Technical Feasibility of Hydrogen Boilers in Homes

A Report for ECOS

January 2023

eunomia

Report For

Environmental Coalition on Standards (ECOS)

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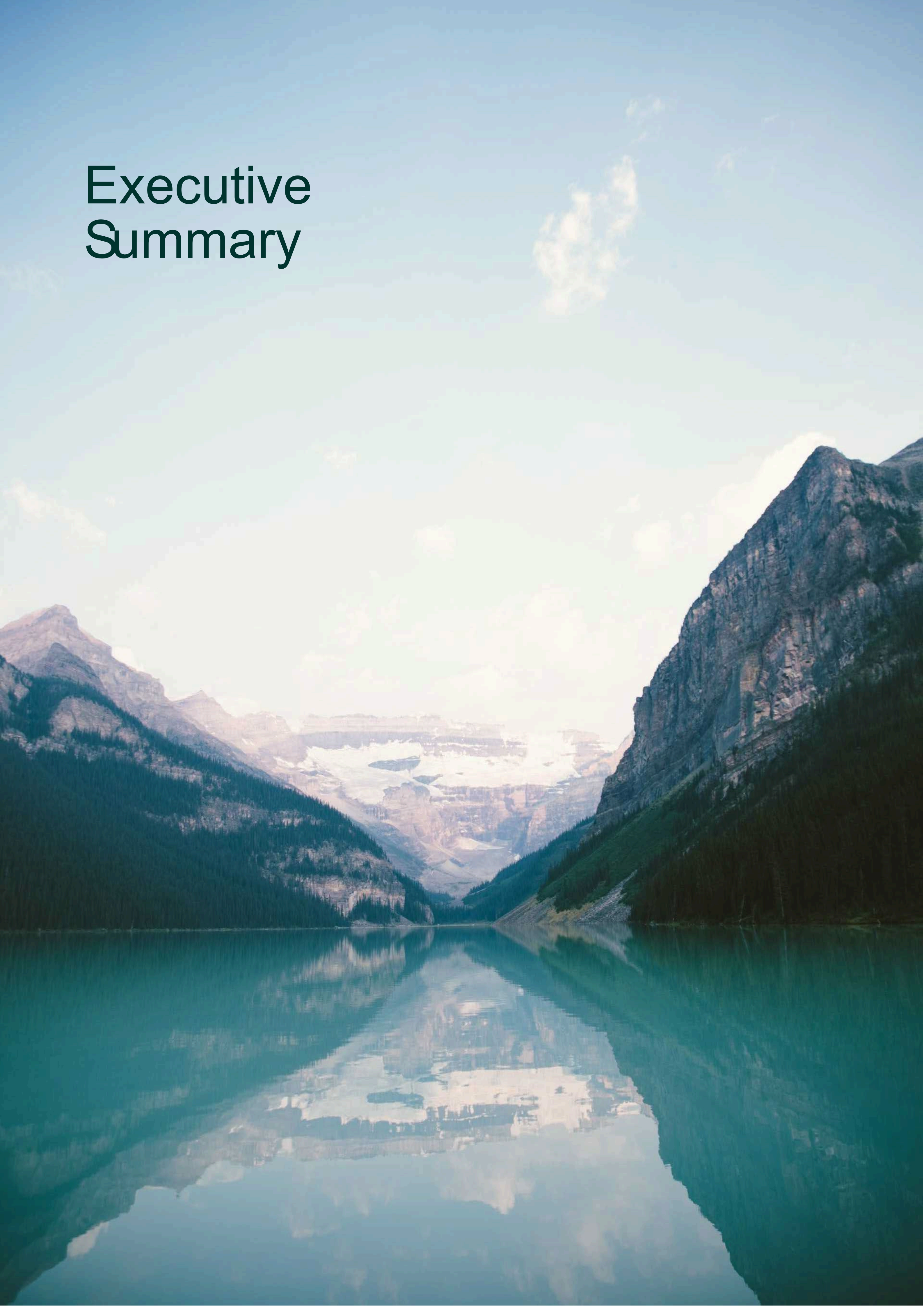
Glossary

