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The future of home heating

The roles of heat pumps and hydrogen

An Energy Futures Lab Briefing Paper

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List of Acronyms

ASHP	Air-source Heat Pump
BEIS	Department for Business, Energy and Industrial Strategy
CCC	Climate Change Committee
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CoP	Coefficient of Performance
DACCS	Direct Air Carbon Capture and Storage
EFV	Excess Flow Valve
EHPA	European Heat Pump Association
EPC	Energy Performance Certificate
EU	European Union
GSHP	Ground-source Heat Pump
GW	Gigawatt
GWh	Gigawatt-hour
GWP	Global Warming Potential
H_2	Hydrogen
HaaS	Heat as a Service
HHP	Hybrid Heat Pump
HP	Heat pump
IMRP	Iron Mains Replacement Programme
$kgCO_2e$	Kilograms of carbon dioxide equivalent
$kgCO_2e$ per kWh	Kilograms of carbon dioxide equivalent per kilowatt-hour of thermal energy
$kgCO_2e$ per kg H_2	Kilograms of carbon dioxide equivalent per kg of hydrogen
kW	Kilowatt
kWh	Kilowatt-hour
MCS	Microgeneration Certification Scheme
$MtCO_2$	Megatonnes (Million tonnes) of Carbon Capture and Storage
MW	Megawatt
MWh	Megawatt-hour
NO_2	Nitrogen Dioxide
RHI	Renewable Heat Incentive
SMR	Steam Methane Reformation
SPF	Seasonal Performance Factor
UK	United Kingdom

Executive Summary

In this Briefing Paper, the prospects for the future of home heating are analysed with specific reference to heat pumps and hydrogen heating. The report is based on extensive literature surrounding the topic of decarbonisation of the heat sector in the UK and will discuss the various advantages, challenges, and technicalities surrounding the two technologies. The evidence gathered and discussed culminates in a set of recommendations that prioritise key areas that require addressing over the course of the next decade.

Heat Pumps

Heat pumps are a well-established technology that are powered by electricity to transfer heat from external sources (e.g., air, ground, water) to provide warmth and hot water to a building. Whilst efficient, with a low carbon footprint when powered by renewable electricity, they have had a limited roll-out in the UK to date and make up less than 1% of installed heat capacity (BSRIA, 2017). Imminent action is necessary to develop the market and reduce costs for low-carbon heating (BEIS, 2021f, p.11). The Government has set a target for 600,000 heat pumps to be installed annually by 2028 (HM Government 2020), with the Climate Change Committee estimating that nearly 19 million heat pumps may need to be installed by 2050 to achieve net zero (CCC, 2019c, p.84). Meeting this demand should be feasible, with transferrable skills and learnings from complementary technologies (e.g. boilers and air conditioners) enabling the manufacturing base to increase. However, consumer awareness of heat pumps is low and they are currently expensive to install. The UK government's Heat and Buildings Strategy sets ambitions, through collaboration with industry, to lower heat pump installation costs by at least 25% – 50% by 2025, and to lower purchase prices and running costs to close to parity with gas boilers by 2030 (BEIS, 2021f). This will require a coordinated approach to technological innovation and consumer engagement and policies to expand the UK supply chain for heat pumps (see 'Policy and regulations' section below).

Hydrogen

Repurposing the natural gas grid with hydrogen would mean no CO_2 emissions at the point of use (as with heat pumps). However, combustion of hydrogen can result in emissions of nitrogen oxides (NOx) air pollutants – this would need to be carefully regulated through an emissions standard for hydrogen appliances. Hydrogen is predominantly derived from fossil fuels in energy intensive production processes. This means that for a hydrogen grid to be a viable strategy for net zero, its production needs to be low-carbon. The UK has endorsed a 'twin track' approach with regards to this, focussing on steam methane reformation with carbon capture (blue hydrogen) or electrolysis powered by renewables (green hydrogen) (BEIS, 2021f, p.68). The differences between hydrogen and natural gas mean that to deliver hydrogen safely into homes, certain sections of the gas grid would need to be retrofitted. Whilst a large proportion of iron pipelines are already being replaced through the Iron Mains Replacement Programme, there remains steel pipework that would need to be replaced if the transmission pipeline is repurposed. Within houses the use of hydrogen heating could be a more familiar experience to consumers, bearing similarities to the use of natural gas heating systems. However, there are several obstacles to overcome before this would be feasible. Properties in areas converted for heating via a hydrogen grid would be subject to a certain level of disruption resulting from home surveys, any required updates of existing natural gas pipework and the conversion or installation of appliances suitable for use with hydrogen.

Barriers to Implementation

Regardless of which heating technologies dominate in domestic settings in the future, there will be some common barriers to uptake faced by each option. With the UK having one of the least thermally efficient building stocks in Europe (ACE, 2015), the demanding timescales necessary to meet net zero, and a low public awareness of alternative heating technologies (BEIS, 2021f), improving energy efficiency, recruiting employees and upskilling existing workforces, as well as improving public awareness, are necessary measures moving forward.

For heat pumps specifically, in the next decade some of the most pressing barriers relate to the installation process. For example, high upfront costs mean they are several times more expensive than a gas boiler, there is a lack of qualified installers, they may require oversized or thicker radiators to be installed alongside them, and typically require more space than modern gas combi boilers. Furthermore, if a large share of UK homes are fitted with heat pumps, the power grid will need reinforcement to manage total and peak electricity demand; smart, flexible operation of heat pumps could help to smooth peaks of demand and reduce some need for physical reinforcement.

A hydrogen heating scenario would face its own set of issues as there are currently very limited sources of low-carbon hydrogen. Although there are plans in place for 5 GW of low-carbon hydrogen by 2030 (HM Government, 2020), this is destined for industry as the harder to decarbonise sectors will take priority. There are also a number of safety concerns related to hydrogen use, which will need addressing before its widescale adoption can take place. Storage facilities to cope with periods of high demand will also need to be established. Green hydrogen, in particular, is not currently cost competitive and a limited carbon capture roll-out means that blue hydrogen is not yet feasible on a commercial level.

Policy and regulations

The Boiler Upgrade Scheme, a three-year, £450 million scheme that will support the installation of approximately 90,000 heat pumps, is the most recent grant support mechanism announced by the Government to increase the deployment of heat pumps in the UK (BEIS, 2021f). However, given the limited success of previous schemes it may not be enough to stimulate market growth to the levels required, with affordability being noted as a key barrier to heat pump uptake. Technological innovation, cost reduction and local job creation could be boosted by government support to expand the UK heat pump market and domestic supply chain. This could include the establishment of a national, dedicated test centre for the development and performance monitoring of heat pumps, and incentives for complementary manufacturers to shift production from established fossil fuel heating technologies to heat pumps. The Government has recently published a consultation on a proposed ‘market-based mechanism for low-carbon heat’ which could oblige fossil fuel boiler manufacturers to progressively increase their sales of heat pumps relative to gas and oil boiler sales.

The creation of a heat pump council, which brings together national and local government, regulators, industry, and civil society could prove important in taking a coordinated approach to developing the heat pump market through consumer engagement and quality assurance via the recommended national test centre for heat pumps. With the increasing amounts of heat pump installations expected in the next decade, demand management policies are required to limit the impact on peak electricity demand and maintain a balanced grid.

In the coming decade there are a number of government planned initiatives that aim to support a low-carbon hydrogen economy and try to overcome the associated barriers of its deployment. A £240 million Net Zero Hydrogen Fund has been set up as a co-investment into the hydrogen economy and a hydrogen business model will be outlined to try to improve the cost-competitiveness of low-carbon hydrogen, which will soon be defined by standards to monitor lifecycle emissions. Hydrogen trials on a neighbourhood scale are due to begin in the next few years and can provide a safety case for the use of the gas. Meanwhile a decision on whether or not to blend the current gas grid with a proportion of hydrogen to reduce emissions and potentially provide a smoother route to a 100% hydrogen gas grid is expected in 2023 (HM Government, 2020; BEIS, 2021f). The government plans to make a strategic decision in 2026 about the role of hydrogen in heating buildings, based on evidence from local trials and research and development (BEIS, 2021f).

It is important to consider how hydrogen could be used in (and whether it should be prioritised for) harder to electrify sectors (e.g., industry and shipping). With respect to its potential application in building heat decarbonisation, we find that hydrogen would be best placed strategically in industrial clusters or as a (hydrogen boiler) component in hybrid heat pump systems. Strategic placement of hydrogen facilities near industrial clusters, where the demand for it is already in place will likely aid development of low-carbon hydrogen. In this way, regions within proximity to clusters could transition away from natural gas to hydrogen heating in homes if hydrogen trials prove it as a viable and safe option.

Our recommendations related to the future of home heating are as follows:

- Energy levies should be moved away from electricity and transitioned over to more carbon intensive fuels;
- Support the development of UK heat pump manufacturing through policy support and incentives for UK-based manufacturers of complementary technologies (e.g. gas boilers, air conditioners) to shift or diversify production to heat pumps;
- Long-term grants (of at least 10 years) are recommended to increase revenue certainty in the heat pump industry;
- Introduction of green financing schemes and products for domestic renewables and energy efficiency measures;
- Establishment of a heat pump council comprising members from national and local government, regulators, industry, and civil society to help coordinate consumer engagement with heat pump deployment;
- Investment in a national research, testing and training facility for heat pumps to monitor and develop the technology further;
- The utilisation of hybrid heat pumps is proposed to take advantage of time-of-use price differences and engage users through 'Heat-as-a-Service' business models;
- Utilisation of low-carbon hydrogen strategically in hard to electrify sectors such as industry and shipping is recommended;
- Low-carbon hydrogen should be clearly defined and standards will need to be in place if the market is to be developed for heat decarbonisation in buildings (The government have recently completed a consultation which aims to create a low-carbon hydrogen standard);
- Support the development of electrolysers in the UK to improve the cost-effectiveness of green hydrogen;
- Focus on the deployment of solutions currently available such as energy efficiency, electrification through heat pumps and heat networks.

1. Introduction

In order to mitigate the dangerous effects of climate change and keep global temperature rises below 1.5 °C, it is vitally important to embark on far-reaching, ambitious efforts to decarbonise the UK's economy and infrastructure.

While renewable technologies are rapidly evolving and dropping in price to provide a cost-effective way to decarbonise the power sector, the heating sector, which is responsible for approximately 23% of UK emissions, is forecast to be more difficult to decarbonise (BEIS, 2018). Heating demand in the UK, as well as accounting for 60 – 80% of final demand in residential and commercial properties (Staffell *et al*., 2019), varies both daily and seasonally, with evening demand considerably higher than midday demand and winter demand many times higher than summer demand. This requires a flexible solution, which until now has been met by fossil fuels – with the UK mostly supplied by natural gas. In addition, domestic heat is largely decentralised, with heat generation in nearly all cases in the UK occurring at the point-of-use. The UK is more dependent on gas central heating than many other European nations (Fig. 1) - since the mid-1970s, most UK households have generated heat via individual natural gas boilers feeding a hot-water delivery system. This technology has the advantages of being widely understood, quick to deliver heat, efficient (with a modern condensing boiler), flexible, and has historically benefitted from low gas prices until recent energy price spikes (Fernández Alvarez and Molnar, 2021). However, natural gas is difficult to decarbonise, and the UK's net zero commitments will necessitate a shift from gas boilers to low-carbon heating systems. Other methods of domestic heating used in the UK include heat pumps, electric resistance heaters and storage heaters, limited deployment of local heat networks and off-gas-grid oil heating. Currently, less than half a million UK homes utilise low-carbon heating, not counting wood-fired stoves or open fires (Green Alliance, 2020).

There are several technologies which could play an important role in the decarbonisation of domestic heat, including heat networks, biogas, heat pumps and hydrogen. This Briefing Paper investigates the challenge of decarbonising domestic heat in the UK, focusing on two leading technology candidates that have recently been the focus of considerable debate – heat pumps and hydrogen heating. In so doing, we recognise that energy demand reduction and the deployment of heat networks are also likely to play a significant role in the transition to low-carbon heat (CCC, 2020). However, these options are not considered as part of the scope of this report, except where relevant to heat pump or hydrogen heating deployment.

Heat pumps are electrically driven and work by transferring heat from the outside of a property to the inside via a transfer medium. This arrangement is considerably more efficient than the direct conversion of electrical energy to heat in an electric radiator or heater, as each unit of electricity consumed can bring typically between 3–5 units of heat into the property. They can be powered by low-carbon electricity, greatly reducing the carbon intensity from natural gas heating. Heat pumps are commercially available in the UK, though uptake is still very limited, with around 265,000 units installed as of 2020 (EHPA, 2021c).

Hydrogen heating in the UK could largely utilise the existing gas grid to deliver hydrogen to domestic properties on the gas grid. The grid would need to be upgraded in order to deliver hydrogen, including the replacement of steel distribution pipes with plastic. There would also be additional challenges and disruption, since each property would need to be surveyed prior to conversion, existing pipework upgraded if necessary and new appliances installed (or existing appliances converted for use with hydrogen) (Frazer-Nash, 2018). Once installed, hydrogen boilers would heat hot water and transfer it to radiators in much the same way as gas boilers. This is argued to require little change in consumer behaviour and may be perceived by householders as a more equivalent technology to gas boilers compared to a heat pump (Williams *et al.*, 2018). Hydrogen can be generated by electrolysis, which when paired with low-carbon generation is known as 'green hydrogen', or by conversion of fossil fuels, which currently has substantial associated carbon emissions.

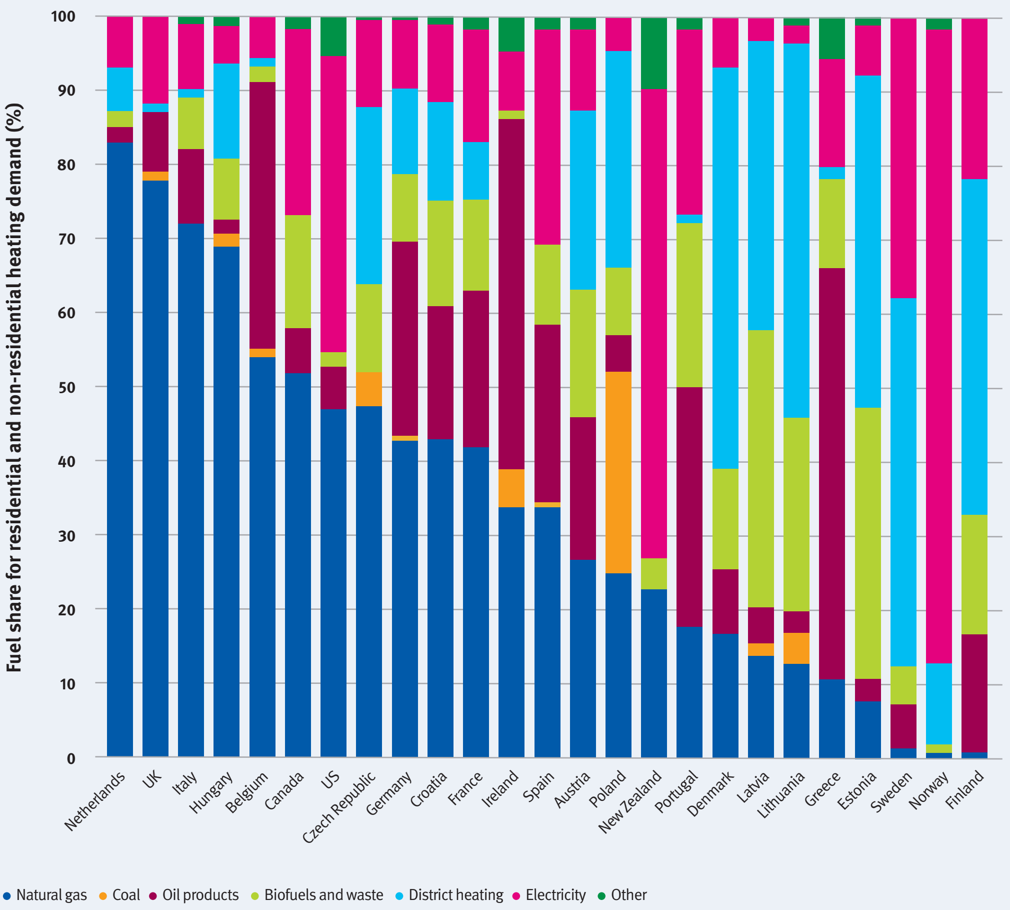

Figure 1: Diversity of fuel shares for residential and non-residential heating in selected countries. Gross & Hanna (2019) based on data obtained with permissions of Vivid Economics and the Department for Business, Energy and Industrial Strategy

1.1 Aim and approach

The aim of this Briefing Paper is to discuss heat pumps and hydrogen heating and their prospects for development and uptake in the UK over the next decade, based on a thorough review of existing literature. It will consider the supply- and demand- side characteristics of the two technologies, advantages and challenges facing them and the feasibility of uptake over the next decade. Each option is also considered in terms of what will need to be prioritised over the next ten years in order to help meet the UK's 2050 net zero target. The evidence has been gathered using a narrative review[1] of academic and grey literature drawn from the Science Direct and Google Scholar databases. The study also updates relevant information based on previous systematic reviews carried out by the authors on international heat decarbonisation policies (Hanna *et al*., 2016; Sahni *et al*., 2017). We also draw upon recent work carried out by the authors focused on heat system change and smart heat in the UK (Gross and Hanna, 2019; Carmichael *et al*., 2020). Finally, we have engaged with selected experts either through inviting comments on the draft Briefing Paper or through holding discussion meetings.

