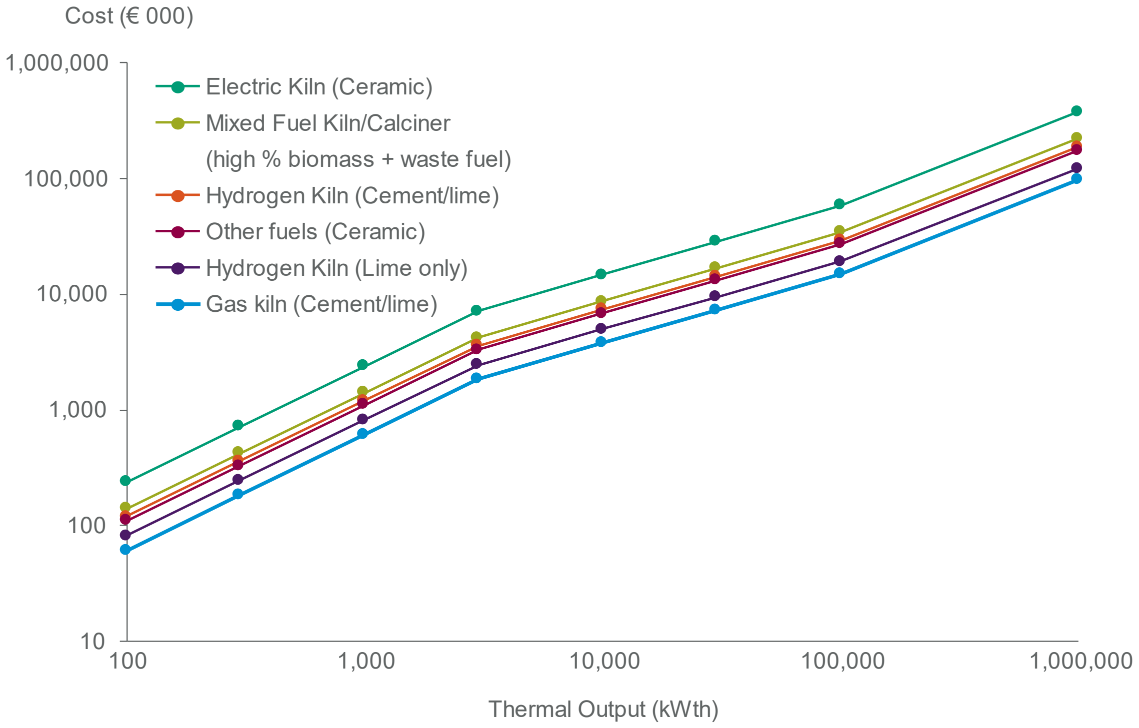


Figure 18: Capital cost of industrial kilns for cement, lime, and ceramics. Other fuels include gas and biomethane for ceramic kilns. Please note log scale.



3 Energy efficiency measures

Energy efficiency measures are considered in the residential, commercial, public, and industrial sectors combined with low carbon heating technologies. While energy efficiency measures cannot eliminate a building's carbon emissions, they are an important contributor to the decarbonisation of heating. In addition to reducing annual demand for heat and improving thermal comfort, energy efficiency measures can improve the suitability of a building for low carbon heating systems (particularly heat pumps), allow heat pumps to operate at lower temperatures improving their efficiency and further reducing fuel costs, and reduce the demand on the electricity network at peak times.

The typical energy savings and costs for individual energy efficiency measures in the residential, commercial, public and industrial sectors are provided in the following sections. The analysis presented here includes the simple payback period for energy efficiency given the existing heating systems in use across the Irish building stock.

The measures analysed in the buildings sectors (residential, commercial, and public) include both building fabric efficiency improvements and changes to more efficient lighting and appliances of several types. In the industrial sector, measures include improved process integration and heat recovery and improved efficiency of motors, air compression, and refrigeration.

3.1 Savings and suitability of energy efficiency measures

The methodology for energy efficiency savings and costs builds upon the methodology developed for the Unlocking the Energy Efficiency Opportunity report [35] (and its accompanying technical appendix [36]). Residential savings were estimated using Domestic Energy Assessment Procedure (DEAP) simulation outcomes. The savings and costs were updated to match the latest BER database and the Residential Cost Optimal report [37] and inflated to real 2019 values.

The tables below summarise the savings and suitability for energy efficiency measures in the residential, commercial, public and industrial sectors. These are also presented in the *Heating and cooling in Ireland today* report [7]. The costs for these measures are explained in further detail in Section 3.2 below.

Measures that improve the energy efficiency of buildings in the residential, commercial and public sectors do this by replacing existing insulating materials with materials that better insulate the property, or by adding additional insulating material to properties where no such material exists. Each fabric material or arrangement of multiple fabric materials has a thermal transmittance (also known as a U-value) which is a metric intrinsic to material that describes the rate of transfer of heat through the materials. A lower U-value corresponds to a higher level of insulation. The energy efficiency measures considered in this study reduce the assumed U-value of types of building fabrics (e.g. walls, windows, flooring) in each archetype. For each measure there is a suitability threshold U-value, below which it is assumed the archetype's existing level of insulation for that fabric type is already sufficiently insulated. If an archetype has a U-value below the threshold suitability U-value for a specific measure, the measure is not considered in this archetype.

3.1.1 Energy efficiency in the residential sector

The U-values presented for the measures in *Table 4* below are taken from the 2018 Cost Optimal report [37]. The method to determine these U-values is as follows:

1. For each energy efficiency measure, consider all U-values present in Table 3.2 of the Cost Optimal report [37], alongside the cost per unit area of fabric improvement from the report. These costs (inflated to a 2019 cost basis) are presented in *Table 8* below.
2. Determine the suitability of these measures in each archetype modelled, using the latest BER database and the methodology developed for the Unlocking report [35]. The suitable stock for each measure is given in *Table 4* below.

3. Calculate the total engineered savings if each measure was applied to the entire suitable stock, using the DEAP model.
4. Select the U-value which has the lowest upfront cost per kWh savings across the entire stock; this U-value is then considered for all archetypes.

For more information regarding the technical potential and savings for each measure, please see the *Heating and cooling in Ireland today* report [7].

Table 4: Suitability constraints and average fuel savings for energy efficiency measures in the residential sector.

Measure	Target value (all buildings above this value considered suitable)	Total properties suitable for measure	Average measure fuel savings / % (before calibration for rebound effect: (SH) = space heating fuel savings, (E) = total electricity fuel savings)
Cavity wall insulation	0.31 wall U-value [37][a], only cavity walls suitable	200,000	11% (SH)
Solid wall insulation	0.22 wall U-value [37][b], only solid walls suitable	535,000	17% (SH)
High efficiency glazing	0.9 window U-value [37][c]	1,310,000	15% (SH)
Floor insulation	0.22 floor U-value [37][a]	316,000	6% (SH)
Roof insulation	0.11 roof U-value [37][b]	981,000	5% (SH)
Draught proofing	Infiltration rate of $5m^3/m^2.hr$	894,000	3% (SH)
Energy efficient lighting	100% efficient lighting (LED lightbulbs)	1,193,000	5% (E)
Energy efficient appliances - "Cold" and "Electrical cooking"	According to previous work [36]; updated in line with archetype updates.	1,407,000	7% (E)
Energy efficient appliances - "Wet" and "Consumer electronics"	According to previous work [36]; updated in line with archetype updates.	1,099,000	5% (E)

a: Option 1, Table 3.2, 2018 Cost Optimal Report; b: Option 2, Table 3.2, 2018 Cost Optimal Report; c: Option 3, Table 3.2, 2018 Cost Optimal Report

3.1.2 Energy efficiency in the commercial & public sectors

The suitability thresholds, target U-values, suitability and average savings for energy efficiency measures in the commercial and public sectors are presented below in *Table 5*. The values given in this table are based on prior work developed for the Unlocking the Energy Efficiency Opportunity report [35], updated to align with the latest non-domestic BER database. The measure is applied to an archetype if the suitability threshold is better than the archetype's existing fabric U-value; if this is the case, then the fabric is improved to the level given in the target U-value. More information on these U-values, total suitable stock and savings for each measure is provided in the WS1 report.