Term	Definition
Burner Plate	The mechanism within the boiler that controls the flame speed and temperature.
Code Plug	Software file that is loaded into the boiler to tell it how to function.
Flame Length	The distance between the flame tip and the midpoint of the base of the flame .
Flame Speed	The measured rate of expansion of the flame front in a combustion reaction.
Flammability Range	The minimum and maximum concentrations at which a vaporous substance will ignite or combust when mixed with air.
Flue Gas	The exhaust gases produced by a boiler.
Gas Velocity	The speed at which the gas is fedto the burner.
Heat Exchanger	Coiled pipes that are pumped with hot gas that transfers the heat to surrounding water.
Light Back	Where the flame speed is greater than the speed of the gas supplyso the flame travels back along the gas supply pipeline.
NO_x	Collective term for toxic gas molecules that are chemical compounds of Nitrogen and Oxygen.
Pre-Mixing	When the fuel is mixed with a gas, normally air, before it enters the combustion chamber.
Flame Failure Devices	A mechanism that stops the flow of gas when the flame is extinguished.

Wobbe Number or Wobbe Index	A combustion parameter calculated as the gross calorific value divided by the square root of specific density. It dictates some combustion/ flame characteristics, determines if a flame will burn safely (no lift-off, light back, sooting etc), and is one of the parameters with limits defined in Gas Safety (Management) Regulations.

Executive Summary



Context

Buildings consume a huge amount of energy. In the EU, they account for 36% of energy-related greenhouse gas (GHG) emissions[1]. Heating appliances contribute to 12% of the total GHG emissions, with two thirds of energy for domestic appliances coming from fossil fuels where natural gas boilers are the dominant heating technology.[2]

One of the frontrunning alternative technologies to natural gas boilers are hydrogen boilers. Hydrogen boilers work in the same way as natural gas boilers, but with the gas supply to buildings switched from natural gas to hydrogen gas. If the hydrogen is sourced from low carbon sources, then by replacing natural gas it can significantly reduce emissions.

Although hydrogen offers the promise of a low carbon emission fuel, there are significant technical challenges associated with switching the gas supply. For example, there are concerns over safety and maintenance, low energy efficiency, and higher heating costs for householders. There is also the logistical challenge of switching gas distribution networks to hydrogen.

With these challenges in mind, this study aims to provide impartial and accurate information on the technical feasibility of hydrogen boilers in a transition to:

- 100% hydrogen using a hydrogen boiler; or
- Hydrogen-ready boilers that can operate on the existing natural gas supply and be later upgraded to accept 100% hydrogen; or
- Use of conventional natural gas boilers to accommodate hydrogen blended with natural gas.

Approach

A literature review was conducted to capture key information and to identify information gaps. A key focus was the findings from European hydrogen trials. This was followed up with six interviews held in November 2022 with key stakeholders involved in the hydrogen trials including boiler manufacturers, technical consultancies, an NGO and a university that worked on the trials. These interviews provided additional perspectives that may have been covered in the literature as well as helping to address any gaps from the literature review.

The research undertaken included consideration of the technological and economic barriers to converting to hydrogen in terms of sourcing the necessary components and materials for manufacture of the boiler units themselves. It also included an assessment of the extent to which safety issues associated with hydrogen place limits on the feasibility of retrofitting boilers.

[1] European Commission (2020), In focus: Energy efficiency in buildings (europa.eu) focus: Energy efficiency in buildings (europa.eu)
[2] Calculated on the basis of data found in Bertelsen, Nis & Mathiesen, Brian. (2020). EU-28 residential Heat Supply and Consumption: Historical Development and Status. Energies. 13. 1894. 10.3390/ en13081894

The research did not examine external factors, such as the economic feasibility of a transition to hydrogen, costs to the consumer versus alternative heating technologies, or the feasibility of converting the natural gas network to hydrogen.

Key Findings

The study examined the technical feasibility of both pure hydrogen boilers and hydrogen blended with natural gas. These are discussed individually below.