The Briefing Paper is divided into five sections. Section 2 provides a primer of the two technologies, discusses their current market conditions, and covers some environmental implications they may have. Section 3 focuses on the demand-side, showcasing the mid- and down-stream aspects of the technologies and how they would work in a domestic household. Section 4 explains the barriers to implementation, exploring the challenges that each technology faces in adoption over the next decade. Section 5 proposes policy recommendations and support to overcome these barriers.

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[1] Narrative reviews provide a general overview of literature related to a particular research topic, and the search method, inclusion of studies and interpretation of the studies reviewed relies upon the judgement and expertise of the authors. Systematic reviews typically set out a clearly defined research question or hypothesis and the search method and inclusion of studies are based on predefined protocols / search criteria (Baethge *et al*., 2019; Pae, 2015).

2. Technologies and supply

The way in which heat pumps or hydrogen-based appliances can or could deliver space and water heating to households varies greatly. This section will introduce the two technologies at hand, discussing their uses, current market conditions in the UK, and environmental implications, forming the basis of the ongoing discussion around decarbonisation of domestic heating.

2.1 Heat Pumps

2.1.1 Types of heat pumps

In a domestic setting, a heat pump (HP) can be installed as a low-carbon means to provide space and water heating. Some HPs also offer cooling in the form of reversible air-to-air pumps. They are powered by electricity and allow for the efficient transfer of heat from an external source (air, ground, or water) into a building. Table 1 gives an overview of the most common types of HPs, classified by their heat source and how it is distributed e.g., an air-to-water heat pump uses ambient air as a heat source and transfers heat into a building via the central heating system either in radiators or underfloor heating.

A HP that uses water as a heat transfer medium (as in a central heating system) is also referred to as a hydronic HP.

Heat pump systems can consist of a single exterior unit (monobloc) or be a split system. Split systems feature two units (one indoor, one outdoor) that can be situated up to 30 meters apart, connected via internal pipework that commonly uses hydrofluorocarbons and therefore require the installer to have a specific F-gas qualification. However, the exterior unit in a monobloc system houses the entire refrigeration cycle, and as such no F-gas qualification is required for its installation. In the UK, air-to-water monoblocs made up 69% of the heat pump market in 2019 (BEIS, 2020a, p.13).

Table 1 Types of heat pumps

Heat source	Output	Name	Acronym
Air	Hot air via fan	Air-to-air	ASHP
	Radiators / Underfloor heating	Air-to-water	
Ground	Hot air via fan	Ground-to-air	GSHP
	Radiators / Underfloor heating	Ground-to-water	
Water*	Hot air via fan	Water-to-air	WSHP
	Radiators / Underfloor heating	Water-to-water	

*Water source HPs are further divided into open- and closed -loop options. Closed loop systems use refrigerant, similar to a ground source heat pump. Open loop, however, abstracts water from a river, or aquifer and circulates this around the system in place of refrigerant, discarding used water upstream once a cycle is complete.

Another option that combines a fossil-fuelled boiler and HP is a Hybrid Heat Pump (HHP). This combination is a lower carbon option than a single conventional boiler and can optimise operational costs and energy efficiency, with carbon emissions that can fluctuate dependent on the heat source.

2.1.2 How heat pumps work

Heat pumps work through a series of heat transfers, with the aim of providing warmth to an indoor space and hot water. The process used is similar to a refrigeration unit in reverse. Figure 2 gives a simplified version of how a hydronic (e.g. air-to-water) HP works (BEIS, 2020a).

1. The contained refrigerant has a lower temperature than the external environment, so heat transfers from the surrounding environment (air, ground, or water) to the refrigerant in the pipe.
2. The refrigerant is compressed into a superheated, high temperature and high-pressure vapour by the compressor using energy from the electricity grid. This increases the refrigerant to a useful temperature.
3. In a hydronic heat pump, a plate heat exchanger is used to transfer heat from the refrigerant into the central heating system.
4. Water returning from the heating system inside the building enters the plate heat exchanger. Here heat from the superheated refrigerant is absorbed by the water, which then leaves the heat exchanger at a higher temperature.
5. Water leaves the heat exchanger and enters the building to be used for heating and hot water.
6. Having transferred much of its heat, the refrigerant is cooler and in liquid phase. It then enters an expansion valve, which will further decrease its temperature.
7. The refrigerant is now at a low pressure and temperature and exists as a liquid/vapour mix to repeat the cycle.

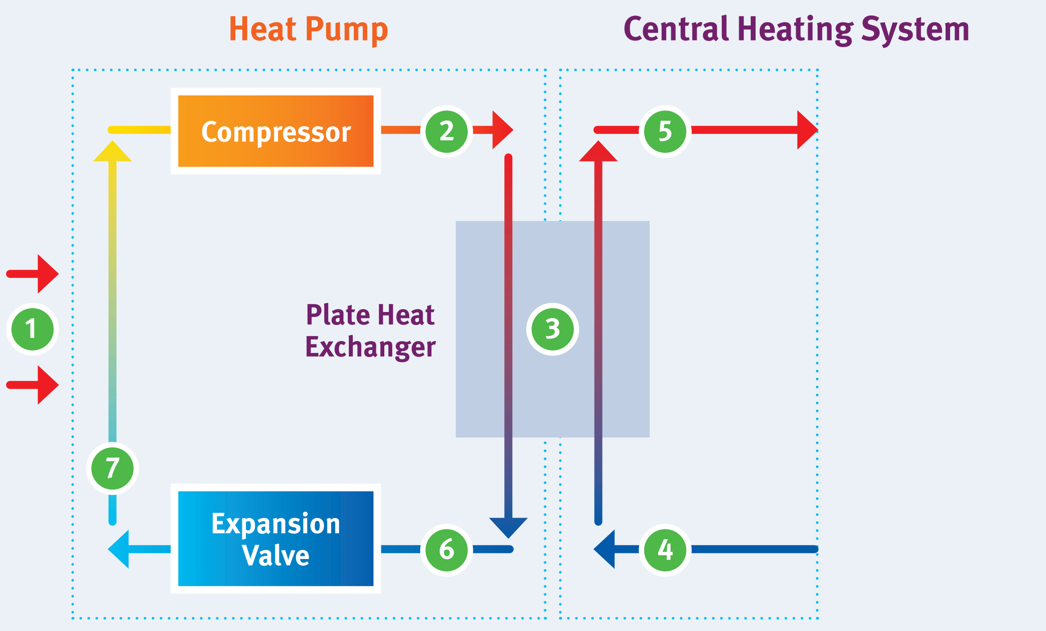

Figure 2: Simplified diagram of how a hydronic heat pump functions

In Figure 2, an air output HP such as air-to-air HP would connect to a fan at point 3, expelling warm vapour and subsequently cooling down the refrigerant before passing through an expansion valve.

2.1.3 Efficiency of a heat pump & cost of installation

The efficiency of a heat pump is measured by its Coefficient of Performance (CoP). The CoP indicates the amount of heat produced per unit of electricity consumed. The higher the CoP, the more efficient the heat pump. As an example, a CoP of 4 suggests that for every 1 kWh of electricity used to power a heat pump, 4 kWh of heat is output. The average CoP of a heat pump is called the Seasonal Performance Factor (SPF) and reflects the technology's efficiency over the course of the year and may also include other elements of the heating system such as circulation pumps. This measure is commonly used as a HP's efficiency varies across different seasons, as external temperatures impact how much heat is transferred from the surrounding environment to the refrigerant. For example, a warmer external temperature would mean the compressor does not need to work as hard to reach a desired temperature, increasing its efficiency (Kensa Heat Pumps, 2014).

Table 2 details the Theoretical CoP, SPF, Observed SPF and respective installation costs for some of the most common heat pumps in the UK. As the most common brands in the UK, theoretical CoP is the reported efficiency by Mitsubishi and Kensa for a range of their air and ground source heat pumps, respectively. The average climate SPFs reported in brackets in the second column are provided by the European Heat Pump Association and are comparable to the observed SPFs. The observed measurements are taken from a sample of 700 heat pumps installed under the Renewable Heat Premium Payment Scheme in the UK, and were calculated with data collected between 31st October 2013 to 31st March 2015. The distinction between these two values is made as there are a number of variables that influence just how efficient a HP is. For instance, the position and orientation of an air-to-air HP in relation to a building as well as the quality of installation impact its efficiency, resulting in the lower observed CoPs (Hong-Wen *et al*., 2020).

Table 2 Heat pump efficiency and expected cost of installation

Heat source	Theoretical CoP[1,2] (SPF)[3]	Observed SPF[4]	Cost of Installation[5]
Air-to-water	2.5 – 2.8 (2.6)	2.45	£8,750 – £21,550
Air-to-air	2.5 – 2.8 (2.6)	2.45	£2,400 – £8,800
Ground-to-water	3.5 – 4.5 (3.2)	2.82	£13,200 – £27,350

Notes to Table 2

1. Source: Mitsubishi Electric (2020)
2. Source: Kensa Heat Pumps (2021)
3. Source: EHPA (2021c)
4. Source: Lowe *et al*. (2017)
5. Source: Myers *et al*. (2018)

2.1.4 UK heat pump market and international comparison

As of 2020 there were 265,000 heat pump installations in the UK (EHPA, 2021c), with 87% of these estimated to be air source heat pumps, 9% ground and water source HPs combined, and 4% HHPs (BEIS, 2020a, p.10 – 11; de Best, 2021). When considered alongside the 26 million fossil-fuelled boilers present in the UK, this means the HP market is marginal, making up less than 1% of installed heat capacity (BSRIA, 2017).

The majority of these heat pumps are hydronic and so rely on radiators and/or underfloor heating to provide warmth (EHPA, 2021b). Their popularity within the UK is partly driven by convenience and climate as most heating in the UK is already provided through radiators in line with hydronic systems and there is little demand for air-conditioning within homes (BEIS, 2020a, p.11).

Across Europe, the Nordic countries, Estonia, Switzerland and France have the most developed markets, normalised by heat pumps installed per 1000 households in 2018 (Figure 3). While these leading countries range from 8% to more than 50% of heat pumps installed in homes, the UK has the second lowest installation stock of the countries shown at less than 1% of households. One factor that has benefitted the speed of heat pump deployment in France and northern Europe is the acceptance of electricity as an energy source for domestic heating (Nowak, 2018). In these countries, a large part of their energy supply is provided by direct electric heaters, so the switch to heat pumps saves on final energy, emissions, and cost. Although Italy has a large gas grid, heat pump deployment increased after the introduction of a special tariff in 2014. Despite the tariff no longer accepting new applications, summertime weather conditions means reversible air-to-air heat pumps remain popular (Pieve and Trinchieri, 2019).

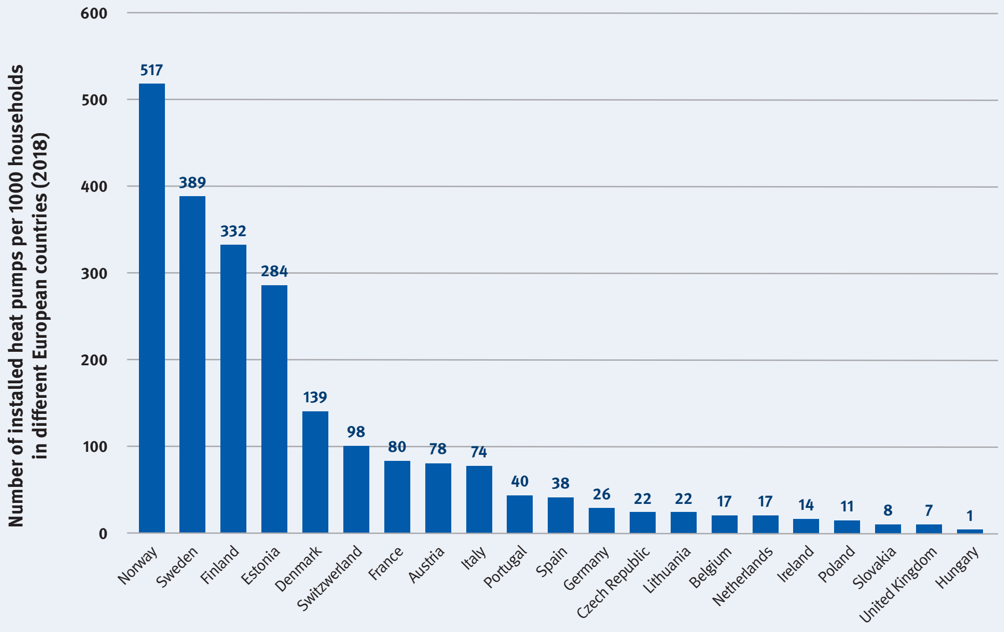

Figure 3: Number of installed heat pumps per 1000 households in different European countries (2018)

Notes to Figure 3

1. The chart data is sourced from EHPA (2021c).
2. The column values are rounded to 0 decimal places.

2.1.5 Carbon intensity

Compared to a natural gas boiler, the carbon emissions per unit of useful energy delivered are much lower. A lifecycle assessment conducted by Sevindik *et al*. (2021) took into consideration the manufacturing, transportation, assembly, installation, maintenance, use, and disposal of an ASHP, GSHP, and natural gas boiler to compare the difference in carbon intensities of the two technologies. They found that per kWh of thermal energy generated for domestic heating, 0.11 $kgCO_2e$ and 0.1 $kgCO_2e$ are produced by an air and ground source heat pump, respectively. On the other hand, the carbon intensity of a natural gas boiler was found to be 0.24 $kgCO_2e$ per kWh of thermal energy. These figures are based on the electricity mix of the UK in 2018, with assumed CoPs of 2.8 (ASHP) and 3.4 (GSHP). Overall, lifetime emissions (assumed to be over 20 years for both technologies) were 96.2 tCO_2e for a natural gas boiler compared to 42.3 tCO_2e and 38.8 tCO_2e for an ASHP and GSHP, respectively.

2.2 Hydrogen

2.2.1 The case for low-carbon hydrogen

When combusted, hydrogen does not emit any CO_2 (although it can result in emissions of NOx air pollutants – see section 4.3.4) and, as a versatile energy carrier that can be used in a range of sectors, several countries have outlined hydrogen strategies to address the growing need to decarbonise (COAG Energy Council, 2019; USDOE, 2020a; BEIS 2021l). With regards to domestic heating, its application could be similar to that of natural gas, with homes converting to hydrogen boilers and appliances, suiting the UK's extensive gas grid and consumption habits. However, despite being the most abundant element in the universe, there are extremely limited natural sources of pure hydrogen. As a result, it is not easily extracted for commercial use and instead requires energy intensive production processes (see Box 1), the most common method being steam methane reformation (SMR) using natural gas.

At an international level, approximately 97% of hydrogen production relies on fossil fuels, resulting in 830 million tonnes of CO_2 being emitted per year, the equivalent of the UK and Indonesia's annual CO_2 emissions combined (IEA, 2019, p.17; Jaganmohan, 2021). Alternative production methods that are both widely deployable and suitable for a net zero transition are therefore required. These could include the electrolysis of water using low-carbon electricity or SMR combined with carbon capture and storage (CCS).

2.2.2 Production methods

2.2.2.1 Blue Hydrogen

Blue hydrogen is the production of hydrogen from fossil fuels but with the resultant CO_2 prevented from reaching the atmosphere through use of CCS technology. It has the advantage of relying on existing technologies that are widely deployed and already used to produce hydrogen for industry e.g., gasification and SMR. However, CCS has not been deployed at the scales envisaged and the amount of CO_2 captured throughout the process is dependent on the type and source of the fossil fuel used. Currently, hydrogen facilities coupled with CCS capture only 50 – 60% of plantwide CO_2 emissions, but demonstration plants have recorded capture rates above 90% (USDEO, 2020b; Bauer *et al*., 2021), however no such facilities currently exist in the UK.