Table 5: Suitability thresholds, target values and average fuel savings for energy efficiency measures in the commercial and public sectors.

Measure	Suitability threshold	Target value	Total suitable stock	Average measure fuel savings / % (SH) = space heating fuel savings (E) = electricity fuel savings
Cavity wall insulation	> 0.6 wall U-value, only cavity walls suitable	0.55 wall U-value	26,000	10% (SH)
Solid wall insulation	> 0.6 wall U-value, only solid walls suitable	0.35 wall U-value	70,000	12% (SH)
High efficiency glazing	> 2.8 window U-value	0.9 window U-value	96,000	27% (SH)
Roof insulation	> 0.3 roof U-value	0.25 roof U-value	108,000	16% (SH)
Draught proofing	> 2.8 window U-value	Reduction in infiltration by 1/3 or infiltration rate of 10 m^3/m^2hr, whichever is larger	96,000	6% (SH)
Energy efficient lighting	All buildings except buildings with 100% energy efficient lighting based on survey	100% energy efficient (LED) lighting	159,000 (not all lighting in all buildings suitable)	23% (E), -9% (SH)
Energy efficient appliances - Office equipment	All buildings are suitable	Dependent on sector [36]	82,000	4% (E), -2% (SH)

Energy efficient appliances - Refrigeration	All buildings are suitable	Dependent on sector [36]	78,000 (number of properties with active cooling)	1% (E), -1% (SH)

3.1.3 Energy efficiency savings in the industry sector

Table 6 and *Table 7* below describe the energy efficiency potential savings in the industry sector. The savings are broken down by potential savings for different industrial processes. Note that the savings for process integration and heat recovery are dependent on industrial process and industrial subsector. The savings for the other processes are independent of the industry subsector and only dependent on the industrial process. Information about how these savings were determined is provided in the *Heating and cooling in Ireland today* report [7].

Table 6: The energy efficiency measures considered for implementation in industry, with the industrial processes for which each measure reduces energy use. Also given is the potential savings for each measure.

Industrial process	Energy efficiency measure	Percentage savings in industrial process / %
High temperature process	Process integration and heat recovery – high temperature processes	Dependent on industrial sector (see *Table 7* below)
Low temperature process	Process integration and heat recovery – low temperature processes	Dependent on industrial sector (see *Table 7* below)
Drying/separation	Process integration and heat recovery – drying/separation	Dependent on industrial sector (see *Table 7* below)
Motors	Improved motor efficiency	20%
Compressed air	More efficient compressed air systems	30%
Lighting	More energy-efficient lighting	19%
Refrigeration	More efficient refrigeration	24%
Space heating	More efficient HVAC	14%

For all measures except the ‘process integration and heat recovery’ measures (the first three rows in *Table 6*), the percentage savings from each measure are independent of the industrial sector. For the ‘process integration and heat recovery’ measures, the potential energy savings from the implementation of these measures depend on the industrial sector due to differences in existing efficiency and grade of heat between processes in industrial sectors. The savings for all three heat recovery & process integration measures are shown in *Table 7* below, for each industrial sector. For all other measures, the savings are independent of industry sector, as shown in *Table 6* above.

Table 7: The potential savings for process integration and heat recovery measures, broken down by industry. The potential savings are equal for high temperature processes, low temperature processes, and for drying/separation.

Industrial sector	Percentage savings for process integration and heat recovery
Cement	7%
Chemicals	11%
Food and Drink	20%
Lime	7%
Metals	3%
Refining	11%
Wood Products	10%
Other Minerals	7%
Other Industry	15%

3.2 Costs of energy efficiency measures

3.2.1 Residential sector

The costs for the five building fabric upgrades (cavity wall insulation, solid wall insulation, high efficiency glazing, floor insulation and roof insulation) were taken from the Cost Optimal report [37], Table 5.5a. These costs are given in units of €/m^2 of fabric area to be installed, and reflect the cost of the fabric insulation itself, but not costs of labour or installation. The cost for each insulation improvement was taken for the corresponding U-values in *Table 4* above, and are given in *Table 8* below.

Table 8: The capex per unit fabric area installed for each fabric energy efficiency measure improvement. The costs are taken from Table 5.5a of the Cost Optimal Report, Section 1 – Residential Buildings.

Energy efficiency measure	Capex per unit area of fabric improvement (€/m^2)
Cavity wall insulation	14.7
Solid wall insulation	116.7
High efficiency glazing	364.9
Floor insulation	332.9
Roof insulation (covering flat and pitched roofs)	137.0
Draught proofing	5.4

The hidden costs for the residential energy efficiency fabric improvements are the same as in the previous work conducted for the Unlocking report [36]. These hidden costs represent project administration costs, project disruption and additional engineering costs.

3.2.2 Commercial and public sectors

The costs for the energy efficiency improvements in the commercial and public sectors are based on the Unlocking the Energy Efficiency Opportunity report [36]. For the fabric energy efficiency improvements, the costs per unit area (or unit length, for draught-proofing measures) are taken from the 2013 Non-Residential Cost Optimal report [38] and inflated to 2019 costs.

The maximum potential for measures installed in each archetype is a key input in determining the total heating and emissions savings in each archetype and in total in the commercial and public sectors. The potential for each measure in each archetype, and the amount of fabric area that would be replaced in each archetype with each energy efficiency improvement was based on the previous work conducted for the Unlocking report [36], updated to align to archetype changes in the latest non-domestic BER database. The costs from the 2013 Cost Optimal report [38] were used as this is consistent with the technical potential and archetype heating demand savings values calculated as part of the previous Unlocking work.

As in the residential sector, the hidden costs for the commercial and public fabric energy efficiency improvements are the same as in the previous work conducted for the Unlocking report [36].

3.2.3 Industry sector

The costs for the energy efficiency improvements in the industrial sector vary by measure and are given in *Table 9* below. A cost-dependent parameter unit was chosen for each energy efficiency measure, with a capex and opex per parameter unit determined. These parameters are given in the second column of *Table 9* below. This aligns with the previous method used to determine the costs for industrial energy efficiency measures in the Unlocking report. The savings, capex (both upfront and hidden) and opex were updated from the previous work for the Unlocking Report [36] using a range of sources; these are given in the accompanying data workbook[9].

Table 9: Capex, opex and hidden cost per for energy efficiency savings in industrial processes. For the values marked with an asterisk (*), please see the note below the table.

Measure	Parameter unit	Variable capex (€ per parameter unit)	Opex (% of capex)	Hidden cost (% of capex)
More efficient HVAC and ventilation	Floor area (m^2)	3.3	2.5%	15%
More efficient refrigeration	MWh final energy consumption per archetype per year	9.2	2.5%	15%
Motor efficiency	MWh final energy consumption per archetype per year	52	2.5%	15%
More efficient compressed air systems	MWh final energy savings per archetype per year	219	2.5%	15%
More energy-efficient lighting	Floor area (m^2)	5.7	0.0%	15%

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[9] Further supporting information is available in Excel for download at https://www.seai.ie/data-and-insights/national-heat-study/Low-Carbon-Heating-And-Cooling-Technologies/

Process integration and heat recovery - high-temperature processes	MWh fuel saved	89[10]	2.5%	15%
Process integration and heat recovery - low-temperature processes	MWh fuel saved	89[10]	2.5%	15%
Process integration and heat recovery – drying/separation	MWh fuel saved	89[10]	2.5%	15%

3.3 Cost-effectiveness of energy efficiency measures

Energy efficiency measures generally have an upfront cost paid at the point of installation, and then provide cost savings for consumers as fuel consumption decreases due the energy efficiency improvements. These upfront costs and annual fuel savings can be used to determine a payback period, which represents the length of time after which the energy efficiency measure will have recovered the entire upfront cost due to the annual fuel cost savings. The payback period for each measure is used to determine the uptake of energy efficiency measures in the modelling underpinning this study; more information about this process and how it is used is given in Section 5.2. The average payback periods (an indicator of the cost-effectiveness of the measures) for energy efficiency measures are given by sector in the tables below. For each measure in each archetype, the sum of the upfront capex and hidden costs were divided by the sum of annual fuel cost savings and any annual opex savings resulting from the measure. To calculate the fuel cost savings in each archetype, the 2020 fuel costs for the fuel consumed by each archetype's counterfactual heating system were used. These payback periods are aggregated across all archetypes in each sector in the tables below and are exclusive of any grants or financial support.