2.2.2.2 Green Hydrogen

Despite electrolysis predating lab scale SMR (grey hydrogen), the reduced cost of hydrocarbons led SMR to develop into the dominant hydrogen supply method with hydrogen production from electrolysis currently limited to demonstration projects (Gielen, Taibi and Miranda, 2019; O'Malley and Sunny, 2021). Within the UK data suggests that it currently makes up less than 1% of hydrogen capacity (Fuel Cells and Hydrogen Observatory, 2021). Theoretically, green hydrogen could be a strong candidate for net zero, given its low emissions profile, however, it faces several barriers to its large scale adoption in domestic heating from the scale of required renewables deployment to cost competitiveness (see Section 4).

2.2.2.3 Turquoise Hydrogen

Methane pyrolysis has been suggested as a timely alternative to grey hydrogen produced through SMR. As it is more environmentally friendly than grey hydrogen and less energy intensive than green hydrogen, it could become a valuable source of low-carbon hydrogen (Sànchez-Bastardo *et al.*, 2020, p.1589). The process is, however, still in the experimental phase and unlikely to be commercialised in the next decade.

2.2.3 Hydrogen production in the UK and industrial clusters

Within the UK, it is estimated that the current hydrogen production capacity is between 3 – 5 GW (Sunny *et al.*, 2020), the majority of which is produced via SMR and used within industries such as oil refineries. The UK's strategy for decarbonisation within industry plans to utilise low-carbon hydrogen in industrial clusters (HM Government, 2021). These are places where there has been coordinated effort across industries to co-locate, allowing them to benefit from shared decarbonisation infrastructure and reduced costs related to carbon abatement.

Certain attributes suit the placement of hydrogen production in industrial clusters, for example, high demands for hydrogen in surrounding locations as well as access to underground storage (Sunny *et al.*, 2020). In the case of blue hydrogen, geological storage for CO_2 also provides convenience (ibid.), whilst green hydrogen production may suit locations close to renewables hubs. In its industrial decarbonisation strategy, the government sets out plans to create four low-carbon industrial clusters by 2030, and at least one net zero cluster by 2040 (HM Government, 2021, p. 86). In order for these industrial clusters (and blue hydrogen production within them) to be low-carbon, the government's strategy requires that CCUS would be operational in two industrial clusters by the mid-2020s, demonstrated at scale through the 2020s and that approximately 3 $MtCO_2$ of industry emissions would be captured per year by 2030 (Ibid.). Currently, around 40 $MtCO_2$ is captured by operational CCUS facilities globally (see section 4.3.6.2), however there are not yet any operational facilities in the UK.

Recently, BP announced plans to construct the UK's largest blue hydrogen production facility in Teeside (BP, 2021). The project aims to produce 1 GW of blue hydrogen by 2030; one-fifth of the UK's Ten Point plan ambition. The location is complementary to the existing hydrogen storage and distribution capabilities present in the area as well as being near North Sea storage sites and pipe corridors (ibid.).

The industrial cluster approach the UK is taking towards hard to decarbonise sectors may be able to assist in the roll-out of hydrogen in domestic heating through the strategic placement of hydrogen fuelled homes. One such example of this is the H21 North of England project, currently in planning, which could use blue hydrogen produced by Equinor transmitted via a gas distribution network to industrial, commercial and domestic appliances (Sadler *et al.*, 2018, p.6).

» BOX 1: Colours of Hydrogen

Hydrogen is often referred to by colours, which indicate its production method – see Figure 4.

Green Hydrogen Electrolysis is a process that uses electricity to split water into hydrogen and oxygen. When renewable electricity is used the result is “green” hydrogen. Green hydrogen is often favoured as a future alternative to grey hydrogen, given the lower carbon emissions produced (see below).

Grey Hydrogen Natural gas can be split into hydrogen, carbon monoxide, and carbon dioxide through a process called steam methane reformation. Most the world’s hydrogen is currently “grey” having been produced through this method. However, the carbon dioxide by-product in this process is released into the atmosphere, contributing to emissions.

Black/Brown Hydrogen Syngas (hydrogen, carbon monoxide, carbon dioxide) is produced in a process called gasification using coal as a feedstock. Hydrogen can be isolated from the syngas mixture and dependent on the type of coal used, lignite or bituminous, is known as brown or black hydrogen, respectively.

Blue Hydrogen The process to make blue hydrogen is similar to grey (and black/brown) hydrogen, only the carbon dioxide produced alongside the hydrogen in SMR or gasification is captured and then stored. This mitigates against the carbon dioxide emissions from grey hydrogen, although there are still upstream emissions produced by methane leakage.

Turquoise Hydrogen Although also reliant on natural gas as a feedstock, the process ascribed to turquoise hydrogen does not produce carbon dioxide gas, when powered with renewable electricity. Rather, methane pyrolysis produces carbon in a solid form, which can be used in other applications and avoids the need for CCS.

Pink & Yellow Hydrogen These terms often refer to hydrogen production through electrolysis but specify the power source as nuclear (pink) or solar (yellow).

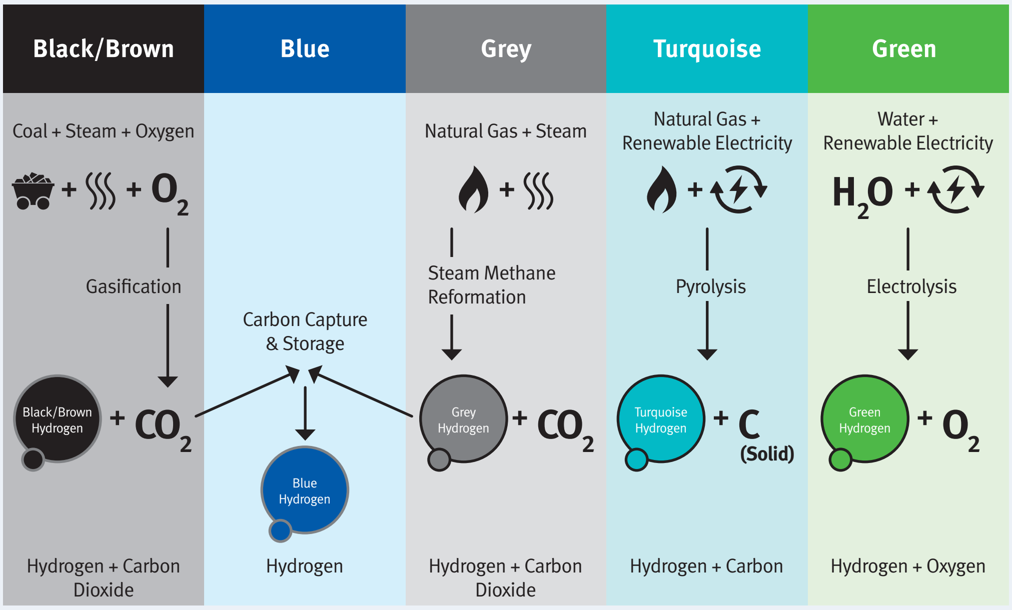

Figure 4: Hydrogen production method by colour.
Based on Edwardes-Evans *et al*. (2020) and National Grid (2022)

2.2.4 Hydrogen trials in the UK

Hydrogen blends have already been trialled at Keele University, where the private gas network was blended with 20% hydrogen. The trial "HyDeploy" was completed in March 2021, with plans to expand to a public network in North-East England (HyDeploy, 2021). The UK Government has outlined its ambitions to support full hydrogen heating trials in local neighbourhoods by 2023 through the use of hydrogen boilers in homes, and in larger villages by 2025, building up to a pilot hydrogen town by the end of the decade (HM Government, 2020, p.10 – 11). H100 in Fife, Scotland will aim to supply 300 homes with hydrogen heating using a new network alongside the existing gas infrastructure, over the course of four years (SGN, 2021).

2.2.5 Carbon intensity

2.2.5.1 Grey hydrogen

With the production of grey hydrogen, direct CO_2 emissions from SMR were found to be the largest source of emissions in a lifecycle assessment conducted by Antonini *et al.* (2020), accountable for more than six times the emissions attributed to the natural gas supply chain. Overall, it is estimated that the amount of CO_2 produced per kilogram of grey hydrogen ranges from 8.9 – 12.9 $kgCO_2e$ (Bhandari, Trudewind and Zapp, 2014).

2.2.5.2 Blue hydrogen

With CCS, dependent on the capture rate and method used, expected carbon emissions fall to 3.4 $kgCO_2e$ per kg of H_2 (Mehmeti *et al.*, 2018, p.9), however, the potential impact blue hydrogen may have is disputed. Although the majority of literature available on the subject reports blue hydrogen having a lower emissions intensity when compared to grey (Sunny, Mac Dowell and Shah, 2020; Barrett and Gallo Cassarino, 2021; Bauer *et al.*, 2021) the figures can differ dependent on the assumptions applied e.g. methane emissions rate of the natural gas supply chain, the efficiency of the carbon removal, and global warming potential (GWP) metric (Bauer *et al.*, 2021).

In their central assumption, Barrett and Cassarino (2021) determine that blue hydrogen would have a 71 – 81% emission reduction compared to burning natural gas over a 100-year time horizon and 61 – 79% reduction on a 20-year time horizon. The difference between these values is attributed to the relatively short atmospheric presence of methane so the GWP used over a longer time horizon is smaller. One example that found blue hydrogen to have a higher impact than burning natural gas is Howarth & Jacobson (2021). On a 20-year timescale, they report that the carbon emissions produced from blue hydrogen were only 9 – 12% less than for grey and fugitive methane emissions were higher. Overall, the greenhouse gas footprint of blue hydrogen was estimated to be 20% greater than burning natural gas (ibid.). Given the uncertainty surrounding its impact, therefore, blue hydrogen needs to be carefully regulated to ensure it is net zero compliant. The government has recently consulted over options for an emissions standard which defines 'low carbon' hydrogen, including a method to calculate greenhouse gas emissions from hydrogen production, and a greenhouse gas emissions threshold to assess different low carbon hydrogen production pathways (BEIS, 2021c).

2.2.5.3 Green hydrogen

Electrolytic hydrogen is only as clean as the electricity it uses. MacDowell *et al.* (2021), detail that for electrolytic hydrogen to be less carbon intensive than SMR combined with CCS, the carbon intensity of the grid should at least be within the range of 30 – 140 $kgCO_2/MWh$, with the UK's 2020 average being at 181 $kgCO_2/MWh$. When reliant on wind energy the carbon intensity of green hydrogen is reported as being between 0.97 – 2.21 $kgCO_2e$ per kg H_2 (Bhandari, Trudewind and Zapp, 2014 p. 159; Mehmeti *et al.*, 2018, p.10). Whilst dramatically lower figures compared to grey hydrogen, it is still worth noting that these figures are not net zero aligned and would require further abatement still.

2.3 Summary

This section has explored the current conditions surrounding heat pump deployment and hydrogen roll-out in the UK. Heat pumps offer low-carbon alternatives to natural gas boilers. Air and ground source heat pumps have been found to produce 0.11 kgCO_2e and 0.1 kgCO_2e per kWh of thermal energy respectively, in comparison to a carbon intensity of 0.24 kgCO_2e per kWh of thermal energy for natural gas boilers. These intensities are based on the UK electricity mix in 2018 and assume CoPs of 2.8 (ASHPs) and 3.4 (GSHPs). Within the UK, air-to-water heat pumps occupy 69% of the heat pump market, however, less than 1% of the UK's domestic heat capacity is currently provided by heat pumps.

Hydrogen capacity is estimated to be around 3 – 5 GW in the UK, the majority of which is used in industrial processes. Most hydrogen production currently relies on the extraction and reformation of fossil fuels and as such low-carbon alternatives are required when assessing its compatibility with net zero. Blue hydrogen, combining fossil fuelled hydrogen production with CCS, alongside green hydrogen, which is produced through renewably powered electrolysis, are two options that could offer an alternative solution. Green hydrogen from wind-powered electrolysis has been estimated to produce 0.97 – 2.21 kgCO_2e per kg of H_2, compared to 3.4 kgCO_2e per kg H_2 for blue hydrogen and 8.9 – 12.9 kgCO_2e per kg H_2 for grey hydrogen. However, the carbon intensity of blue hydrogen is disputed and can vary considerably based on various factors such as the methane emissions rate from natural gas, the availability and efficiency of CCS, and the global warming potential metric used. Both blue and green hydrogen require technological development and upscaling to provide the amount of hydrogen capacity required for domestic heating, with limited infrastructure in place to complement their roll-out.

3. Distribution and demand

This section will consider how a heat pump or hydrogen strategy could evolve to meet the growing demands for low-carbon domestic heating and what this may mean for end users. Despite the current heat pump market being relatively small in the UK, manufacturers are confident that this can develop at a successful rate, given that heat pumps are a mature technology and widely deployed in countries outside of the UK. Wider heat pump adoption by households would require thorough installation practices and sufficient consumer acceptance due to their fundamental differences to gas boilers. These points are elaborated on in Sections 4 and 5. The consumer experience of hydrogen boilers may be relatively similar to that of gas boiler end users connected to the grid, however its delivery is more complex with the need to upscale production, supply chains, and storage, and repurposing the gas grid bringing its own complexities.

3.1 Heat Pumps

3.1.1 Supply Chain

In the UK, approximately 85% of residential buildings (23 million) are connected to the gas grid (CCC, 2016). The annual deployment of at least 600,000 HP systems by 2028 is thought to be necessary to keep the UK on track to reach net zero and by 2050 the CCC estimate that nearly 19 million HPs will need to be installed in their "Further Ambition" scenario (CCC, 2019c, p.84).

Imminent action is necessary to develop the market and reduce costs for low-carbon heating options (BEIS, 2021f, p.11). Currently, the UK heat pump market is relatively small (see 2.1.4) with only a few UK-based manufacturers, meaning that most stock is imported from abroad. As HPs are expected to play a large part in the decarbonisation of domestic heating, understanding the potential growth of the UK's manufacturing supply chain could help optimise their roll-out (BEIS, 2020a, p.9). Whilst achieving 19 million installed HPs by 2050 will prove challenging, the support of well-established industries that offer similar components and transferable skills could help with deployment.

3.1.1.1 Meeting demand

According to interviews conducted by BEIS with HP manufacturers, achieving 19 million installed HPs in the UK by 2050 is unlikely to cause a manufacturing issue, with high confidence in their ability to increase supply by 25 – 30% year-on-year, for the next 15 years. This would mean an annual installation rate of 1,149,000 HPs by 2030, in line with the CCC recommendations (BEIS, 2020a, p.84).

The confidence of manufacturers to achieve this level of roll-out is due to several reasons (BEIS, 2020a). Firstly, HPs are a mature technology, having been produced on a large scale outside of the UK for many years. They already have well-established supply chains in place through which most HP components (except compressors) are sourced from outside of the UK, with low manufacturing demand not enough to support component manufacturing. However, existing UK based HP manufacturers have seen increases in local businesses sourcing components with increasing demand for HPs. These local supply chains could develop as required to meet the UK's growth in demand providing it is cost-effective to do so. Further to this, manufacturers of technologies that rely on similar materials and components (e.g. boilers, air conditioners, fridges) could switch to heat pump manufacturing if viable. As other countries' markets have grown and developed, production capacity has not limited the supply chain, with accurate forecasting being an important factor in enabling the market to meet demand (BEIS, 2020a, p.84).

3.1.1.2 Establishing UK based manufacturers

The boiler industry is well-established in the UK with 55% of demand being met through domestic based manufacturing (BSRIA, 2021). Whilst boilers may differ technologically to heat pumps, they are constructed of similar materials and the industry offers complementary skills to HP production. Air conditioning (AC) systems also use similar materials to HPs, with some European manufacturers utilising the same facilities for AC and HPs production.

In the UK, three main companies occupy two-thirds of the air-to-water heat pump market (69% market share in 2019): Mitsubishi 31 – 35%; Daikin 16 – 20%; and Samsung 11 – 15% (BEIS, 2020a p. 12 – 13). Of those three companies, Mitsubishi is the only one to have their heat pumps manufactured within the UK, alongside Global Energy Systems and Big Magic Thermodynamic Box, whose shares in the UK market lie below 1% (ibid.). Recently, Vaillant, whose market share lies between 1 – 5%, announced plans to expand their boiler manufacturing site in Derby to produce air-to-water heat pumps, starting in 2022 (Vaillant, 2021). The UK ground source heat pump market is even more concentrated, with two companies sharing two-thirds of sales: Kensa 41 – 45%; and NIBE 16 – 20%; producing their heat pumps in the UK and Sweden, respectively (BEIS, 2020a p. 13). Across both technologies, 68% are imported into the UK whilst 32% are produced in the UK (BEIS, 2020a p. 53).

According to the European Heat Pump Association (EHPA) the 265,000 installed heat pumps in the UK has helped support 2,000 jobs in 2020 required for their production, installation and maintenance (EHPA 2021a). Looking forward, the anticipated increase in UK based manufacturing could help support 10,000 new jobs (BEIS, 2021f). There are only 1,100 certified heat pump installation companies in the UK (ibid.). It is estimated that an additional 12,400 heat pump installers will be required by 2025 and 50,200 by 2030 to support the growing market (HPA, 2020). To achieve this, there will need to be a level of encouragement aimed at gas engineers, electricians and those with relevant and transferable skills to retrain (BEIS, 2021f, p.56).

3.2 Hydrogen

3.2.1 Transmission & Distribution

The UK has an extensive gas network composed of transmission, distribution, and service pipelines covering approximately 7,600 km, 280,000 km, and 255,000 km, respectively (Dodds and Demoullin, 2013). Transmission networks supply high-pressure natural gas from import terminals to regional distribution networks, which gradually lower the pressure at reduction stations, so it is suitable for delivery to end users via short service pipelines. The pipeline material differs dependent on its age and use; post-1970 polyethylene was used in distribution pipelines, whereas prior to this steel and iron were favoured for transmission and distribution, and copper for service pipelines.

3.2.1.1 Suitability for hydrogen delivery

Ensuring the gas grid is safe and suitable for hydrogen delivery is fundamental for a national conversion, however, given the differences between the two gases this would not be a straightforward transition. Factors influencing the ability of the current gas network to facilitate hydrogen delivery include the material, pressure, age, and condition of the pipework (Haeseldonckx and D'haeseleer, 2007). As the pressure increases, embrittlement is more likely to occur in hydrogen pipelines constructed of high-strength steel, which is problematic for the integrity of high-pressure transmission and distribution segments, and may require their replacement (Dodds and Demoullin, 2013).

Pipeline Type	Component	Pressure (bar)	Length (km)	Composition	
				Pre-1970s	Post-1970s
Transmission	Transmission	70 – 94	7,600	High-strength Steel	
Distribution	High Pressure	7 – 30	12,000	High-strength Steel	
	Intermediate Pressure	2 – 7	5,000	Steel	HD polyethylene
	Medium Pressure	0.075 – 2	30,000	Iron	MD polyethylene
	Low Pressure	< 0.075	233,000	Iron	MD polyethylene
Service	Building Connections	< 0.075	255,000	Copper	MD polyethylene

Table 3 UK Gas Network Overview. Based on Dodds and Demoullin (2013)

Polyethylene, used in distribution and service pipelines since the 1970s, should be suitable for the distribution of hydrogen. This material has been used in the Iron Mains Replacement Programme (IMRP), which began in 2002 and aims to replace most iron pipelines within 30 metres of homes within 30 years. The service was started due to societal concern of the safety of cast iron pipelines, and once complete will leave limited iron pipework on the distribution system. As polyethylene is more porous to hydrogen, however, leakage may increase in transitioning away from natural gas. Studies have however shown this figure to be incremental (0.001% of average annual volume) and not enough to present a safety hazard (Haeseldonckx and D'haeseleer, 2007; Dodds and Demoullin, 2013).

3.2.1.2 Cost of conversion

The cost of converting the grid will depend on the existing infrastructure, how much of it requires replacing or upgrading, and the cost of replacing each component. Although the IMRP, with an expected completion date of 2032, will continue regardless of a hydrogen conversion, research commissioned by BEIS estimates that following the completion date 5% of iron and 100% of steel pipework will still need to be replaced across the gas grid (Element Energy, 2018, p.77 – 82). Further to this, certain components such as gas meters and detectors may require replacement to ensure compatibility, which come with associated labour costs.

In their base case evaluation of cost, Element Energy estimate a capital expenditure of £22.2 bn to make the grid suitable for hydrogen distribution (ibid.), with the largest expected costs arising from the replacement of domestic gas meters and their labour and installation costs (£7 bn combined). With an estimated 23 million consumers connected to the gas grid (CCC, 2016), the conversion of the gas grid would amount to approximately £960 per household. There are, however, many uncertainties around this estimate, which revolve around the lack of understanding as to whether all gas meters would require replacement and just how much of the existing infrastructure is suitable for hydrogen after the IMRP.

3.2.2 End-use

On the consumer side of the hydrogen conversion, appliances, and the way they are used, will require some adjustment. Hydrogen levels in the HyDeploy trial (see 2.2.4) were limited to 20% when blended with natural gas for three main reasons:

- This level was deemed unlikely to increase the risks associated with the use of natural gas for consumers or members of the public by the Health and Safety Laboratory in the UK (Hodges *et al.*, 2015);
- Consumers are not affected from a supply or demand standpoint with this blend composition (HyDeploy, 2017);
- All gas appliances manufactured after 1996 are operational at a 23% hydrogen mix (HyDeploy, 2017).

In order to increase this 20% blend to 100% hydrogen for a given area, a property-by-property conversion would be required. Frazer-Nash (2018) note that, “a switchover will require multiple visits to collect information and undoubtedly result in some physical disruption to the property” (Ibid., p.24). Householders might need to be offered incentives by way of compensation for this disruption (Frazer-Nash, 2018). This process would comprise of initial house surveys, note any necessary pre-conversion preparations, assess the condition of existing pipework and upgrade it if required, and take an inventory of gas appliances. Hydrogen boilers and appliances (discussed in Section 4.3.3) will be required for the domestic use of hydrogen, which may appeal more to consumers given the similarities they would bear to gas appliances (Williams *et al.*, 2018).

3.2.2.1 Delivery of conversion

In the UK, the Gas Safe Register would be well placed to oversee the conversion. In 2018, it consisted of over 130,000 individual engineers from 74,000 employers, of which 80% are qualified to work with natural gas within residences. The size and success of a hydrogen roll-out could be dependent on upskilling current operatives and establishing a conversion workforce. Frazer-Nash Consultancy estimate that with no growth in the existing Gas Safe engineers work force, conversion could take up to 16 years, but with a dedicated team of 100,000 the necessary residential conversions could, in theory, be complete within 4 years indicating the importance of a specialised task force (Frazer-Nash, 2018, p.4).

3.3 Summary

The UK heat pump market is relatively small, however, manufacturers are confident in their ability to increase heat pump deployment to suit the growing need for low-carbon domestic heating options. This is aided by complementary technologies that are established and utilise similar components e.g., boilers and air-conditioners. From an end-use perspective, heat pumps are likely to be experienced as a new technology to many homeowners and will require adjustments to how they are used in comparison to familiar heating technologies such as boilers (discussed further in Section 4).

The extensive gas grid in place could be repurposed for the wide-scale deployment of hydrogen. The Iron Mains Replacement Programme (currently underway and due to finish in 2032) will mean that a large part of the distribution system will be suitable for hydrogen, however, once complete there will still be a need to replace steel pipelines if the transmission pipeline is repurposed. A transition to 100% hydrogen in a given area would involve some level of disruption to householders in preparing existing properties for the conversion. Post-installation, consumers are nevertheless likely to experience the use of a hydrogen boiler as a relatively familiar technology, given the similarities it would bear to gas boiler heating systems currently widespread in the UK.

4. Barriers to Implementation

Whilst the discussion has so far orientated around how a heat pump or hydrogen-based strategy could theoretically be made possible, the present section will analyse some of the main barriers regarding their implementation. Heat pumps' main concerns revolve around high upfront costs to homeowners, consumer preferences, and the challenge full scale electrification may bring to the power grid. Hydrogen, however, faces issues in scaling up production of a relatively nascent technology; in creating demand, becoming cost-competitive, and uncertainties regarding safety. In this section, we first consider several general barriers to uptake which apply to both technologies, including poor building energy efficiency and low consumer awareness of low-carbon and alternative heating options. We then discuss specific barriers in relation to heat pumps and hydrogen in turn. The section ends with a review of literature that compares the two from a cost perspective on both a system-wide and household level.

4.1 General barriers to heat pump and hydrogen heating deployment

4.1.1 Building energy efficiency

The UK has one of the oldest and least thermally efficient building stocks in Europe (ACE, 2015) and improving this building energy efficiency will help to reduce carbon emissions from heating no matter which mix of heat sources and technologies are deployed (Rosenow and Lowes, 2020). Doing so will also help to insulate the UK against disruptive events such as the current energy price spikes (Hannon and Clarke, 2021). While the energy efficiency of homes has improved in the UK over the last decade, still only 40% of dwellings are in Energy Performance Certificate (EPC) bands A to C (MHCLG, 2021). In order to achieve net zero by 2050, the Climate Change Committee estimates that building insulation will need to be improved in 15 million homes, and draught proofing installed in a further 8 million dwellings (CCC, 2020). This will require wide-scale and consistent home refurbishments over the next few decades.

4.1.2 Industry skills and training

The current UK skills base in heating and energy efficiency industries needs to be scaled up significantly to support a transition to low-carbon heating. To improve the building fabric energy efficiency of the entire UK building stock, it has been estimated that a trained workforce of 230,000 would be required by 2030, implying a need to train 12,000 workers every year until 2025, and 30,000 workers annually between 2025 and 2030 (Green Jobs Taskforce, 2021; Oswald *et al*., 2021). 1.7 million new gas boilers are installed in the UK each year, maintained by approximately 130,000 gas safe engineers (Green Jobs Taskforce, 2021; BEIS, 2021f). As noted in Section 3.1, there are currently only around 1,100 heat pump installation companies registered to the Microgeneration Certification Scheme (BEIS, 2021f), while the government's Ten Point Plan sets an ambition to install 600,000 heat pumps annually by 2028 (HM Government, 2020). The government aims to have four industrial clusters utilising hydrogen production operational by 2030, with an objective that at least one cluster would achieve net zero by 2040, requiring effective deployment of CCUS (ibid.). The demanding timescales targeted to establish these clusters suggests that recruitment and training of the requisite labour will be challenging, although there may be some scope to utilise transferable skills in the current oil and gas sector workforce (Green Jobs Taskforce, 2021).

4.1.3 Public awareness

A challenge for consumer engagement in the UK is that there is a relatively low public awareness of low-carbon or 'alternative' heating technologies (BEIS, 2021f) including heat pumps and hydrogen boilers. For example, a survey of 2,000 consumers carried out by the Energy Systems Catapult (2020) revealed that only around half of respondents were aware of low-carbon heating. Many thought that converting to low-carbon heat technologies would be difficult or expensive, and only around half realised that gas boilers contribute to climate change (Energy Systems Catapult, 2020). In a separate survey with around 1,000 respondents living in households connected to the gas grid, 42 per cent of respondents had never heard of ASHPs or GSHPs, while approximately half had not heard of hydrogen boilers (Williams *et al*., 2018).

4.2 Heat Pumps

4.2.1 Financial Barriers to Uptake

At present, heat pumps are a small market segment in the UK, comprising around 1% of installed heating systems. Compared to the mature boiler market, they are substantially more expensive to install. Running costs are higher than they need to be due to greater policy costs on electricity than gas prices (see Section 5.1.2). Analysis for BEIS conducted by Myers *et al*. (2018, p.9–11) and presented in Table 2 (section 2.1.3) estimate that air-to-water heat pumps start at around £9k to install, based on the size of the property and the amount of retrofitting required. Ground-to-water heat pumps are estimated to start from £13k, once again based on property size and required retrofitting. Air-to-air heat pumps are the cheapest installation option, ranging from £2.4k for a one-bedroom flat to £8.8k for a four-bedroom house. In comparison, costs for replacing gas boilers range from £2.2 – 6.2k depending on the size of boiler and ancillary work required on the controls and heating distribution system (Myers *et al*., 2018, p.7). The installation costs of hybrid heat pumps, where the heat pump acts in concert with a gas boiler, may reflect the costs of each separate technology as most installers will consider these as two separate installations. Similarly, servicing and maintenance costs may effectively be doubled.

In a survey of public attitudes in which around 4,000 people in the UK participated (BEIS, 2021a), 55% of respondents stated that they would only replace their current heating system when it breaks down or starts to deteriorate. An additional one in five (19%) would however consider replacing their heating system while still operational. Similarly, in a primary research study of around 2,900 household owner-occupiers in Great Britain, Ipsos MORI & EST (2013) found that most replacements were prompted either by heating system breakdown (30%), anticipated breakdown as homeowners' heating systems near the end of their life (14%), a need for frequent repairs (14%), or the system no longer operating effectively (9%). There is a risk therefore that many consumers will go for a quick and familiar replacement as the performance of their current heating system starts to decline towards the end of its lifespan, or following a break down. Research undertaken in 2015 by Clarke (2018) suggested that consumers at that time had a 'tipping point' of approximately £3k for low-carbon heating installation, above which they would not pay. The cost for even a simple air-to-water heat pump installation is substantially over this price, meaning that a cost reduction or subsidy will be required to upscale this technology.

4.2.2 Consumer Preferences, Installation & Maintenance

Heat pump installation requires several steps to provide efficient heating within a home. An on-site survey is carried out to assess the energy efficiency of the home as well as the location and size requirement of the outdoor unit, heat distribution method (e.g., underfloor heating, radiators), installation level, and more. Several alterations may be necessary in the event of a heat pump being installed, such as the addition of a hot water tank, buffer tank, insulation upgrades, and radiator and pipework replacements. If a ground source heat pump is being installed this will also require groundwork to place subterranean pipes. If homeowners want to take advantage of government support mechanisms to fund their installation, such as the Renewable Heat Incentive (RHI), then the installation of the HP must be carried out by a MCS approved installer. However, there is currently no certification required by law for the installation of a heat pump if it is privately funded.

Once installed, day to day use differs between heat pumps and boilers; whereas boilers can be turned on and off and react quickly to a desired change in temperature, heat pumps are designed to run for longer periods of time at a continuous pace. This is due to the difference in temperature reached by the two systems. In the case of space heating, heat pumps deliver heat between 35 – 60°C, which is comparably lower than a conventional fossil fuelled boiler, capable of reaching temperatures over 80°C (BEIS, 2021d, p.6). The contrast in temperature is the reason why heat pumps suit the instalment of larger radiators and work better with underfloor heating; both options having larger surface areas to emit heat. Retrofitting an existing property to effectively utilise a heat pump instead of gas central heating, therefore may entail a certain level of disruption. Replacement of radiators and upgrading of insulation measures will therefore be needed in addition to the heat pump installation itself in many homes. However, improved insulation measures will be required in any case for many properties to meet UK net zero targets. Well-insulated homes will allow for more efficient retention of lower-temperature heat, increasing the efficiency of heat pumps substantially. Newbuild houses will require little or no modification for heat pump installation due to improved insulation building regulations.

Siting and competent installation of heat pumps is critically important to maximise their efficiency. Poor siting of outdoor units can decrease efficiency substantially, leading to greater running costs and poor customer satisfaction. Installations may also require substantial modification to the heat distribution system in some homes and installation of a hot water tank if one does not already exist. There are fewer qualified installers for heat pumps than for gas boilers, meaning labour costs may be higher and installers more difficult for customers to find. The UK also has a current shortage of F-gas qualified installation engineers of around 50,000 (BEIS, 2020a, p.18), who are required to install split air-source heat pump units. If the UK is expected to see a large increase of heat pump installations, upskilling of engineers will need to be a priority. Heat pumps require annual servicing to ensure they are running at peak efficiency (US DOE, 2021). Dirty filters as well as larger blockages can drastically reduce performance.

Hybrid heating systems that combine an electrically driven heat pump and a fossil fuelled boiler may have the potential to offer convenience whilst limiting emissions. Running the heat pump component on a continual basis with thermal storage offers greater emission reductions compared to a gas boiler with 55% of annual emissions being saved, and based on 2016 prices could reduce installation costs by £450 – £2,800 compared to a standalone heat pump for a typical semi-detached house in the UK (Element Energy, 2017).

4.2.3 The Power Grid

Although heat pumps can supply on average about 2.5–4 kW of heat per kW of electricity used, heat pumps draw considerable amounts of power from the electricity supply. The average household uses approximately 12,000 kWh of heat energy per year, which with a heat pump CoP of 3 would require 4,000 kWh of electrical energy for a heat pump to supply. This will place a significant extra load on the power grid – both in total across the year and at times of peak demand. The majority of the UK's heat demand occurs between November and February, with daily peaks occurring in the morning and evening. Research funded by BEIS estimates a 20% penetration of heat pumps will create a 14% increase on peak winter evening GB electricity demand – an increase of approximately 7.5 GW (Love *et al.*, 2017). A morning electricity demand peak will also begin to form. Heat pumps naturally spread their load more than gas boilers due to their method of operation, meaning that the peaks are less defined than the equivalent gas demand. However, this will still require reinforcement of local distribution networks. Methods of spreading the heat demand across the day, including thermal storage and smart controls, could help defer some physical reinforcement (ibid.)