The term 'rebound effect' is used broadly to describe the effect whereby the reduction in energy use observed after carrying out an energy efficiency measure is less than predicted by simple engineering models. This phenomenon is linked to the tendency of such simple engineering models to over-estimate the energy use of poorer performing dwellings which occupants often under-heat in order to reduce their energy costs. When building efficiency is improved, savings are less than predicted by engineering models due to 'comfort-taking' as the occupants are now able to heat the building to a more comfortable temperature. In this study, we account for rebound effects in the residential sector by calibrating the expected heating demand savings; the method is explained in further detail in the *Heating and cooling in Ireland today* report [7] in this National Heat Study. While the occupants' cost savings will be less than predicted, they will also benefit from improved dwelling comfort. This rebound effect calibration is therefore accounted for after the payback period has been calculated for each measure, and so does not affect uptake of energy efficiency measures. This calibration does however reduce the expected heating demand savings in the buildings where it is applied, and therefore reduces the emissions savings from reduced fuel use.

3.3.1 Residential sector

The stock-weighted average payback period for energy efficiency measures in suitable buildings in the residential sector is given in *Table 10* below. There is a wide range of average payback periods, from 3.4 years for energy-efficient appliances to nearly 300 years for floor insulation. Note that these are the average payback periods across the whole sector; these are calculated in-model for each archetype when considering uptake of energy efficiency.

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[10] The variable capex values presented for the three 'process integration and heat recovery' measures are for non-ETS industrial sites excluding industrial sites in the 'Metals' subsector, which have a cost of 159 € per unit. For ETS industrial sites, these costs vary by industrial subsector; for industrial sites in the 'Cement', 'Lime' and 'Other Minerals' subsectors these values are 68 € per MWh fuel saved; for industrial sites in the 'Wood Products' subsector these values are 39 € per MWh fuel saved; for industrial sites in the 'Food and Drink' subsector these values are 42 € per MWh fuel saved; for all other industrial subsectors, these values are 89 € per MWh fuel saved, as in the table above.

Table 10: The average payback period of energy efficiency measures in the residential sector, using sector-specific 2020 fuel costs.

Measure	Payback period (years)
Cavity wall insulation	10.9
Draught proofing	10.9
Energy efficient appliances - "wet" and "consumer electronics"	12.4
Energy efficient appliances -"cold" and "electrical cooking"	3.4
Energy efficient lighting	8.3
Floor insulation	298.0
High efficiency glazing	44.7
Solid wall insulation	45.4
Roof insulation	17.4

3.3.2 Commercial and public sectors

The stock-weighted average payback period for energy efficiency measures in suitable buildings in the commercial and public sectors are given in *Table 11* below, by sector. Generally, payback periods for energy efficiency measures are lower than in the residential sector due to the higher fuel costs in services sector archetypes. A high proportion of commercial and public buildings use electricity for direct heating which has a high cost per unit heat supplied, and so energy efficiency measures are generally more cost effective. Note that as in the residential sector, these are the average payback periods across the whole sector; these are calculated in-model for each archetype when considering uptake of energy efficiency.

Table 11: The average payback period of energy efficiency measures in the commercial and public sectors, using sector-specific 2020 fuel costs.

Sector	Measure	Payback period (years)
Commercial	Cavity wall insulation	2.7
Commercial	Draught proofing	2.0
Commercial	Energy efficient appliances - office equipment	0 (payback within first year)
Commercial	Energy efficient appliances - refrigeration	0 (payback within first year)
Commercial	Energy efficient lighting	7.4
Commercial	Solid wall insulation	7.6
Commercial	Roof insulation	9.2
Commercial	High efficiency glazing	32.9
Public	Cavity wall insulation	1.3
Public	Draught proofing	1.6
Public	Energy efficient appliances - office equipment	6.2
Public	Energy efficient appliances - refrigeration	1.1
Public	Energy efficient lighting	2.3
Public	Solid wall insulation	3.2
Public	Roof insulation	6.3
Public	High efficiency glazing	22.8

3.3.3 Industry sector

The average payback periods for energy efficiency measures in the industrial sector is given in *Table 12* below. Note that these payback periods are a heating-demand-weighted average instead of a stock-weighted average. Hence, these values are heavily influenced by the payback periods of measures in a small number of sites with high heating demands.

Table 12: The average payback period of energy efficiency measures in the industrial sector, using sector-specific 2020 fuel costs.

Measure	Payback period (years)
More efficient HVAC and ventilation	0.9
Motor efficiency	10.9
More efficient compressed air systems	1.8
More energy-efficient lighting	7.3
Process integration and heat recovery - high temperature processes	1.7
Process integration and heat recovery - low temperature processes	0.9
Process integration and heat recovery - drying/separation	1.5

4 Technical Potential for Low Carbon Heating

It is important to understand the extent to which all the low carbon heating technologies considered in this study are suitable to be installed in buildings and industrial sites across Ireland, as this can clearly identify which technologies can be widely deployed to decarbonise heating in a high proportion of properties and which technologies are more suited to decarbonise heating in more niche applications. The technical potential of technologies presented in this section refers to the maximum possible uptake of each renewable technology based on the suitability constraints presented in this section. There are several reasons why a renewable heating technology may be unsuitable for deployment in a building or on an industrial site, such as:

- The lack of available space for the technology within a given property.
- The lack of a hot water storage tank (and inability to install one due to space constraints), which is necessary for technologies such as heat pumps that do not provide fully dispatchable heat.
- The lack of available fuel for the given technology; this is relevant for technologies that use hydrogen as a fuel, as hydrogen is not readily available for use by consumers across the heat sector.
- The inability of a given technology to provide heat at a high enough heat grade for certain industrial processes; this is relevant for the electrification of heat in certain pieces of industrial equipment e.g. calciners.

4.1 Technical potential methodology for buildings

The technical suitability of each renewable technology has been assessed in each archetype, based on key archetype characteristics. These archetype characteristics include sector, building type, counterfactual heating system, floor area, heat loss considerations (for standalone heat pump technologies; see Section 4.1.1 below), gas distribution grid proximity and existing connection, industrial subsector, and industrial process type, among other characteristics. Details on how these characteristics are applied to determine suitability of technologies at an archetype level are given in the Assumptions Log in the data workbook[11] accompanying this report, with a summary of the main characteristics for key technologies within the commercial, public and residential sectors given in *Table 13* below. For hybrid technologies, the suitability considerations of each component of the hybrid technology are applied.

Table 13: A summary of the primary suitability considerations in the commercial, public and residential sectors, for a selection of key technologies.

Tech	Suitability criteria (residential)	Suitability criteria (commercial & public)
ASHP	Heat loss constraint, HW storage availability, space constraint	Peak heat loss constraint, space constraint
GSHP	Heat loss constraint, HW storage availability, space constraint	Peak heat loss constraint, space constraint
High T ASHP	HW storage availability, space constraint	Space constraint
H2 boiler	Gas connection, proximity to gas grid	Gas connection, proximity to gas grid
Biomethane boiler	Gas connection, proximity to gas grid	Gas connection, proximity to gas grid

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[11] Further supporting information is available in Excel for download at https://www.seai.ie/data-and-insights/national-heat-study/Low-Carbon-Heating-And-Cooling-Technologies/

Solid biomass boiler	Not suitable for apartments, space constrained if not already on solid/oil counterfactual, not suitable in areas with air quality concerns	Space constraint, not suitable in areas with air quality concerns
Hybrid (ASHP + H2 boiler)	Gas connection, proximity to gas grid, space constraint	Gas connection, proximity to gas grid, space constraint
Electric resistive	Fuse limit	Suitable for all
District heat	All buildings not on counterfactual electric heating, within selected small areas	All buildings not on counterfactual electric heating, within selected small areas

4.1.1 Heat pump suitability constraints

All heat pump technologies have a floor space suitability constraint, based on archetype-specific data from the latest domestic and non-domestic BER database. Furthermore, for certain heat pump technologies (ASHP, GSHP, Communal ASHP, ASHP + solar thermal, and ASHP + solar PV HW) we also consider the peak heating demand of a property (in W/m^2) in determining suitability. As described in Section 2.1.1 above, if a property has a peak heating demand per unit floor area greater than 100 W/m^2 (HLI of approximately 4.5) then the property is assumed to be unsuitable for these standalone heat pump technologies and is not considered for uptake. The 100 W/m2 threshold is based on guidance from the UK's Microgeneration Certification Scheme [8]. This method of determining heat pump suitability was selected in line with aim of exploring what may be possible for decarbonising Irish buildings and recognising the scale of the challenge ahead.

Note that this consideration is applied to each archetype in combination with each energy efficiency package; this results in some archetypes being unsuitable for these technologies with no energy efficiency measure uptake, but suitable with some additional energy efficiency measures. This is explored in more detail in Section 5 below. This heating demand constraint does not apply to hybrid heat pump technologies with a boiler (i.e. ASHP + hydrogen boiler, ASHP + bioliquid boiler) as the boiler component provides a peaking function for heat supply, and so these archetypes with high heat demand are considered technically suitable for these technologies.

Also note that this only relates to technical suitability, not economic suitability; some archetypes with heating demand per unit floor area close to but below this 100 W/m^2 threshold are considered technically suitable, but the resulting cost from this high fuel use to meet this high heating demand could lead to other technologies being preferred when consumer decision making is considered. The NEMF considers heat pumps in competition with other renewable and counterfactual technologies; heat pumps will not be selected for installation within a building unless they are the most cost-effective amongst the technically suitable options. A higher threshold for technical suitability than has been used previously (see Section 5 below) allows heat pumps to compete with the other options on this financial basis.

4.1.2 Gas combustion technology suitability constraints

Most of the gas technologies rely on a connection to a gas distribution grid to supply the fuel; the exception is off-grid biomethane boilers in the commercial and public sectors, and industrial sites which can either use gas from the transmission or distribution grid, or containerised biomethane delivered by road transport. This gas distribution grid can supply biomethane (via grid injection) or hydrogen to these technologies for combustion. All archetypes with an existing gas technology are assumed to have an existing gas distribution network connection and are suitable for these technologies.

Furthermore, we have explored a significant expansion of the gas distribution network to allow archetypes without an existing gas distribution network connection to decarbonise using a low-carbon gas. Eligibility for this was determined by assuming homes and buildings within 20m of the existing gas distribution network could pay to connect to the distribution network. This was estimated to be approximately 467,000 existing homes in Ireland [39]. This represents 35% of all homes in Ireland without an existing gas distribution network connection. Due to lack of available data on the spatial distribution of our archetypes in relation to proximity to the gas distribution network, 35% of all residential archetypes without an existing gas connection were assumed to be suitable for this expansion. Also due to lack of available data, this same percentage was assumed to apply to all commercial and public archetypes without an existing gas network connection. No gas network expansion was considered for industrial archetypes without an existing gas network connection. It is assumed that all industrial sites that would both want to use gas as a fuel and are suitable for gas use (due to industrial process suitability constraints) have already been used connected to the gas network. Based on consultation with DECC, no expansion of the gas network beyond the in-fill connections described above has been considered within the National Heat Study.

In the commercial and public sectors, consideration was also given to use of biomethane technologies through the bottling and shipping of biomethane, in addition to grid-injected biomethane. All commercial and public properties without an existing gas network connection were considered suitable for these off-grid gas technologies, however due to the high cost of bottling and distributing this biomethane relative to other low carbon heating technologies (e.g. heat pumps, solid biomass boilers), economic constraints are generally the limiting factor for uptake of these off-grid gas technologies rather than this technical suitability constraint.

4.1.3 Electricity

In domestic archetypes, the fuse limit was considered for the installation of electric resistive heating. A fuse limit of 12 kW was used, and even when accounting for peak heating demand in the archetypes with the highest peak heating demand, this fuse limit was not exceeded. Therefore, electric resistive heating is considered suitable in all properties. Electric storage heating does not have the same fuse limit considerations, and so this technology is also considered suitable in all residential properties. In commercial and public buildings, this fuse limit is not considered for electric resistive heating, and so electric resistive is considered suitable in all archetypes in these sectors. Electric storage heating is not considered suitable in these sectors based on historical trends of direct electric technology use [36].

4.1.4 Other biomass fuels

In the residential, commercial and public sectors, biomass and bioliquid boilers are not considered suitable in archetypes without existing solid or oil boilers. This was treated as a proxy for urban buildings, where air quality concerns about the particulate emissions from these systems make them unsuitable. This is however not a perfect metric to determine how rural or urban a building in as some oil and solid boilers are used in some urban areas. There is also a space constraint applied to this sector, where properties deemed too small for a heat pump are also considered too small for these biogenic fuel boilers. In the residential sector, apartments are also not considered suitable for these systems.

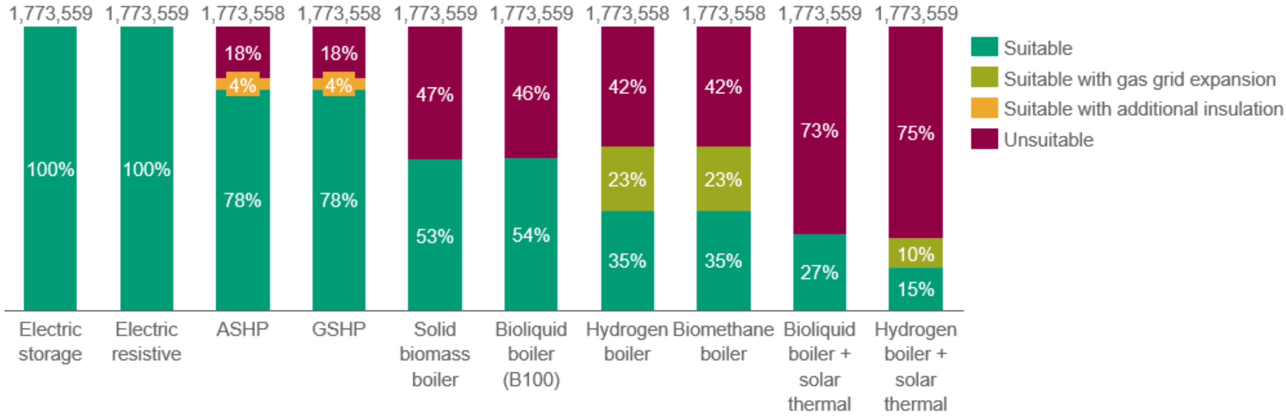
4.1.5 District heating

District heating uptake is considered based on heat density and DH infrastructure cost calculations at high spatial resolution. This is explained in further detail in the *Heating and cooling in Ireland today* [7] *and District Heating and Cooling* [19] reports. When being applied to buildings in each small area, all residential, commercial and public systems are considered suitable, except buildings with existing electric heating systems. This is because these properties would require the addition of a wet heating system to deploy district heating. So, these archetypes were considered to prefer the uptake of other systems that would not require the deployment of a wet heating system.