4.3 Hydrogen

4.3.1 Hydrogen supply

In the UK Hydrogen Strategy, the government expects the demand for hydrogen in domestic heating to be relatively low in 2030; below 1,000 GWh (BEIS, 2021l, p.62). With total annual domestic gas consumption in the UK in 2019/20 being 325,183 GWh this would have represented around 0.3% of demand in 2020 (BEIS, 2020b, p.19). This approximation increases dramatically over the course of the proceeding five years, with the demand range expected to be between 0 – 45,000 GWh by 2035 (BEIS, 2021h, p.15). This would require over 5 GW of hydrogen deployment specifically for domestic heating, to meet the upper estimation of 45,000 GWh by 2035. Further, despite such a high aspiration, the Energy Networks Association (ENA) foresee the 5 GW outlined in the UK's Ten Point Plan needing to be increased to 10 GW by 2030 (ENA, 2020, p.11). This is also a sentiment advanced by the UK Hydrogen & Fuel Cell Association who claim the 5 GW is "lacking in ambition" (UKHFA, 2021, p.10). With the current UK capacity of hydrogen estimated to be between 3 – 5 GW, a current target of 5 GW of low-carbon hydrogen for industry in 2030 (HM Government, 2020; Sunny *et al.*, 2020), and no operational blue hydrogen facilities, it is uncertain as to where this supply will come from. Regardless, the two most likely candidates, blue and green hydrogen, face their own sets of challenges before wide-scale deployment (see subsections 4.3.6 & 4.3.7).

4.3.2 Storage

Storage facilities are required to support the gas grid system during intra-day and inter-seasonal periods of high demand. As hydrogen has a very low volumetric energy density, large volumes of space are required for storage. It is possible to increase its storage density so that a smaller volume of space is required, but this would require energy input or hydrogen binding materials. There is currently limited research into the wide-scale storage of hydrogen beyond underground storage. The ways in which hydrogen is stored can be divided into three main categories: 1) physical storage, 2) adsorption, 3) chemical storage (Andersson and Grönkvist, 2019).

Currently, physical storage of hydrogen in salt caverns is the only wide-scale method implemented, an example of which can be found in Teesside in the UK. This method requires minimal construction, has low leakage rates, is relatively quick to inject and withdraw hydrogen, and has reduced levels of contamination. Centralised storage sites like this would allow for large volumes of hydrogen to be accumulated during periods of low demand (summer) for use during peak seasonal heat demand (winter). However, this option is restricted by geological conditions, with only specific regions in the UK being able to cater to this form of storage e.g., Teesside, Cheshire Basin and East Yorkshire. Safety risks with the storage of hydrogen in salt caverns would also need to be managed: these include the potential release of toxic chemicals due to bacterial metabolism converting hydrogen to methane; and given hydrogen's low ignition temperature and wide flammability range, leakages could lead to fire or an explosion in confined spaces in particular (Portarapillo and Di Benedetto, 2021).

Aside from physical storage, adsorption and chemical storage are still being actively investigated as alternatives, given the geographical restraints presented by underground options. However, the uncertainties surrounding these replacements (such as reactor designs and heat supply for dehydrogenation) make it challenging to consider these options accurately from an economic standpoint and draw comparisons (Andersson and Grönkvist, 2019).

4.3.3 Household costs

4.3.3.1 Internal pipework

As well as the transmission and distribution system, domestic pipework may also require replacement to adjust to hydrogen conversion, which could increase the cost of conversion if large amounts of work are necessary. Work prepared for BEIS, indicates how the inaccessibility of domestic pipework could present a significant barrier in the conversion to hydrogen (Frazer-Nash, 2018, p.3 – 4). This is because natural gas pipes are often enclosed in concrete or otherwise isolated, which would make it challenging to inspect or replace them if necessary.

Prior to deployment, gas tightness tests will be required to examine the integrity of internal pipework. This process requires home surveys taking approximately 1 – 2 hours per property and would require the gas supply to be cut for 10 – 20 minutes (Frazer-Nash, 2018). The cost of these pre-conversion tasks is less certain as there are a variety of materials used for domestic pipework (copper, steel, polyethylene) and hydrogen presents a different range of safety hazards, but estimates range from £100 to £500 per property (Sadler *et al*., 2016; Element Energy, 2018).

4.3.3.2 Hydrogen boilers

For nationwide use, the roll-out of a hydrogen-based grid would be in combination with the use of hydrogen-ready boilers in domestic settings. Manufacturers such as Baxi and Worcester-Bosch have developed prototypes of these boilers based on a conventional gas boiler. As hydrogen has a higher flame speed and is colourless when combusted, a hydrogen-ready boiler has alterations to its ignition system and flame detection. The cost of replacing a natural gas-fired boiler with a hydrogen gas-fired boiler would be alike, as the process and components are similar. For the boiler unit itself, estimates currently average £850 – £1,000, increasing up to £2,500, the latter assuming only 10,000 boilers are commissioned (Sadler *et al*., 2016, p.146; Element Energy, 2018, p.89). These estimates are comparable to the price of a natural gas combi or system boiler which are within the range of £850 – £1100 (ibid.).

4.3.3.3 Hydrogen appliances

Although appliances manufactured since 1996 can operate with a 23% hydrogen blend, to function entirely on hydrogen gas would require adaptations or replacement. For example, a natural gas-fired hob would not be suitable for use with hydrogen given that its invisible flame would mean the consumer would not be able to use the appliance safely, discussed in 4.3.4. The deployment of dual fuel technologies that can function on both natural gas and hydrogen may aid the transition, limiting the time and effort required to carry out the conversion. Including house visits, labour, and appliance changeovers the H21 project estimated approximately £840 per household (Sadler *et al*., 2016, p.145).

Overall, with the inclusion of labour and overheads the H21 project estimates an overall cost of £3,078 per property in making the pipework, boilers, appliances, and homes safe for hydrogen usage (Sadler *et al*., 2016, p.147). This cost is similar to that of the conversion from town gas to natural gas on the Isle of Man in 2010 at £3,500 per property. It is, however, important to note that the forecast expected cost of £3,078 would only be made possible through mass manufacturing and deployment of hydrogen appliances.

4.3.4 Safety concerns

Hydrogen and natural gas have different properties, which affect the way they can be handled safely. Hydrogen is non-toxic and produces no carbon monoxide when combusted meaning that there is no risk of carbon monoxide poisoning associated with its use. Furthermore, as it is lighter than air, when there is a leak it dissipates at a faster rate. However, it burns with an invisible flame, leaks at a rate approximately three times greater than natural gas, and has a lower ignition energy, which are factors that may complicate its uptake in domestic settings.

Regarding flame detection, whilst the use of colourants has been suggested as a possible solution (Frazer-Nash, 2018), investigations by the Hy4Heat program concluded that adding colourant into the network or internal pipework should not be carried out. This is due to use of a colourant potentially impacting the integrity of the pipework and the safety of the end-use appliances, among additional operational complexities. Instead, thermochromic materials are suggested as a means of indicating an appliance is on (similar to electric hobs) and UV and temperature detection for use in boilers (Hy4Heat & BEIS, 2021a, p.68 – 71). With regards to leakages and ignition, a risk assessment carried out under the Hy4Heat programme determined that with the use of two Excess Flow Valves (EFVs) the assumed risk of a hydrogen conversion in a domestic setting was no greater than the current natural gas setup in place. An EFV would limit the flow rate to the service pipe of the building, with one of the recommended valves being placed upstream of the meter installation, and the other located within the smart meter installation (Hy4Heat & BEIS, 2021b).

When hydrogen is combusted in pure oxygen the only product is water vapour (H_2O), however, except for some specialist applications, hydrogen combustion will take place in the presence of air. As hydrogen burns with a very hot flame the resultant reaction can produce nitrogen oxide (NO) as a by-product, which reacts in the atmosphere to form nitrogen dioxide (NO_2). NO_2 is a globally regulated air pollutant that is harmful to health (Lewis, 2021) and experiments conducted by Cellek & Pinarbaşi (2018) found that the number of point NOx emissions produced by a hydrogen boiler compared to a natural gas boiler can be up to six times higher. Lewis (2021) comments on the challenge of balancing thermal efficiency and NOx emissions, with an emphasis placed on the importance of developing of new emissions standards for hydrogen appliances in relation to NOx pollutants to mitigate the effects of hydrogen combustion.

Further recommended safety measures for a community trial require the compliance of regulations and standards currently in place for natural gas (hydrogen appliances must include flame failure devices and comply with PAS4444, which are guidelines specific to hydrogen-fired gas appliances), adequate ventilation in properties, the inspection of internal pipework, the inclusion of odorants in the gas mix, and hydrogen detection alarms (Hy4Heat & BEIS, 2021b, p.23 – 24).

4.3.5 Cost-competitiveness

Fossil fuel-based hydrogen production is a mature technology with well-established supply chains, which means that current low-carbon alternatives are not cost competitive. Moreover, as a derivative of natural gas, blue hydrogen is naturally more costly without incentives toward abatement. In their hydrogen strategy, the European Commission estimated various costs associated with hydrogen production methods as shown in Table 4 (European Commission, 2020, p.4).

This price differential favours fossil fuel-based production and therefore gives little incentive to procure low-carbon hydrogen, especially green, without an associated cost for CO_2 emissions. As the development of large-scale, low-cost hydrogen production is an important precondition to its success (Maclean *et al*., 2016), looking at ways to reduce its levelised cost is necessary.

Table 4 Estimated cost of per kg of hydrogen by production method

Hydrogen Production Method	Cost per kg H_2[2]
Fossil fuel-based	£1.29 (€1.50)
Fossil fuel-based with CCS	£1.72 (€2.00)
Renewable	£2.15 – 4.73 (€2.5 – 5.5)

[2] Converted from Euros:GBP with 1:0.86

4.3.6 Blue Hydrogen

4.3.6.1 Net zero alignment

Whilst blue hydrogen is based on the familiar production of fossil fuel-based techniques such as steam methane reformation (SMR), carbon capture and storage (CCS) is a vital step in the process that could make blue hydrogen a low-carbon alternative. CCS aims to capture CO_2 from large sources of production, such as power generation, or directly from the atmosphere (DACCS). Once captured the CO_2 requires transportation to a storage facility and injection into geological formations for its permanent sequestration.

Although it is suggested that blue hydrogen may help increase demand for low-carbon hydrogen, and in that way increase the market available to green hydrogen (Bauer *et al*., 2021; UKFCA, 2021), blue hydrogen is not aligned with net zero ambitions. Natural gas leakages upstream and carbon capture inefficiencies mean that whilst in theory it could capture a vast majority of emissions, its actual environmental impact is disputed (Howarth and Jacobson, 2021). Standards and regulations that carefully monitor operational and supply chain emissions should therefore be put in place for strategies that rely on it as a solution.

4.3.6.2 Carbon capture and storage

In 2021 there were 27 operational, commercial CCS facilities globally and a further four facilities under construction, capturing a combined 40 $MtCO_2$ per year (Global CCS Institute, 2021). Natural gas processing facilities were responsible for the large majority of this captured CO_2, whilst hydrogen production was the source of 3.3 $MtCO_2$ captured in 2020 (IEA, 2020a). An additional 102 CCS facilities were in various stages of development in 2021, with potential to capture a further combined 108 $MtCO_2$ per year (Global CCS Institute, 2021). Despite CCUS deployment tripling in the last decade, it has fallen short of capacity expectations in that it lags behind other clean energy technologies. For example, 40 $MtCO_2$ is just 13% of the IEA's roadmap for CCUS developed in 2009, which stated that 100 large-scale CCUS projects, capturing 300 $MtCO_2$/yr by 2020 would be required to meet climate goals (IEA, 2009, p.22). In the IEA's latest roadmap to achieve net zero emissions

(IEA, 2021), global CCUS capacity would need to be rapidly scaled up to 1.6 $GtCO_2$/yr by 2030 and 7.6 $GtCO_2$/yr by 2050.

CCS faces numerous barriers in its own right that have hindered its deployment, such as insufficient value placed on emissions, interdependency of the value chain on other industries, and lack of viable business models (Global CCS Institute, 2020, p.25; Sunny, Mac Dowell and Shah, 2020). Wang *et al.* (2021) found that 43% of CCUS projects announced in the last 30 years have been cancelled or postponed, and concluded that most CCUS projects are high-risk and low-return with respect to direct economic outputs, and heavily dependent on public funding in the absence of high carbon prices. Without CCS, methane-derived hydrogen is not low-carbon and its current lack of deployment is concerning for strategies that may depend on its success.

4.3.7 Green Hydrogen

With high production costs and high energy losses, green hydrogen has multiple barriers to overcome before it is seen as a viable alternative to grey hydrogen and can be widely deployed. The major expenditure in green hydrogen production is the cost of renewable electricity required to operate electrolysers, followed by the cost of the electrolyser facilities themselves (IRENA 2020b). In 2019, the average renewable energy plant would have produced green hydrogen at a cost that was two to three times more expensive than grey hydrogen (IRENA, 2020a). This could result in high end-user costs and, as it needs to be cost competitive with both fossil fuels and different shades of hydrogen, poses an issue for the success of green hydrogen. Conversely, a recent analysis by Longden *et al.* (2022) suggests that green hydrogen production could become cheaper than blue hydrogen in the near future, due to greater potential to reduce costs through scaling up and deployment of renewables and electrolysers in comparison to fossil fuel production with CCS.

The production of green hydrogen incurs a 30 – 35% loss in energy through the process of electrolysis, which means higher levels of renewable generators are required to produce hydrogen than if electricity is used directly. It is estimated that the amount of offshore wind farm capacity required to replace gas boilers with green hydrogen in the UK is 30 times more than currently deployed (Phillips and Fischer, 2021). This brings questions as to whether renewables will be able to develop at the pace required to support increasing electrification and green hydrogen development (IRENA, 2020a).

4.4 Scenario comparisons

The following subsections will draw on relevant literature to compare how hydrogen and heat pump pathways are expected to fare in 2050 in relation to cost. Whilst a whole systems-based model reveals similar costings for each strategy, at a household level there is a higher differential between the two.

4.4.1 Systems-based approach

The Climate Change Committee's (CCC) report on "Hydrogen in a low-carbon economy" estimates that the overall system costs associated with full electrification or full hydrogen pathway would not differ significantly in 2050 (CCC, 2018). This includes scenarios where the gas grid has limited or benign use, meaning that the sunken costs associated with having a decommissioned gas grid does not make a hydrogen pathway more affordable. The findings presented are based on analysis carried out by Strbac *et al.* (2018), who assessed three potential pathways; full hydrogen conversion, full electrification, and a hybrid scenario with the majority of heating demand covered by electricity and the use of biomethane or low-carbon hydrogen for peak periods. Different decarbonisation scenarios and their associated costs were also predicted, namely, 0 $MtCO_2$/yr, 10 $MtCO_2$/yr, and 30 $MtCO_2$/yr.

Across the different decarbonisation scenarios, hybrid pathways were predicted to have the lowest system cost per year in 2050, followed by full electrification and then full hydrogen strategies. Whilst all three were similar in cost at 30 $MtCO_2$/yr, ranging from £81.6 bn/yr – £89.6 bn/yr, the cost differential between electrification and hydrogen pathways increased significantly in a net zero strategy, with a full electric and hydrogen system costing £92.2 bn/yr and £121.7 bn/yr, respectively. The reason for this increase being attributed to the need for green hydrogen and high renewable investment as opposed to blue hydrogen, which is not compatible with net zero unless carbon capture rates were to evolve to 100% (Strbac *et al*., 2018).

4.4.2 Household scale

Although extremely useful to analyse whole system costs of different strategies, how these costs may be allocated across the economy also needs consideration. The International Council on Clean Transportation (ICCT) carried out a household level cost analysis of seven different low-carbon domestic heating options[3] (Baldino *et al*., 2020). The assessment aimed to project the costs and carbon intensity related to each for a UK homeowner in 2050.

4.4.2.1 Assumptions

With regards to the hydrogen pathways the following assumptions were made. By 2050, the SMR and CCS process will use renewable electricity, and it is further assumed that some of the hydrogen produced would be used in place of natural gas as a process fuel. Upstream leakage rates are between 0.5% – 2% for the production and transport of natural gas and CCS capture rates range between 70 – 90%. In scenarios with high hydrogen demand, the cost of replacing steel pipelines in the UK and charge for their use is incorporated into the model. There are short term storage fees, but seasonal storage cost is not accounted for.