4.2 Technical Potential in Residential

The technical potential for a selection of key renewable technologies in the residential sector is given in *Figure 19*. Heat pumps are suitable in over 80% of the stock (when considering energy efficiency improvements), whereas solid biomass or bioliquid are only suitable in just over half of the residential building stock. It is worth noting that the stock suitable for a solid biomass boiler is also suitable for a bioliquid boiler (B100); if a bioliquid boiler was installed in all suitable properties there would be no additional buildings that could install a solid biomass boiler, due to similar key archetype characteristics that the suitability is based on. The technical potential for biogenic fuels (biomethane, solid biomass or bioliquid) does also not account for resource constraints on the feedstocks used to produce these fuels (considered in the *Sustainable Bioenergy for Heat* report [21]). The only technologies suitable for full uptake in the residential sector are direct electric heating technologies (electric resistive and electric storage).

Figure 19: Technical potential for low carbon heating systems in Irish residential buildings.



4.3 Technical Potential in commercial & public sectors

The technical potential for a selection of key renewable technologies in the commercial sector is given in *Figure 20*, and for the public sector in *Figure 21*. These are generally similar as the key archetype characteristics used to determine suitability for technologies are the same across these two sectors. The differences between the two sectors are due to differences in the archetypes themselves. For example, more commercial buildings use electricity as the primary heating source. Compared to the technical potential in the residential sector, building fabric improvements can improve heat pump suitability in these sectors by much more than in the residential sector. This relative improvement is because commercial and public buildings are generally less space-constrained and have poorer initial fabric efficiency than dwellings. Solid biomass boilers and bioliquid (B100) boilers have much lower technical potential in terms of the percentage of buildings suitable due to the lower percentage of buildings with an existing oil or solid boilers in the commercial and public sectors.

Figure 20: Technical potential for low carbon heating systems in Irish commercial buildings.

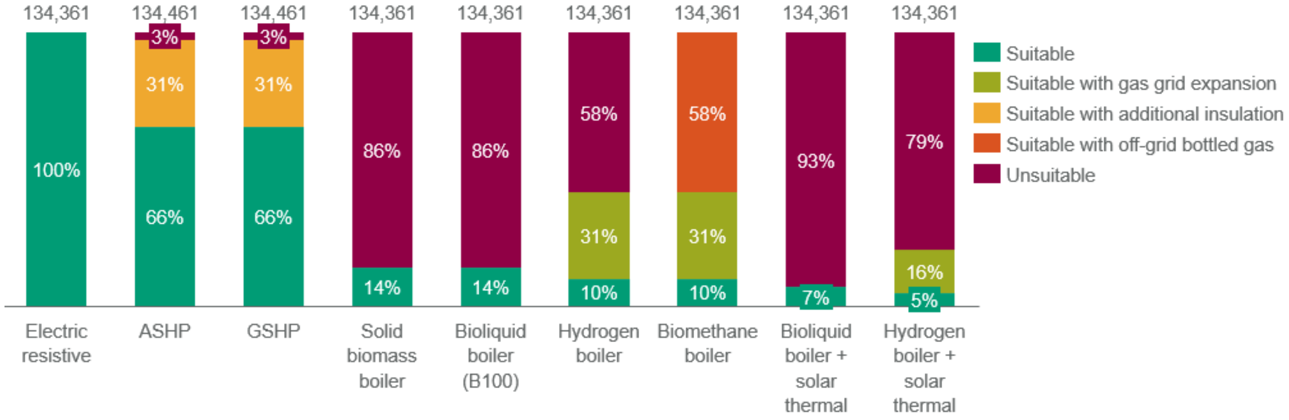
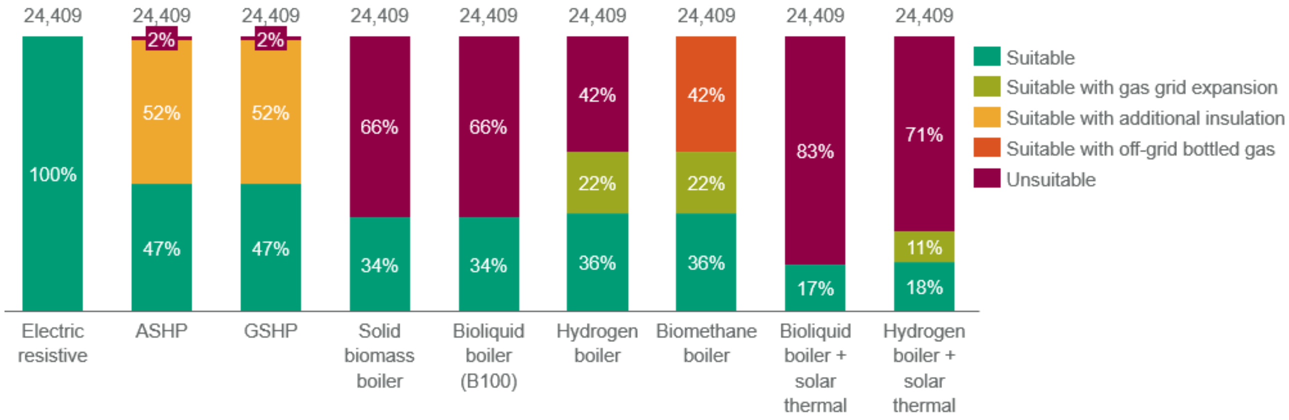


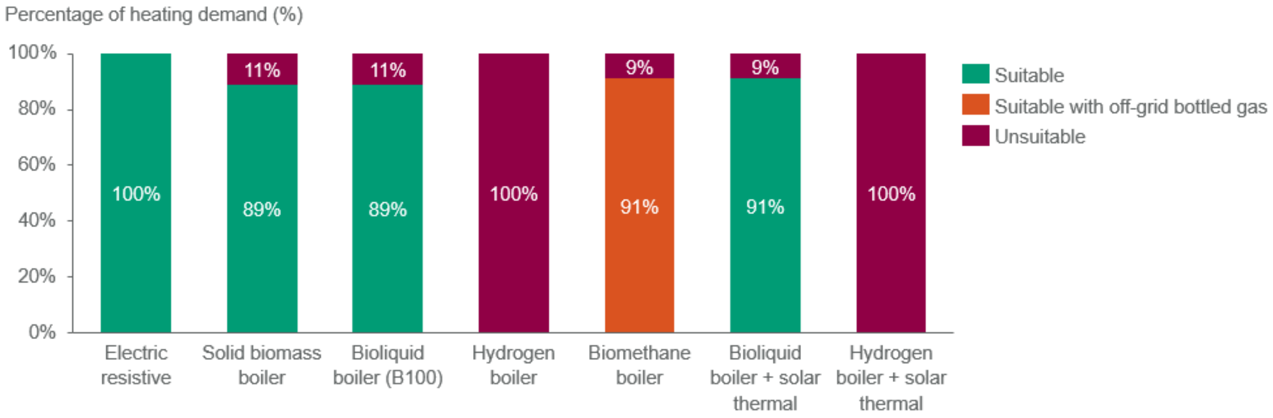
Figure 21: Technical potential for low carbon heating systems in Irish public buildings.



4.4 Technical Potential in Agriculture

The technical potential for a selection of key renewable technologies in the agriculture sector is given in *Figure 22* below. As agricultural buildings are typically located away from gas grids, the suitability of renewable technologies in the agriculture sector is much more constrained than in other sectors. There is no suitability for hydrogen boilers (or biomethane boilers without bottled biomethane) to decarbonise heating in the agriculture sector, and the only technology suitable to decarbonise the entire stock is electric resistive heating. It is worth noting that although the solid biomass boiler and the bioliquid boiler (B100) technologies only can be taken up in 22% of buildings. This proportion of the stock represents the majority (89%) of heating demand. The remaining proportion of agricultural buildings have minimal space heating demand and generally low per-stock hot water demands in the Dairy subsector. These remaining buildings are only suitable for direct electric heating due to process suitability for hot water heating in these archetypes.