In the hybrid scenario using blue hydrogen, a median value of carbon intensity was multiplied by the percentage of heat demand expected to be covered by hydrogen to determine the overall carbon intensity. This value was estimated to be 21% and is further reasoned by Baldino *et al*. (Baldino *et al*., 2020). To reflect a lower hydrogen demand in this scenario it is assumed that trucks would instead be used for the transportation of liquified hydrogen. With regards to heat pump scenarios, the CoP of the heat pumps were assumed to be 3.19.

Across all scenarios, renewable electricity from wind or solar is assumed to have zero-carbon intensity and similarly for the production of electrolytic hydrogen. Emissions regarding the manufacturing of the heating technologies were also not accounted for.

4.4.2.2 Results

Their findings are presented in Figure 5 which demonstrates that the lowest cost option are household heat pumps, followed by hybrid heat pump variations. Carbon intensities are denoted with triangles and demonstrate the significance of relying on blue hydrogen boilers. The natural gas comparator is given as a reference for carbon intensity.

Renewable electricity and natural gas prices were the main drivers behind the heating scenarios, and as there is a high level of uncertainty that comes with predicting energy prices in 2050, a sensitivity analysis was carried out. This determined that even if renewables were 50% more expensive, and natural gas 50% cheaper than predicted a heat pump would still be the most cost beneficial option. Further, for a boiler with green hydrogen to be cost competitive with blue, either renewables would have to be 50% lower in cost, or natural gas 50% more expensive (Baldino *et al*., 2020).

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[3] Heating technologies analysed were: fuel cells, hydrogen boilers, hybrid heat pumps, and heat pumps. Each hydrogen option was also assessed with both green and blue options.

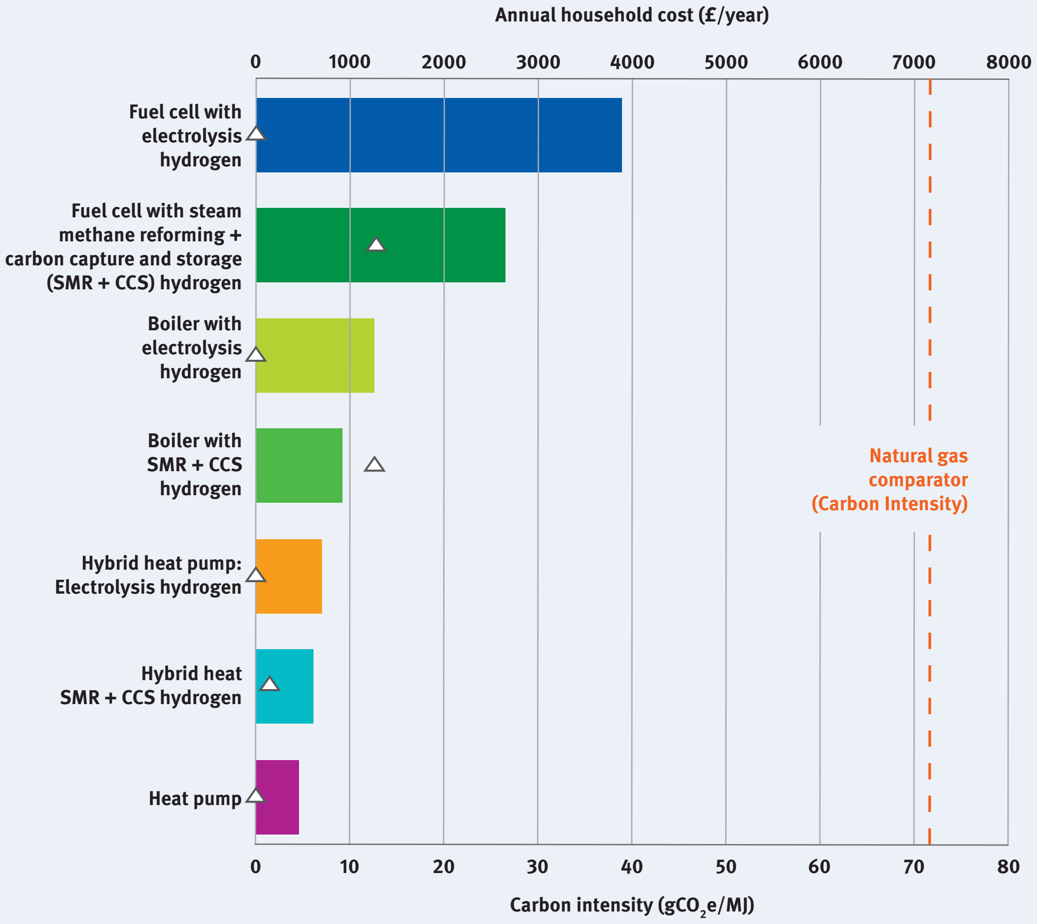

Figure 5: Cost comparison and carbon intensities of different decarbonisation pathways for households in the UK. Image courtesy of Baldino *et al*. (2020)

4.5 Key barriers that will need addressing in the next ten years

4.5.1 General

- There is an urgent need to improve thermal efficiency of UK buildings, both as a means to reduce heating demand and to optimise performance of heat pumps or hydrogen boilers.
- There are currently significant shortages of skilled workers in heat pump installation and maintenance, and gas installers do not currently possess requisite skills for installation of hydrogen boilers.
- Low-carbon or alternative heating systems remain unfamiliar and poorly understood amongst the general public.

4.5.2 Heat pumps

- Installation and up-front purchase costs of heat pumps are currently a key barrier to uptake. For example, the cost of installing an air-to-water heat pump system is typically around four times the cost of replacing a gas boiler.
- Heat pumps require competent specification and installation to maximise their performance and efficiency; the current lack of qualified installers is a priority area for action.
- Low-temperature heat pump systems need to be fitted in conjunction with adequate home insulation and may also require oversized or thicker radiators to be installed.
- Heat pumps are typically comprised of several separate components and therefore have greater space requirements than gas combi boilers, which is a constraint to uptake in certain residential apartment types in particular.
- If a large share of UK homes is fitted with heat pumps, this will have a significant impact on total and peak electricity demand. While heat demand from heat pumps is more distributed across different parts of the day compared to gas boilers, there will still be a need for grid reinforcement of local distribution networks.

4.5.3 Hydrogen

- The ability to meet demand could be a significant barrier in hydrogen's household use as there are very limited sources at present. Furthermore, its use in sectors that are harder to decarbonise will likely take priority.
- If hydrogen is to be used within residences, ensuring it is safe to do so is paramount. This will be an area of priority in the coming years, aided by further hydrogen trials.
- Storage facilities would be required to cope with periods of high heating demand. There is currently limited research into wide-scale hydrogen storage beyond underground storage. Safety risks with hydrogen storage in salt caverns would need to be managed.
- At present, low-carbon hydrogen is not cost competitive, which poses a barrier to its deployment. Green hydrogen is currently more expensive to produce than blue hydrogen but may have more potential to experience cost reductions from scaling up and deployment of renewables and electrolysers compared to fossil fuel production with CCS.
- CCS infrastructure has not been deployed on the scale that was anticipated. Without CCS, hydrogen derived from methane cannot be low-carbon.
- Greater capacity of renewable generation will be required to produce green hydrogen than if electricity is used directly – placing additional demands upon electrification.

5. Policy support and regulation

In this section, we consider polices and regulations which could help to address existing barriers to both heat pump and hydrogen deployment and resolve current inadequacies with policy implementation.

5.1 Heat Pumps

In general, there is a low uptake of heat pumps in the UK, with approximately 265,000 heat pump installations nationwide as of 2020 (EHPA, 2021c), representing around 1% of installed heating systems. Less than 500,000 homes utilise low-carbon heating (Rosenow and Lowes, 2020). By way of comparison, France has an installed stock of 3.1 million heat pumps, Sweden 2 million and Germany 1.1 million (EHPA, 2021c). To meet the UK's net zero emissions target, by 2050 heat pumps may need to be installed in 17 to 19 million homes, with an additional 5 million homes connected to low-carbon heat networks (CCC, 2019a).

5.1.1 Subsidising upfront and ongoing costs

As discussed in Section 4, the upfront costs of heat pumps remain well above consumers' general willingness to pay for alternative heating. It is important therefore that there are financial support mechanisms in place to help the roll-out of heat pumps nationwide.

An international review of low-carbon heat policies revealed that European countries that have deployed heat pumps more extensively than in the UK have generally implemented grants covering part of the purchase cost (Hanna *et al*., 2016; Sahni *et al*., 2017). These grants have frequently included minimum requirements for the performance of heat pumps (typically using the seasonal performance factor). In the UK, financial incentives have been available from time to time but not on a continual basis and have supported either the upfront or ongoing costs of the technology. Previously available, active, and proposed subsidies supporting heat pump installation or resulting heat use in homes are summarised in Table 5.

Notes to Table 5

1. The Heat and Buildings Strategy states that biomass boiler installations "will need to be located in a rural area and not have an existing mains gas connection, as well as meet high standards for emissions, to mitigate any negative impact on air quality in line with the government's Clean Air Strategy" (BEIS, 2021f, p.194–195).

Name of subsidy	Details	Years active	Outcome (Approximate installations)
Low Carbon Buildings Programme grants	Upfront grant for microgeneration technologies. Paid an average grant of £900 for ASHPs and £1200 for GSHPs installed in homes (Gardiner *et al.*, 2011).	2006–2011 (UK)	19,000 microgeneration systems installed, including 1,500 ASHPs and 1,500 GSHPs (Gardiner *et al.*, 2011).
Renewable Heat Premium Payments (RHPP)	Offered small grants including £850 for ASHPs and £1,250 for GSHPs and WSHPs installed in off-gas grid homes (DECC, 2013).	2011–2014 (GB)	5,900 ASHPs and 2,230 GSHPs / WSHPs installed through the scheme (DECC, 2014).
Renewable Heat Incentive	Pays fixed tariff over seven years for heat use from ASHPs, GSHPs, biomass, and solar thermal. Heat pumps required to have a minimum SPF of 2.5.	2014–2022 (GB)	58,000 ASHPs and 12,250 GSHPs installed in homes up to July 2021 (BEIS, 2021k).
Green Homes Grant	Government funded two thirds of the cost of home improvements up to £5,000 including ASHP/GSHPs & heating controls. Low-income households could receive 100% of costs up to £10,000 (BEIS, 2021e).	September 2020 – March 2021 (England).	3,924 ASHPs, 955 hybrid heat pumps and 29 GSHPs installed up to December 2021 (BEIS, 2021m).
Boiler Upgrade Scheme grants	Households and small businesses can receive a £5,000 upfront capital grant to install an ASHP or £6,000 to install a GSHP (BEIS, 2021f). Installations must replace existing fossil fuel or direct electric heating systems (except in custom-builds). In some limited cases, £5,000 grants will be available to support biomass boiler installations[1] (BEIS, 2021n). Heat pump installations will require a minimum seasonal CoP of 2.8 (BEIS, 2021n).	£450 million government funding available for grants from 2022 to 2025 in England and Wales (BEIS, 2021f).	Announced in the government's Heat and Buildings Strategy (BEIS, 2021f).

Table 5 UK subsidies implemented or proposed to stimulate the uptake of heat pumps

Overall, while financial incentives for low-carbon heat have been available in the UK throughout the last 15 years, subsidies have changed several times over this period. They have lacked consistency from one scheme to the next (some being grants covering upfront costs, while the Renewable Heat Incentive covers running costs), have varied in geographical coverage (UK / GB / England and Wales / England), and have often been compromised by budget overspends or underspends (Connor *et al*., 2015; Praetorius *et al*., 2010). Financial incentives for heat pumps therefore require greater longer-term foresight in their design and implementation.

The domestic Renewable Heat Incentive (RHI) has been active since April 2014 and has been extended until 31st March 2022. The domestic RHI scheme was initially scheduled for introduction in 2011, but was not opened until three years later, causing uncertainty in the emerging low-carbon heat market and supply chain. During this period the government introduced a limited grant scheme, the Renewable Heat Premium Payments (RHPP), which subsidised a small portion of household installation costs. While this grant supported the installation of around 8,000 heat pumps, not all of the RHPP budget was spent (Connor *et al*., 2015; Hanna, Leach and Torriti, 2018).

With respect to heat pumps installed in homes, the domestic RHI scheme pays a fixed tariff to householders based on heat usage over seven years following installation. Heat pumps must have a minimum SPF of 2.5 to be eligible for RHI payments, and products and installers must be certified by the Microgeneration Certification Scheme (Ofgem, 2021). The RHI has seen modest uptake of heat pumps with around 70,000 units installed from 2014 to 2021 (BEIS, 2021k). A criticism of the scheme is that it has mainly supported biogas, biomass and bio-CHP, which have provided the majority of heat delivered in buildings as a result of the RHI (Lowes, 2020).

The purpose of the Green Homes Grant was to kickstart economic activity during the COVID-19 pandemic in 2020 and 2021, however the scheme was active for just six months. The grant supported a variety of energy efficient and low-carbon household interventions and offered generous vouchers worth £5,000 for the installation of heat pumps (£10,000 for low-income households) (BEIS, 2021e). Only around 3,000 heat pumps have actually been installed through the scheme, and the generally low uptake of supported measures has been attributed to various factors – insufficient registered or skilled installers to satisfy demand, the short timeframe over which funding was available, and delays in issuing vouchers (EAC, 2021). The sudden closure of the scheme after such a short period is not helpful for future grant schemes which depend upon market confidence in the heat pump industry (Committee of Public Accounts, 2021).

The government plans to introduce the 'Boiler Upgrade Scheme' grants in Spring 2022, effectively replacing the Renewable Heat Incentive. The Boiler Upgrade Scheme will subsidise £5,000 of the upfront cost of installation for ASHPs and £6,000 for GSHPs, and is planned to run until 2025 with £450 million of funding available to support the grants (BEIS, 2021f). Unlike the RHI, there would be no ongoing or quarterly payments to cover the cost of heat consumption. However, the £5,000 / £6,000 grants supported by the Boiler Upgrade Scheme may be insufficient to overcome the gap between consumers' willingness to pay for an alternative heat system (up to approximately £3,000 according to Clarke (2018)) and the actual installation costs of heat pumps. The typical cost of installing air-to-water heat pumps can be at least around £9,000 and ground source heat pumps can cost between £13,000 and £27,000 to install (see Table 2). Moreover, the Boiler Upgrade Scheme is set only to be funded for three years, which does not help to create revenue certainty or confidence in the heat pump industry that subsidy support will be available over the longer term while installation costs remain high. The funding is also well below what is needed for required levels of deployment; if for example all the £450

Country	Green finance mechanism	Years active	Scheme / mechanism description
France	Crédit d'Impôt pour la Transition Énergétique (CITE)	2005 – 2020	Tax credits for purchases of equipment for primary residences (Article 200 of the General Tax Code) to promote both sustainable development and energy conservation.
	Eco-loan	2009 – present	0% loan for energy-efficient renovation in new and existing residential dwellings.
Germany	National Action Plan on Energy Efficiency	2014 – 2017; 2017 – 2020	A consumer information, advice and financial incentive campaign to increase uptake of energy efficiency measures.
	CO_2 Building Renovation Programme	2015 – present	Low interest loans and subsidies of up to €30,000 for energy efficient residential renovations.
Italy	Energy Efficiency Tax Rebate Programme	2007 – present	Tax credits available at 110% of costs of retrofitting energy efficiency measures (increased from 45%).
	Renewable energy for heating and cooling support scheme (Conto Termico)	2013 – present	Between 40% and 65% of investment costs repaid in annual instalments of two to five years.

Table 6 International examples of green financing mechanisms to support heat pump and energy efficiency deployment[1]

Notes to Table 6

1. The table has been adapted from MCS (2021) and Sahni *et al*. (2017)

million was used to support the installation of ASHPs, the scheme would fund £5,000 grants for 90,000 heat pumps. This equates to 30,000 annual heat pump installations, approximately equivalent to current rates of deployment (EHPA, 2021c). Therefore, alternative means of overcoming this affordability barrier and stimulating heat pump uptake will be required to attain the government's target of 600,000 heat pumps installed annually by 2028 (HM Government, 2020). Section 5.1.2 considers the role of technological innovation and potential for reducing heat pump capital and installation costs.

Apart from upfront costs, another financial barrier to the uptake of heat pumps in the UK is that the price of electricity incorporates higher policy costs of decarbonisation compared to natural gas. Conversely, CO_2 emissions from household electricity use have decreased due to a higher installed capacity of renewable generation in the UK (Lord, 2021). As a solution, the UK could follow examples set by Germany and France, i.e. by including a carbon price in the cost of gas bills and transferring policy costs from electricity bills to general taxation (Wolf, Dupont and Newton, 2021). Several European countries with widespread deployment of heat pumps, such as Denmark, Finland and Sweden, have also had carbon taxes in place since the early 1990s (Hanna *et al*., 2016). In addition to grants towards the upfront costs of heat pumps, the government should identify and facilitate new ways in which consumers could access affordable capital towards the costs of installation, such as mortgage additions, tax credits, low interest loans offset against a lower end user cost of electricity and access to flexible time-of-use tariffs. Table 6 illustrates several examples of such green financing mechanisms which have been implemented in France, Germany and Italy. The UK's Heat and Buildings Strategy sets out plans to trial, and develop the supply of and market for, green finance products (BEIS, 2021f).

5.1.2 Technological innovation, cost reduction and industry growth

Investment subsidies by themselves are not sufficient, particularly given their tendency to be time or budget limited, and should form part of a broader mix of policy support. The upfront costs of heat pumps in the UK remain too high and the industry has only developed (or been supported) modestly, and therefore not to a sufficient extent to bring costs down to more affordable levels. Technologies have potential to experience reduction in costs over time through increased production and accumulated industry learning including through interactions with users, and the resultant rates of cost decrease are referred to as 'learning rates' or 'experience curves' (Gross *et al*., 2013).

International evidence shows that significant cost reductions have taken place in countries where there has been a widespread uptake of heat pumps aided by a portfolio of supportive polices and industry initiatives, for example in Sweden from 1985 to 2008, consumer prices of GSHPs approximately halved (Kiss *et al*., 2012). In the Heat and Buildings Strategy, the UK government sets out ambitions, through collaboration with industry, to reduce HP installation costs by at least 25% – 50% by 2025, and to lower purchase prices and running costs to close to parity with gas boilers by 2030 (BEIS, 2021f). Evidence on the deployment of heat pumps to date suggests this rate and level of cost reduction may be challenging to achieve. A study carried out by Renaldi *et al*. (2021) on the UK indicates that learning rates experienced by heat pumps have been modest: the authors found that from 2010 to 2019, the capital costs of ASHPs decreased by 5.5% and those for GSHPs declined by 3.3%. These rates became marginally positive when installation costs were included, indicating that the cost of heat pumps have actually increased slightly over the last decade in the UK (Heptonstall, Winskel and Gross, 2021).

An analysis by Knobloch *et al*. (2019) models a residential heat decarbonisation policy scenario in which a carbon tax raises the cost of fossil fuel heating and subsidies are available for renewables. This scenario projects that investment costs of ground source heat pumps could fall by 45% in 2030 and 66% in 2050 compared to a 2014 baseline. The Climate Change Committee's 2019 net zero analysis assumes that air source heat pumps will experience an 11% cost reduction between 2025 and 2050, accounting for their capital and installation costs, but excluding the cost of any additional required residential heating upgrades such as new radiators or a hot water cylinder (CCC, 2019c, CCC, 2019b; Heptonstall, Winskel and Gross, 2021).

In order to facilitate learning and technological cost reduction, and as discussed in Section 3.1.1.2., the government should support expansion of the emerging heat pump manufacturing base in the UK to help create more jobs and develop local skills in the heat pump industry. Apart from four manufacturers which make heat pumps in the UK, two thirds of ASHPs and 60% of GSHPs are imported from other countries (BEIS, 2020a). There is a risk that the UK could continue to be outcompeted by manufacturers from abroad, resulting in an offshoring of investment and job creation. Supporting the growth of a UK manufacturing base in heat pumps would help to create highly skilled jobs, stimulate local technological innovation and potentially an export market as well (Lowes, 2021).

In Section 3 we noted the confidence of UK heat pump manufacturers in their potential to significantly scale up production capacity. There is an opportunity for UK-based boiler and air conditioner manufacturers to manufacture heat pumps by sourcing similar raw materials and components used for these technologies. The government should consider supporting or incentivising these complementary manufacturers to shift or diversify production to heat pumps. The government has recently published a consultation on a proposed 'market-based mechanism for low-carbon heat' planned for introduction in 2024, which would provide a market incentive to help correct for under-investment by the heating industry in heat pumps, in comparison to incumbent fossil fuel heating technologies (BEIS, 2021j). The lead option set out in the consultation is to oblige gas and oil boiler manufacturers to increase their share of heat pump sales over time relative to fossil fuel boiler sales (Ibid.). In addition, government policy should coordinate a managed transition from gas boiler to heat pump manufacturing, providing grants for the reskilling and upskilling of current gas industry employees to help make such a shift (BEIS, 2020a).

As UK demand for heat pumps grows, it should bring greater certainty on investment returns and potentially increase the number of UK based HP and component production. With a recent government target to increase UK based heat pump manufacturing and supply to at least 300,000 units per year by 2028, this may provide incentives (BEIS, 2021f, p.17). However, how demand growth is defined varies between manufacturers; some call for more long-term government strategies that go beyond electoral cycles, stable regulatory systems, financial incentives such as tax breaks, or additional quality assurance standards required for the installation of HPs (BEIS, 2020a).

In countries such as Sweden and Switzerland, the establishment of dedicated test centres for heat pumps which observed increases in heat pump CoPs between the 1990s and 2000s were important in raising technical standards and providing quality assurance to consumers, and as a means of quality control for investment subsidy programmes (Kiss *et al*., 2012; Hanna *et al*., 2016). In a drive to achieve cost reductions through repetitive learning and experience, Octopus Energy have set up two heat pump test installation houses in Slough. The company plan to train their own engineers (and other third party engineers) in practicing and optimising the installation of a heat pump and hot water tank (and removing a pre-existing gas combi boiler) in a 1970s brick-built house and 2000 era timber-frame house. Octopus Energy are also planning to create a research and development centre to test heat pump hardware in weather chambers to simulate different weather conditions and help promote continuous innovation (Jackson, 2020). The last comprehensive, national UK field trial of heat pumps (involving a collaboration between the Energy Saving Trust, government and industry) took place between 2008 and 2013 (EST, 2013). The government should create a dedicated national test centre and training facility overseen by a heat pump council (see Section 5.1.4 below). The role of the test centre would be to provide wide access to performance information, and coordinate training of engineers and installers, drawing on international examples.

The UK government has introduced the £60 million Net Zero Innovation Portfolio 'Heat Pump Ready' Programme, providing funding for projects in the development, demonstration and optimised deployment of heat pumps, including solutions which help to reduce costs and 'hassle' experienced by consumers (BEIS, 2021f, BEIS, 2021g). This is welcome but the international evidence suggests that the government should go further and establish a dedicated, national test centre, helping to facilitate more coordinated, systematic technological innovation in heat pump systems and improve heat pump products offered to consumers. For example, high-temperature heat pumps have been developed which represent only a small share of the UK heat pump market. These high-temperature heat pumps may be more appropriate than lower temperature heat pumps for retrofitting in existing properties, since they can supply heating at an output temperature of at least 65°C. This means that they can be more easily integrated with standard smaller or thinner radiators typically used in conventional, high temperature central heating systems sourced by a boiler (BEIS, 2016).

5.1.3 Regulation, standards and certification schemes

As discussed in Section 4.1, minimum building energy efficiency standards will need to be tightened, and the government should consider making upfront grants for heat pumps conditional on buildings where they are installed having minimum energy efficiency / insulation requirements, or minimum EPC ratings (similar to the Low Carbon Buildings Programme grant – see Praetorius *et al.* (2010)).

It is important that the government introduces regulation which signals a long-term commitment to deploying the 600,000 heat pumps committed to in its Ten Point Plan. With reductions in housing emissions having stalled, the CCC has recommended that from 2025 no new homes should be connected to the gas grid, rather, they should source heat from low-carbon options such as heat pumps (HPs), alongside use of complementary infrastructure (such as district heating) and improvements to energy efficiency (Holmes *et al.*, 2019, p.9). In the Heat and Buildings Strategy a BEIS consultation to evaluate this matter was mentioned, alongside the intention to phase out the installation of new fossil fuel boilers from 2035 (BEIS, 2021f, p.134).

Installer certifications, technical standards and quality labels have been key to raising consumer confidence where heat pumps have been taken up extensively in several European countries (Hanna *et al.*, 2016). The UK field trial of heat pumps led by the Energy Saving Trust from 2008 to 2013 found that maximising the quality of design, commissioning and installation of heat pumps is key to optimising their performance (EST, 2013). In the UK, the Microgeneration Certification Scheme (MCS) has been in place since 2008 to provide quality assurance for installers and microgeneration products and EST (2013) observed that heat pumps in the second, later phase of its trial experienced improved performance when subject to updated MCS installer standards. Currently, the MCS has a process of annual surveillance whereby accredited certification bodies can randomly select a shortlist of installations to inspect for any given installer, from which the installer then chooses which installation is inspected (MCS, 2020). In order to receive the Renewable Heat Incentive, heat pumps and other microgeneration technologies and their installers must be MCS certified (Ofgem, 2021), however this does not prevent installers fitting systems if potential recipients of the RHI choose not to benefit from it or if they do not meet its requirements (Clarke, 2019).

5.1.4 Consumer engagement, behaviour change and smart heat

In Section 4.1 we note that in the UK, public awareness of low-carbon heating technologies such as heat pumps remains low. International evidence on the effective deployment of heat pumps in Sweden and Switzerland highlights the role of industry groups (e.g. heat pump

associations) in collaboration with government in coordinating marketing and information campaigns, improving technical standards, and raising consumer confidence in the technology (Kiss *et al*., 2012; Hanna *et al*., 2016). In the UK, heat pump industry representation could be streamlined since there are currently three separate heat pump associations: the Ground Source Heat Pump Association, the Heat Pump Association and the Heat Pump Federation.
In setting out a policy package to achieve a wider uptake of heat pumps in the UK, Lowes *et al*. (2021) recommend creating a "heat pump council" comprised of national and local government, regulators, industry and civil society. This body could coordinate consumer engagement and oversee consumer protection, facilitate supply chain development and monitor the progress of the heat pump market (ibid.). It could also provide a quality assurance role via an independent test centre for heat pumps, such as that recommended in Section 5.1.2.

There is also an opportunity for heat decarbonisation policy to engage users through smart heating and flexibility. A route to accelerating a transition to low-carbon heating and stimulating the uptake of heat pumps is through 'Heat-as-a Service' (HaaS) business models. Instead of the traditional model of pay-per-use based on metered energy units, HaaS customers pay for a specific level of thermal comfort and flexibility, for example being able to use digital systems to control the temperature and duration of heating in different rooms (Energy Systems Catapult, 2019; Carmichael *et al*., 2020). A trial by the Energy Systems Catapult (2019) suggests that householders with HaaS may be more willing than the population at large to substitute their gas boiler with a low-carbon heating system.

The Freedom Project trial (Freedom Project, 2018) found that smart hybrid heat pumps can be optimally managed to supply heating with equivalent thermal comfort to a conventional heating system while also responding rapidly to market price or carbon intensity signals. This automated flexible hybrid heating could form the basis of a HaaS product, although it would need to be supported by a new market and regulatory framework (Carmichael *et al*., 2020). However, an analysis of user learning during the Freedom Project trial found that users of smart hybrid heat pumps did not understand or use the technology in an optimal way (Parrish, Hielscher and Foxon, 2021). For example, some hybrid heat pump users in this trial incorrectly went on to understand that a heat pump on its own cannot adequately heat a household. This study also found that if users involved in the trial experienced thermal discomfort, they were able to override the hybrid heat pump smart controls enabling the system to switch from electricity to gas heating and vice versa. Therefore, it is important to provide users with clear information on how to use hybrid heat pump systems and optimise costs.

Some studies also highlight the potential role of more active users rather than passive consumers. Evidence from Finland, where there has been a rapid uptake of air-to-air heat pumps for space heating in particular over the last two decades, indicates that user-led online discussion forums specifically for users to share their experiences of different heat pumps (and issues such as sizing, costs etc.) played an important role in convincing people that heat pumps were appropriate for the cold Finnish climate (Sovacool and Martiskainen, 2020; Martiskainen, Schot and Sovacool, 2021).

5.1.5 Policies to manage electricity demand and impact on the power grid from heat pumps

It will be challenging to balance the UK's variable heat demand with intermittent supply from renewables within the constraints of the existing distribution grid. The installation of more electric heat sources will, without demand management policies and systems, produce a significant increase to peak demand and will necessitate network reinforcement, especially at the distribution level. One approach to this challenge could be to utilise hybrid heat pumps linking an electric heat pump with a gas boiler. Such a hybrid system can switch to the gas boiler during periods of high demand (e.g. spells of cold weather) to reduce electricity use and pressure on the grid. By switching between electricity and gas, hybrid heat pumps can take advantage of time-of-use price differences and tariffs (Carmichael *et al.*, 2020). The usage of hybrid systems can also reduce the cost of reinforcing distribution networks, as the boiler will take some of the strain from the electricity network during high demand periods. Micro-CHP plants for larger buildings and campuses can also be used to add flexibility to the system. Smart heating controls for heat pumps can also assist by smoothing out demand over longer periods of time, especially if linked to a smart meter to obtain real-time tariff signals.

Without access to demand flexibility, network reinforcement and security of supply will be needed. A 2018 analysis for the CCC showed that low-carbon electricity supply flexibility can be improved by installing a greater quantity of firm low-carbon generation sources, such as nuclear and, if available, CCS (Strbac *et al.*, 2018). It can also be improved through installing grid-scale storage to augment peak-time demand.

5.2 Hydrogen

5.2.1 General

Two of the main barriers discussed in Section 4.3 to a hydrogen-based strategy are its supply and cost constraints. There are no blue hydrogen or carbon capture facilities yet operational in Great Britain, and only six green hydrogen plants have been commissioned and built since 2000 (IEA, 2020b). Given the risk associated with such a roll-out, and steep increase in supply required, policy intervention stands to play a crucial role to ensure security of supply. The government plans to make a strategic decision in 2026 about the contribution of hydrogen to heating buildings and helping to achieve Net Zero, based on accumulated evidence from local trials and research and development (BEIS, 2021f). Key steps that would enable a hydrogen backed strategy include governmental support in creating practical business models and clear goals pertaining to the regulatory certainty on supply standards.

5.2.1.1 Capital expenditure grants and support

In the UK Government's Ten Point Plan for a Green Industrial Revolution, low-carbon hydrogen is highlighted as a key proponent in achieving net zero ambitions with support of a £240 million Net Zero Hydrogen Fund between 2022 – 2025, designed to de-risk private sector investment of low-carbon hydrogen and lessen the lifetime costs of projects by providing an initial co-investment (BEIS, 2021l, p.74). This, amongst other measures, will assist in the production of 5 GW of low-carbon hydrogen by 2030 (HM Government, 2020, p.10 – 11). Just how much of this will be dedicated to domestic heating is uncertain, however, it is important to acknowledge it as it could spur investment into low-carbon hydrogen and support its production.

5.2.1.2 Hydrogen business models

The Energy Networks Association (ENA) calls for governmental support to map out viable business models for a successful hydrogen conversion with necessary plans of action in place for its transportation, storage, and production by 2025 (ENA, 2020). As of August 2021, a consultation request has been submitted by the Department of Business, Energy and Industrial Strategy to gain stakeholder insight into the matter with the hope of a successful model reducing the cost gap between low-carbon hydrogen and fossil-fuelled derivatives without CCS (BEIS, 2021i), thereby improving its cost competitiveness.

Due to the high upfront costs of hydrogen infrastructure and associated risk of investment, a policy-based approach with subsidisation is unlikely to be successful. Instead, economic regulation or private law contracts are preferred financing mechanisms for the storage, production, and transportation of hydrogen. As a contractual approach would allow hydrogen production to compete against other low-carbon alternatives (whereas economic regulation is more suited to monopolies), attract strategic investors, and is consistent with other policy interventions it is thought to be better suited to hydrogen production (BEIS, 2021i, p.22). On the other hand a Regulatory Asset Based (RAB) approach is recommended for its transport and storage (ENA, 2020).

5.2.1.3 Low-carbon hydrogen standards

The Ten Point Plan outlines an aspirational 5 GW of low-carbon hydrogen, and the UK has endorsed a 'twin track' approach to meet these hydrogen requirements with low-carbon production expected to occur via steam methane reformation with carbon capture (blue hydrogen) or electrolysis powered by renewables (green hydrogen) (BEIS, 2021f, p.68). At the time of writing a consultation has been completed by BEIS which aims to define low-carbon hydrogen and create a hydrogen standard. This should help to provide clarity in differentiating between the origins of hydrogen in the UK, incentivising the procurement of low-carbon hydrogen, while helping to limit the resultant emissions through the application of life cycle assessments (BEIS, 2021c).