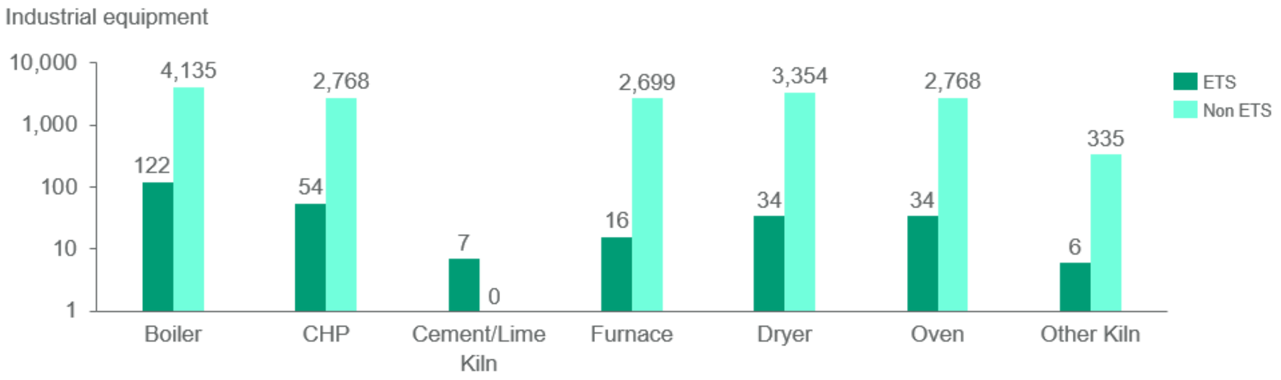
Figure 22: Technical potential for low carbon heating in the Irish agricultural sector.



4.5 Technical Potential in Industry

Technology suitability in the industry sector is linked to technology type rather than the characteristics of the industry site itself. The technology must be able to meet the temperature and other process requirements of a specific manufacturing process. The existing technology in use at specific industry sites is a useful guide as to these requirements. *Figure 23* below shows the split of existing heating demand by technology type and Emission Trading Scheme (ETS) status. Boilers are the most common industrial equipment in both ETS and non-ETS categories and also represent the most significant heat demand. Boilers are followed in number by dryers, CHP systems, ovens, and furnaces. While few cement and lime kilns operate in Ireland, these contribute about 20% of total industrial heat demand.

Figure 23: The estimated number of pieces of industrial equipment by industrial equipment type, and by ETS status, presented on a log scale.



The breakdown of suitability for the low-carbon and renewable technology options is given in *Table 14* below. Generally, low-carbon industrial technologies are only suitable to replace existing industrial heating technologies of the same technology type. For example, a gas furnace can only be replaced by a low-carbon furnace. An important exception to this rule is the replacement of boilers by industrial heat pumps (both high temperature and medium temperature heat pumps). The heat pump technology can meet the same energy service demand as a boiler in many cases. The other exception to this is when existing CHP systems are replaced by direct heating technologies with the improvements to existing electricity grid connections modelled to replace the electricity demand that would be generated by the CHP plant. When this occurs the grid upgrade costs required to enable a significant increase in grid electricity consumption are included in the cost of the technology.

Each technology type (e.g. boilers, CHP, dryer, furnace) was assessed against each low carbon fuel. The total heating demand that each fuel type could meet is given in *Table 14*. This suitability was determined based on stakeholder feedback, and internal Element Energy low-carbon industry expertise. Electricity, biomethane, and hydrogen are the primary suitable low carbon energy vectors for most industrial technologies. Of the 17 TWh total industrial demand, 10.3 TWh are suitable for decarbonisation using electricity (including heat pumps), 10.8 TWh are suitable for biomethane, and 13.5 TWh are suitable for hydrogen. While solid biomass is suitable only for boilers and CHP, it is a technically suitable decarbonisation option for 10 TWh of industrial heat demand. Note that *Table 14* presents heat demand; actual fuel consumption will differ based on the efficiency of each technology.

Cement kilns and calciners represent a significant heat demand that is not suitable for decarbonisation with the fuels mentioned above. These are instead suitable for biological and non-biological wastes, mixed fuel (comprising biomass as well as waste fuel), and CCUS. The potential for CCUS in Ireland is discussed in detail in the *Carbon Capture, Utilisation and Storage (CCUS)* report [20].

Table 14: Technical potential (GWh) for low carbon fuels in the industry sector for each technology type.

Technology Type	Biomass	Biomethane	Electricity	Heat Pump (High temp)	Heat Pump (Med temp)	Hydrogen	Mixed Fuel	Bio and non-bio waste	Total heat demand (GWh)
Boiler	6,499	4,656	6,499	532	1,031	5,875	-	-	**6,499**
CHP	3,498	3,275	-	-	-	3,390	-	-	**3,498**
Cement/lime kiln/calciner	-	-	-	-	-	276 (lime only)	3,079	982	**3,079**
Furnace	-	2,025	-	-	-	2,136	-	-	**2,136**

Dryer	-	338	1,509	-	-	1,294	-	31	**1,509**
Oven	-	488	631	-	-	538	-	-	**631**
Kiln (other)	-	20	133	-	-	67	-	-	**133**
Heat demand potential served by each fuel	9,997	10,802	8,772	532	1,031	13,524	3,079	1,013	**17,486**

5 Heat pump suitability and heat loss indicators

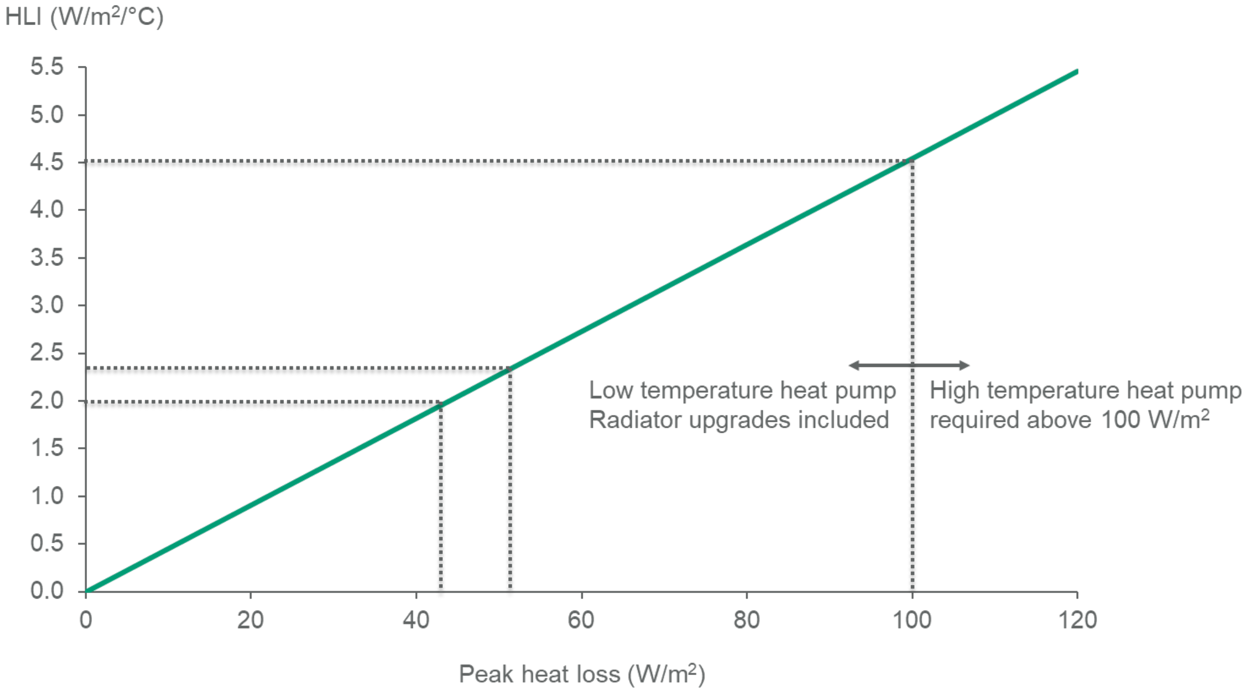
5.1 Peak heat demand and heat loss indicator

Section 0 presented the fraction of buildings that are deemed technically suitable for ground- and air-source heat pumps. As noted, this is based on the building's peak heat demand (in W/m2) and MCS guidance that buildings with specific heat demand below 100 W/m2 are technically suitable for heat pumps if the heating system is appropriately upgraded [8]. This method of determining suitability is different from the standard used to determine eligibility for financial support from government for heat pump installation, which relies on the heat loss indicator (HLI). This section compares the two methods and discusses the impact of energy efficiency measures on the HLI of the Irish building stock.