5.2.1.4 Hydrogen trials and appliances

As described in Section 2.2.4, there are plans in place for hydrogen heating trials at a household, street, and neighbourhood level. How these trials perform will give key indications as to the safety of using hydrogen in homes. Moving forward it is pertinent that any consumer concerns over a transition away from natural gas are addressed and users of hydrogen appliances are clearly instructed on the differences that may apply. Safety standards for appliances under the Hy4Heat programme (PAS4444) could form a basis for wide-scale standardisation of hydrogen appliances.

As a full hydrogen conversion would only realistically occur post-2030, government regulations that require the compatibility of natural gas appliances with hydrogen could be important in bridging the gap (Dodds and Demoullin, 2013, p.7193). A consultation on the case to enable, or require, gas boilers to be hydrogen ready by 2026 is expected (BEIS, 2021j) and given the ambition of phasing out new installations of natural gas boilers by 2035 (BEIS, 2021f), there are clear market signals for low-carbon alternatives to help develop the end user market.

5.2.1.5 Blending

Injecting the current natural gas grid with a percentage of hydrogen has been discussed as an area that could play a strategic role (BEIS, 2021f). The use of a hydrogen blend is not unfamiliar territory; town gas, used prior to the discovery of natural gas, was approximately 50% hydrogen combined with methane and carbon monoxide (BEIS, 2021l, p.76). The blending of low-carbon hydrogen into the grid has potential benefits as it would support its production and establish a demand source. It could also provide insights that lend themselves to a 100% hydrogen gas grid roll-out and reduce the emissions intensity of the existing gas grid (ibid.). For example, the incorporation of hydrogen could accelerate some technical and regulatory changes such as reforming gas consumer billing or adjustment to the Gas Safety (Management) Regulations, which currently only allow the hydrogen content of the grid to be 0.1% by volume (Legislation.gov.uk, 1996; BEIS, 2021l). Furthermore, a 20% hydrogen blend into the grid is reported to be able to save 7% of emissions from gas use (HM Government, 2020).

However, there are some drawbacks associated with blending. Other sectors exist, such as industry, that could be better suited to the long-term use of hydrogen. As the UK government is waiting until 2026 to make a strategic decision about hydrogen's use in heating buildings (BEIS, 2021f), the role it will play in the coming decades is still uncertain, limiting the potential benefits blending could bring. The Ten Point Plan and the Heat and Buildings Strategy mark 2023 as the year in which a final policy decision on blending will be made, once its use case has been assessed (HM Government, 2020; BEIS, 2021f).

5.2.2 Blue Hydrogen

5.2.2.1 Carbon capture and storage

Aside from hydrogen production, CCS plays a role in a variety of net zero pathways (CCC 2020; IEA, 2021). The UK could in principle benefit from CCS with an estimated capacity of 78 billion tonnes CO_2 storage, a figure equal to 200 years' worth of UK annual emissions (BEIS, 2021b, p.5). However, given the prior discussion in Section 4, there are numerous barriers to overcome before CCS can be successful. The need for a commercially viable business model is evident in Sunny *et al*. (2020) and whilst this cannot be achieved through government intervention alone, collaborations with industry and stakeholders to ensure the sector attracts investors, is cost effective, and is able achieve a desired capture rate of 10 $MtCO_2$ by 2030 will be important (BEIS, 2021b).

Although incentives have been introduced to support CCS in countries such as the UK, US, Canada and Norway, these have not resulted in a pipeline of future projects, and demonstration has typically been supported on a stop-start basis (Kazaglis *et al*., 2019). Accelerating the deployment of CCS at scale would require more concerted and long-term policy commitment from the 2020s, including through creating new markets to allow early-stage CCS technologies to reach full commercialisation. Potential market creation mechanisms could include obligations or incentives for fossil-fuel consuming industries to sequester their CO_2 emissions, or Contract for Differences (CfDs) for CCS in the industrial sector. A further requirement would be coordinating the development of new or repurposed infrastructure to transport CO_2 with the development of CO_2 stores and capture plants (Kazaglis *et al*., 2019). It has been recommended that a new public delivery body would be needed to coordinate these (Temperton, 2019).

5.2.3 Green hydrogen

Aside from demonstration projects there is limited infrastructure in place to produce green hydrogen, with high costs being a significant barrier in its deployment. An important step to reduce the associated costs would be to encourage and support the deployment of electrolysers (IRENA, 2020a). In order to take advantage of economies of scale, however, predictable demand would almost certainly be a prerequisite for the expansion of production (Agora Energiewend and Guidehouse, 2021).

5.2.4 Is heat decarbonisation in buildings the best use of hydrogen?

Some analyses contend that hydrogen may be better employed in sectors other than heat decarbonisation in buildings. For example, Ueckerdt *et al*. (2021) conclude that hydrogen and hydrocarbon fuels containing CO_2 would provide a more expensive route to heat decarbonisation than direct electrification. The authors therefore recommend that hydrogen would best be prioritised in sectors that are difficult to electrify, for example steel making, long-haul flights and shipping (Ueckerdt *et al*., 2021). Similarly, Lambert (2020) suggests that the most promising use of hydrogen for decarbonisation is likely to be in industrial applications (e.g. iron and steel, cement production and some manufacturing) and transport, specifically fuel cell electric vehicles (FCEVs).

The central Sixth Carbon Budget scenario set out by the UK Climate Change Committee (CCC) also features a more prominent role for low-carbon hydrogen in shipping or industry (CCC, 2020).

5.3 Heat pumps and hydrogen as complementary technologies

Heat pumps benefit from their complementarity with other heating technologies, including district heating. They can also be combined with boilers (including gas and potentially hydrogen boilers) in hybrid systems. Heat pumps can therefore contribute in a variety of ways in heat decarbonisation pathways. In Sweden for example, some district heating systems use large capacity heat pumps as a heat source (Collier, 2018), and heat pumps can also be used to recover heat via exhaust air from buildings supplied by district heating (Dzebo and Nykvist, 2017).

The CCC (2018) have advised that hydrogen could contribute to heat decarbonisation in buildings, mainly via hybrid heat pump systems incorporating a heat pump and hydrogen boiler. In these hybrid systems, the hydrogen boiler would help to meet peak demands during very cold winter days. The core 'Balanced Net Zero Pathway' of the Sixth Carbon Budget projects that the majority of heat needed for buildings would be supplied by heat pumps or district heating in 2030 and 2050, and only 5% of the total heat demand would be met by hydrogen boilers by 2050 (CCC, 2020). Even this core pathway with a moderate pace of technological and behaviour change would require rapid scale up of hydrogen trials in the 2020s. The CCC's alternative 'Headwinds' scenario allows for a faster rate of technological innovation and earlier commercialisation of hydrogen in the 2030s led by conversion of industrial clusters, however this pathway would have higher dependence on blue hydrogen and steam methane reforming and CCS, as well as increased natural gas imports (CCC, 2020).

5.4 Key policies and regulations over the next ten years

5.4.1 Heat pumps

- Funding for the government's planned Boiler Upgrade Scheme grants supporting heat pump installation from 2022 to 2025 is well below what is needed for required levels of deployment. Alternative means of overcoming this affordability barrier include green financing schemes and market products, and supporting industry initiatives to achieve cost reduction through technological learning and experience.
- The government should act to remove differences between the relative policy costs of decarbonisation incorporated into electricity and gas prices, thereby helping to reduce running costs of heat pumps.
- The government is supporting expansion of UK heat pump manufacturing capacity to create more jobs and develop local skills. In addition, government policy should coordinate a managed transition from gas boiler to heat pump manufacturing, providing grants for the reskilling and upskilling of current gas industry employees to help make such a shift.
- The research supports the creation of a "heat pump council" comprised of national and local government, regulators, industry and civil society. This body could coordinate consumer engagement, facilitate supply chain development and provide a quality assurance role via an independent, national test centre for heat pumps.
- The role of the test centre would be to provide wide access to performance information, coordinate training of engineers and installers, and facilitate technological innovation.
- The installation of more electric heat sources will, without demand management policies and systems, produce a significant increase in peak electricity demand. One approach to this challenge could be to utilise hybrid heat pumps which can take advantage of time-of-use price differences and tariffs. There is also an opportunity to engage heat pump users through smart heating functionality and 'Heat-as-a Service' (HaaS) business models.

5.4.2 Hydrogen

- Between 2022 – 2025, a £240 million Net Zero Hydrogen Fund will support the deployment of low-carbon hydrogen.
- In 2022, business models to support a hydrogen economy and reduce the cost gap between low-carbon hydrogen and fossil fuel derivatives are expected.
- Low-carbon hydrogen standards will need to be in place to develop the market and create demand by distinguishing hydrogen by origin. The government has recently completed a consultation with the aim to define low-carbon hydrogen and create a hydrogen standard.
- Blending could help create a demand for low-carbon hydrogen in domestic settings and would require the adjustment of current regulations e.g. Gas Safety (Management) Regulations, which might help if hydrogen is considered as a long-term solution in decarbonisation of domestic heat. However, there are other sectors that could benefit more from its long-term application. A decision on the suitability of hydrogen blending is expected by 2023.
- Hydrogen heating trials are anticipated on a local neighbourhood scale in 2023, before a larger village trial in 2025. How these progress will play a large role in assessing hydrogen's use case before a strategic decision is made in 2026.
- Once this decision is in place a clearer path for hydrogen heating in the home can be established. Until then it is important to focus on low-regret options that would suit both the domestic and industrial sectors in decarbonisation.

6. Summary and recommendations

This Briefing Paper sets out to compare prospects for a renewables-supplied domestic electric heating and a hydrogen-based supply chain, looking at the advantages and disadvantages of each strategy in a near-term timeframe (the next ten years). Both options are also considered with a view as to what will need to be achieved over the next decade in order to contribute to the UK's 2050 net zero target.

It is beyond the scope of this report to consider other technologies or energy sources which might also contribute to heat decarbonisation, such as district heating, biomass and waste heat. However, we recognise that in any likely low-carbon future, heat pumps and hydrogen may contribute to meeting the UK's heat demand as part of a wider portfolio of technologies. We also do not consider specifically the role of improving building energy efficiency, however this will clearly be essential to UK heat decarbonisation given that much of the building stock is old and thermally inefficient.

6.1 Summary of findings

Heat pumps are available to be deployed now for the decarbonisation of heating, and government policy should prioritise removing significant barriers to their uptake, including high costs relative to gas boilers and low consumer awareness and acceptance. Achieving the government's target of installing 600,000 heat pumps per year by 2028, and fitting heat pumps in up to 19 million homes by 2050 will require a coordinated strategy and a strong, interactive partnership between government, regulators, industry, and consumers of heat pump technology. Reaching these levels of deployment is likely to require clear market signals, for example through longer-term subsidy schemes and regulations setting out clear timescales for the phase out of natural gas heating in new and existing buildings. In particular, the Government should act to support expansion of the UK heat pump manufacturing base and a dedicated test centre. A clear training and reskilling strategy will also be needed to train the tens of thousands of heat pump installers or maintenance engineers required to support a transition to low-carbon heating.

A strategic decision from the Government around the use of low-carbon hydrogen as an alternative to natural gas is only expected in 2026. Prior to this, a pragmatic approach is necessary to determine its suitability within households, particularly in reference to its safe use and cost effectiveness, whilst wider system issues such as storage provisions, grid retrofits, and deployment of carbon capture plants and electrolysers require due consideration. As low-carbon standards come into place, business models develop, and hydrogen trials begin, the future of hydrogen in our homes will become clearer.

We find that hydrogen would be best placed strategically in industrial clusters or as a (hydrogen boiler) component in hybrid heat pump systems, whilst blending of the natural gas grid may occur before 2026. It is important to consider how hydrogen could be used in (and whether it should be prioritised for) harder to electrify sectors (e.g., industry and shipping), beyond heat in buildings. In the current decade, UK heat and buildings policy should focus on the energy efficiency refurbishment of the UK housing stock, electrification of domestic heating through heat pumps, and deployment of heat networks. It is likely that hydrogen as a viable source through the gas grid will only be feasible from the early to mid-2030s, at the very earliest. There has been significant recent demonstration activity to determine the feasibility of converting the gas grid to hydrogen, and this should continue to be supported through the current decade. However, policy support for field trials on heat pumps has been sporadic. In such a case, focussing efforts on increasing heat pump performance, improving installations and the consumer experience, and encouraging use of heat pumps is recommended in the short term, whilst efforts to improve hydrogen research is localised around industrial clusters.

Heat pump installation, maintenance and manufacturing activities offer nationwide job creation benefits. Strategic placement of hydrogen facilities near industrial clusters, where the demand for it is already in place will likely aid development of low-carbon hydrogen. In this way, regions within proximity to clusters could transition away from natural gas to hydrogen heating in homes if hydrogen trials prove it as a viable and safe option. Heat pumps and hydrogen boilers also offer complementary possibilities as a flexible resource through their integration in hybrid heat pump systems.

6.2 Policy recommendations

In light of our discussion of the relative merits and drawbacks of heat pumps and hydrogen for decarbonising heating in the UK, we therefore set out the following recommendations for policy makers focusing on actions that should be prioritised between now and 2030. These recommendations also have a view to preparations that will be required for further deployment of low-carbon heat beyond 2030:

1. Energy levies should be moved away from electricity and transitioned over to more carbon intensive fuels to reduce the running costs of heat pumps. To that effect, we welcome the intention in the government’s Heat and Buildings Strategy to implement this.
2. The government should support the development of heat pump manufacturing within the UK to boost technological innovation, local job creation, and help to meet the target to install 600,000 heat pumps annually by 2028. This could be facilitated through policy support and incentives for UK-based manufacturers of complementary technologies (e.g. gas boilers, air conditioners) to shift or diversify production to heat pumps. The Government’s recently published consultation on a ‘market-based mechanism for low-carbon heat’ may help to achieve this – through a proposed obligation for fossil fuel boiler manufacturers to increase their proportion of heat pump sales relative to gas and oil boiler sales. In addition, government policy should coordinate a managed transition from gas boiler to heat pump manufacturing, providing grants for the reskilling and upskilling of current gas industry employees.
3. The Heat and Buildings Strategy has introduced a new Boiler Upgrade Scheme grant for heat pumps of £5000 – £6000, over three years starting from 2022. However, this is likely to support the installation of less than 90,000 heat pumps over that period. We therefore propose long-term grants of at least 10 years to increase revenue certainty in the heat pump industry and help reduce the effective cost of heat pumps to be comparable to gas boilers.
4. We recommend introducing appropriate green financing schemes and products for domestic renewables and energy efficiency measures, following the example of similar measures which have been used successfully in Germany, France and Italy to reduce heat pump costs and support green initiatives.

5. We recommend that the Government should establish a heat pump council comprised of national and local government, regulators, industry and civil society. This body could coordinate consumer engagement, facilitate supply chain development and provide a quality assurance role via an independent, national test centre for heat pumps.

6. The Government should invest in a national research, testing and training facility for heat pumps with a range of roles including: to test and develop new improved technologies, helping to reduce technology costs and creating greater efficiencies; to carry out regular field trials and monitoring of heat pump CoPs or SPFs, and performance of hybrid heat pump systems and smart-functionality; coordinate and provide retraining and reskilling of the workforce; to become a national centre for excellence. Results from test and field trials should be fully transparent and readily accessible to industry and wider society.

7. Electrification of heat could significantly increase peak electricity demand without demand management policies and systems in place. Possible approaches to address this challenge include utilising hybrid heat pumps which can take advantage of time-of-use price differences and engaging heat pump users through 'Heat-as-a Service' (HaaS) business models.

8. Further clarity is needed on the role of hybrid systems which use a heat pump in combination with a gas/hydrogen boiler to boost heat on demand when needed, and whether these might be a good solution for harder to treat homes.

9. Hydrogen production would be best used strategically and its deployment prioritised in sectors which are hard to electrify or decarbonise such as heavy industry, shipping, aviation and heavy transport. Hydrogen could contribute to heating in buildings in areas where hydrogen production facilities are located close to industrial clusters.

10. Low-carbon hydrogen should be clearly defined and standards will need to be in place if the market is to be developed for heat decarbonisation in buildings, helping to create demand by distinguishing hydrogen by origin. The Government has recently completed a consultation with the aim of creating a low-carbon hydrogen standard.

11. To achieve 5 GW of low-carbon hydrogen by 2030, improving the cost-effectiveness of low-carbon hydrogen is fundamental. It is therefore important to invest in and support the electrolyser manufacturing industry within the UK.

12. The research finds that hydrogen infrastructure is not going to be viable for domestic heating applications at scale for at least the next 10 years and therefore, the Government should focus on deploying solutions which are available now including energy efficiency, electrification through heat pumps and heat networks as the main focus for its strategy.

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