The HLI threshold of 2 to 2.3 was introduced to avoid adverse consumer reactions during rollout of a relatively novel technology under the Better Energy Homes Scheme This ensured that heat pumps were installed only where very low flow temperatures could be achieved, reducing the risk to consumers from poor installation and high costs resulting from low heat pump efficiency. In contrast, the National Heat Study seeks to explore what could be possible, recognising the scale of the decarbonisation challenge. It is assumed that heat pump installations follow best practice guidelines and that radiator upgrades are installed where required to enable a building's heat demand to be delivered through the radiators at suitable flow temperatures. The operational implementation of any low carbon heating support scheme must take a view on the balance between the risks posed to consumers from installing heat pumps in less efficient homes and the drawbacks of limiting eligibility to high efficiency dwellings, including the challenges associated with energy efficiency improvements.

A building's HLI specifies the rate heat is lost from the building per degree C difference between the indoor and outdoor temperatures ($W/m^2/°C$). The peak heat demand used above can be divided by the indoor-outdoor temperature difference on the peak demand day to determine the HLI. We assume an average indoor temperature of 20 °C [40] and a peak winter outside temperature of -2 °C [41]. This gives an indoor-outdoor temperature difference of 22 °C. This relationship is shown graphically in *Figure 24*. An HLI of 2.0 corresponds to a peak heat loss rate of 44 W/m^2 while an HLI of 2.3 corresponds to a peak heat loss rate of 51 W/m^2.

Figure 24: Relationship between peak heat loss rate and HLI.



The following section presents the variation in HLI seen across the Irish residential building stock (as represented by the archetypes used in the NEMF) in their current (initial) state, and the changes if shallow, medium, or deep retrofit packages were adopted.

5.2 Aggregation of energy efficiency measures

The cost, suitability and potential heating demand savings for each suitable measure are considered on an archetype basis. When considering the uptake of measures in each archetype in the modelling, the following process is followed:

1. The payback period of each measure is calculated based on the in-year fuel costs for the fuel used by that archetype. Details of this payback period calculation are given in Section 3.3 above.
2. Three custom energy efficiency 'packages' (shallow, medium, and deep) are produced for each archetype, each with a payback period threshold which is defined by sector as an input into the modelling. These thresholds are typically between 3 years (shallow) and 10 years (deep).
3. All individual measures with a payback period less than or equal to the payback threshold for the packages are included in the package.
4. All packages are considered for uptake in combination with each renewable technology that is suitable in each archetype. Renewable energy technologies are also considered for installation alongside no energy efficiency measures, and energy efficiency can be installed without installing a new heating system.
5. In the residential sector, the expected fuel savings from the uptake of these packages is calibrated to take into account the rebound effect; more information is provided on this process in the *Heating and cooling in Ireland today* report [7]. The rebound effect calibration is not considered in other sectors.

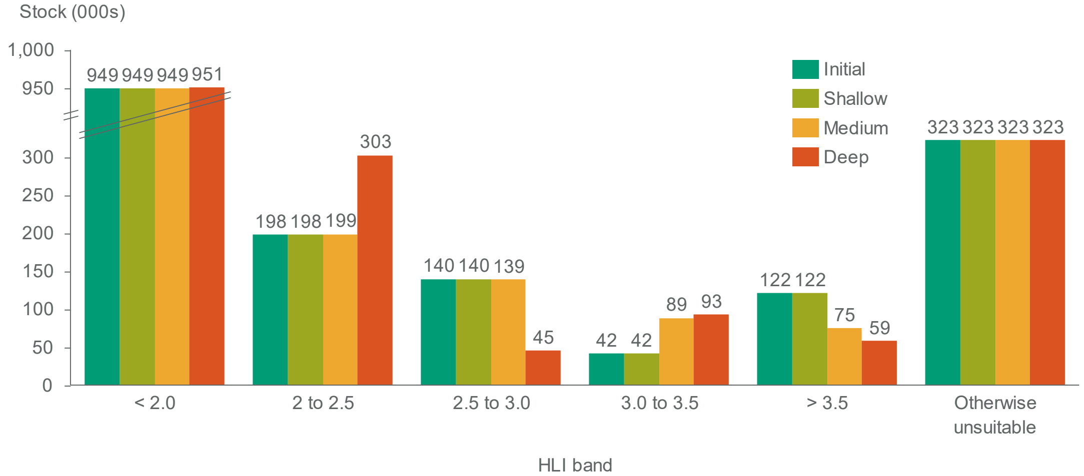
5.3 Fabric energy efficiency and HLI impact

Figure 25 presents a set of histograms for the residential sector. Each of the four sets of coloured columns represents the HLI distribution if the whole stock in that sector adopted a certain level of energy efficiency package. The ‘Initial’ energy efficiency package is buildings in their current state with no additional energy efficiency measures taken up. The shallow, medium, and deep energy efficiency packages are determined for each archetype individually within the NEMF based on the payback period for individual efficiency measures in each archetype; this process is explained in Section 5.2 above. The final column indicates the stock deemed unsuitable for ASHPs for reasons other than high heat loss. This primarily includes highly space-constrained dwellings which may struggle to accommodate an ASHP and/or required ancillary equipment.

In *Figure 25* it can be seen that dwellings move towards lower HLI at higher efficiency levels. However, this mostly occurs at HLI values above 2.0. With deep retrofit applied across the stock, there are 100,000 more buildings within 2.0 to 2.5 band [12]. These tend to move from the bands 2.5 to 3.0 and > 3.5. The buildings in these less efficient bands can achieve better payback periods for energy efficiency measures because they use more fuel and their starting fuel bills are higher. Therefore, there is more energy efficiency uptake, in these less-efficient properties (which generally have poorer HLI values), because they save more fuel costs from energy efficiency implementation.

Below 2.0 there is almost no change between the energy efficiency levels. This is partly because buildings within these HLI bands are not suitable for additional energy efficiency measures specified in the model (see Section 3.1 above). This is because for the more affordable measures, the building U-values are already below the thresholds for application of energy efficiency measures, i.e. the savings below this point become quite marginal, and because more expensive measures have long payback periods and are not adopted. The figure also indicates that buildings at higher HLI do not adopt energy efficiency measures significant enough to bring them below HLI of 2.0. This is a result of the short payback periods required by the consumer decision making mechanism (see Section 3.3) and the long payback periods associated with the higher impact energy efficiency measures.

Figure 25: HLI bands across the residential sector, if the whole stock had uptake of each energy efficiency package (shallow, medium, deep). The 'Initial' energy efficiency band is with no energy efficiency improvements.



This plot compares the combination of energy efficiency packages specifically with ASHPs, with the packages combined using payback periods calculated using 2020 fuel prices and current existing energy efficiency grants to encourage uptake. If policy support for energy efficiency improvements was higher, then more energy efficiency measures would be included in these packages, and the stock in the non-initial state columns would generally shift towards lower HLI values (to the left) as the HLI for these buildings will drop with greater energy efficiency uptake.

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[12] Note that the full building stock used here has been scaled up from the BER database. This is a population estimate rather than a BER sample.

While the NEMF does not prohibit buildings with HLI above 2.0 from adopting ASHPS, it does capture the increased energy costs that these buildings will face. *Table 15* presents the achievable flow temperatures and ASHP space heating efficiency at different levels of HLI, consistent with that presented above in 2.3. In addition to a higher annual demand for heat, buildings with lower efficiency will face higher costs again due to the reduced operational efficiency of their ASHPs.

Table 15: Impact of heat loss rate and HLI on flow temperature and space heating efficiency.

Peak specific heat loss (W/m2)	HLI (W/m2/deg C)	Flow temperature (deg C)	Space heating efficiency
0 to 30	0 to 1.4	35	333%
30 to 50	1.4 to 2.3	40	316%
50 to 80	2.3 to 3.6	45	284%
80 to 100	3.6 to 4.5	50	260%
>100	>4.5	55+	<235%

6 Fuel cost and emissions inputs

The technologies presented in this report use a variety of fuels, many of which have varying costs based on the sector and annual consumption of fuel. We have modelled these varying fuel prices in this study, with a description of the assumed fuel prices in 2020 provided in this section. These 2020 fuel prices can vary out to 2050 in the modelling based on wholesale fuel price changes, varying environmental levies on fuels and the impact of network costs on fuel prices; these future fuel prices are presented in the *Net Zero by 2050* report [9].

Table 16 shows the fuels and 2020 fuel price sources for each fuel considered in this study. Most fuel prices were taken from two publicly available SEAI fuel price sources [42] [43]. In these sources some fuel prices vary depending on the amount of fuel consumed each year. This approach to banding certain fuel prices based on annual fuel consumption is considered in our modelling, with the fuel prices given in *Table 17*. Emissions factors are also provided for the fuels.

These fuel prices are given for 2020. For fuels that have prices calculated by the model, these are not given below; please see the relevant fuel reports for further information about these calculated fuel prices. The model calculates the fuel price in all years after 2020; where relevant these include wholesale fuel price projections, calculated levelized network costs, and biogenic resource costs and resource constraints. More information on how these are calculated for each fuel is in the following reports:

- Electricity – the *Electricity Infrastructure* report [44].
- Hydrogen – the *Low Carbon Gases for Heat* report [12].
- Biogenic fuels – the *Sustainable Bioenergy for Heat* report [21].

The wholesale fuel price projections for fossil fuels (solid mineral fuel, oil, natural gas) are based on the UK’s Department for Business, Energy & Industrial Strategy’s projections [45].

Table 16: The sources for the 2020 fuel prices for the fuels considered in this study, with an indication of whether the fuel price is banded based on annual fuel consumption. And emissions factors is also provided for each fuel.

Fuel type	Data source for 2020 cost	Banded?	Emissions factor ($kgCO_2$ / kWh)
Solid mineral fuel	Residential: [42] Commercial, Public, Industry, Agriculture: [43]	Yes	0.3406 [46]
Oil	Residential: [42] Commercial, Public, Industry, Agriculture: [43]	No	0.2591 (residential), 0.2651 (other sectors) [46]
Natural gas	Residential: [42] Commercial, Public, Industry, Agriculture: [43]	Yes	0.2047 [46]
Electricity	Residential: [42] Commercial, Public, Industry, Agriculture: [43]	Yes	0.3245 (2019 value; future values calculated in-model) [46]
Hydrogen	Calculated in-model; see WS5 report	Yes	Calculated in-model
Biomass	Calculated in-model; see WS2 and WS7 reports	No	Calculated in-model
Bioliquid	Calculated in-model; see WS2 and WS7 reports	No	Calculated in-model
Biomethane/biogas	Calculated in-model; see WS2 and WS7 reports	No	Calculated in-model
Bio waste	Calculated in-model; see WS2 and WS7 reports	No	Calculated in-model
Non-bio waste	Assumed to be the cost of avoiding the Irish landfill levy; calculated using [47]	No	Taken from ETS dataset; non-publishable
Mixed fuel	Calculated as a weighted-average from the costs of solid mineral fuel (20%), non-bio waste (20%), bio waste (40%), and biomass (20%)	No	0.1315 (using same weighted average as the cost calculation)

Table 17 gives the 2020 fuel price for each fuel, disaggregated by sector and consumption band where appropriate. Please note for residential solid fuels, these bands (and the corresponding modelled emissions factor) are calculated based on an assumption of varying fuel mixes, as follows. The lowest residential solid fuel consumption band used the solid fuel price source, as in *Table 16*. The highest consumption band uses a price of zero, assuming that sod peat or wood is used at zero cost. The central consumption band is assumed to have a fuel price equal to 64% of the lower consumption band, based on analysis of the Energy Balances data and the BER database.

Table 17: The fuel price for each consumption band of each fuel, differentiated by sector where the fuel price is different between sectors. The fuel consumption band upper and lower annual fuel consumption limits and 2020 fuel cost is given.

Fuel	Sectors	Min consumption (kWh)	Max consumption (kWh)	2020 fuel cost (c / kWh)
Solid fuels	Residential	0	5,000	6.1
Solid fuels	Residential	5,000	7,000	3.9
Solid fuels	Residential	7,000	No upper limit	0.0
Oil	Residential	0	No upper limit	7.7
Natural gas	Residential	0	5,556	8.8
Natural gas	Residential	5,556	55,556	7.7
Natural gas	Residential	55,556	No upper limit	6.9
Electricity	Residential	0	1,000	37.8
Electricity	Residential	1,000	2,500	31.3
Electricity	Residential	2,500	5,000	25.3
Electricity	Residential	5,000	15,000	21.7
Electricity	Residential	15,000	No upper limit	18.4
Oil	Commercial, Public, Agriculture	0	No upper limit	8.1
Electricity	Commercial, Public, Industry, Agriculture	0	20,000	25.0
Electricity	Commercial, Public, Industry, Agriculture	20000	500,000	19.2
Electricity	Commercial, Public, Industry, Agriculture	500,000	2,000,000	15.8
Electricity	Commercial, Public, Industry, Agriculture	2,000,000	20,000,000	12.5
Electricity	Commercial, Public, Industry, Agriculture	20,000,000	70,000,000	11.4
Electricity	Commercial, Public, Industry, Agriculture	70,000,000	No upper limit	10.8
Natural gas	Commercial, Public, Industry, Agriculture	0	278,000	6.2
Natural gas	Commercial, Public, Industry, Agriculture	278,000	2,778,000	5.1
Natural gas	Commercial, Public, Industry, Agriculture	2,778,000	27,778,000	4.0

Natural gas	Commercial, Public, Industry, Agriculture	27,778,000	No upper limit	3.0
Non-bio waste	Industry	0	No upper limit	-2.7
Solid mineral fuel	Industry	0	No upper limit	1.7
Oil	Industry	0	No upper limit	7.7
Mixed fuel	Industry	0	No upper limit	3.0

Glossary

Term	Description
Archetype	A simplified representation of a normally large number of real-world items, such as buildings.
ASHP	Air Source Heat Pump
CCUS	Carbon Capture Utilisation and Storage
CHP	Combined Heat and Power
ETS	Emissions Trading Scheme (regarding the EU’s emissions trading scheme)
Final energy	The actual amount of energy used to meet a demand (i.e. actual fuel used). These data are reported in aggregated form in the National Energy Balance. Also known as final energy. Corresponds to the energy consumption that normally appears on energy bills.
GSHP	Ground Source Heat Pump
HP	Heat Pump
HHP	Hybrid Heat Pump
kWh	Kilowatt hour; a unit of energy
MSW	Municipal Solid Waste
ND-BER	Non-domestic Building Energy Rating
NEMF	National Energy Modelling Framework
Non-ETS	This refers to industrial sites or other greenhouse gas emitters which are not part of the EU’s emission trading scheme.
SCOP	Seasonal Coefficient of Performance (SCOP) – annual average heat pump performance given the variation in outside temperature and heat demand over a typical year.
TRL	Technology Readiness Level
Useful energy demand	The amount of energy required to fulfil a demand. Does not take any losses into account (for example, due to technology conversion efficiency).

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