Blended

Most existing gas boilers are capable of burning up to 20% hydrogen within their standard limits. Trials have demonstrated that this is effective and safe with minimal disruption to households. Trials have also shown that gas boilers do not experience any noticeable damage when fired on a 20/80% blend of hydrogen/natural gas and that their technical performance is not negatively impacted.

The safety concerns for burning with 20% hydrogen are the same as for a boiler burning 100% natural gas. Technical studies and practical trials have demonstrated that there are no reported increases in gas escapes, Carbon Monoxide alarm activations or flammable substance detections.

The consensus among manufacturers is that 20% is the maximum blend for safe limits within domestic use. Above 20% would likely require heavy upgrades and alterations to various components within the natural gas boiler. Whilst circa 90% of the natural gas boiler and hydrogen boiler components are the same, it would not be economically viable to convert an existing natural gas boiler to burn more than a 20% blend of hydrogen. Instead, manufacturers are focusing on hydrogen-ready boilers (discussed below).

Given that natural gas boilers have not been optimised for burning a hydrogen blend, the performance, efficiency and cost to the consumer is likely to be lower than a brand new 100% hydrogen appliance.

Pure Hydrogen

Hydrogen-ready boilers are being developed to prevent homeowners from needing a whole new boiler if the network switches to hydrogen gas. A hydrogen-ready boiler is designed to burn hydrogen and then retrofitted to accommodate natural gas. This means that most of the components needed for hydrogen firing are already present, meaning only a small conversion process is required.

Hydrogen-ready boilers can be converted to run on 100% hydrogen in 1-2.5 hours by a qualified gas engineer for a cost of circa €200. Due to safety concerns, consumers would not be able to undertake this conversion themselves.

Although most of the components in a hydrogen and natural gas boiler are the same, certain components are likely to require replacement/alteration by an engineer at the time of switchover. This includes:

- The burner, owing to the different flame properties (flame speed, position, temperature) of hydrogen and natural gas. Manufacturers have successfully designed burners that can safely operate with hydrogen. Note that burners which can fire both 100% natural gas and 100% hydrogen are technically challenging and are unlikely to be economically viable.

- The flame detector, due to the shorter hydrogen flame length compared to natural gas, and the unsuitability of ionisation probes for hydrogen. Alternatives using UV, infrared and light sensors are all proven and available. Similarly, faster-acting Flame Failure Devices may be required, replacing current thermoelectric models with UV or infrared alternatives.
- Some of the materials used in the valves, seals and gaskets may need to be replaced with more robust types of material as they come into regular contact with hydrogen. Inlet gas pipes and supply pipes would not need to be modified.
- The code plug settings will need to be changed so that the boiler is coded to run on hydrogen rather than natural gas. This would be a very simple procedure that would not require any physical changes. It is unlikely that boilers will be able to detect the fuel and automatically switch their settings themselves, necessitating this simple manual switchover.
- There are other, less significant, technical considerations that will be taken into account but will not pose any major obstacles to the feasibility of roll out.

Manufacturers are confident in their development of hydrogen-ready boilers. Large scale trials will be the next steps to prove its real-world feasibility, and these are planned in some countries such as the UK. For manufacturers, the next steps will be to scale up and commercialise their hydrogen-ready boilers. However, manufactures are waiting for policy support that will enable them to make investment decisions before this begins. Prototype hydrogen-ready boilers have been produced, though none are presently available on the market. Furthermore, additional research is required to verify the efficiency and useful operating lifetime of hydrogen boilers.

The same safety concerns for 100% hydrogen burning compared to blended are very similar, but there is less evidence surrounding safety concerns for 100% hydrogen. These safety concerns are summarised below.

- The risk of explosion with pure hydrogen for a small leak is no greater than with natural gas. In larger leaks, there is a greater explosive risk with hydrogen than natural gas, with greater likelihood of an explosion causing significant structural damage. Trials have indicated that incorporating additional Emergency Flow Valves could reduce the risk, as could the installation of ventilation ducts in rooms with hydrogen, and the design of hydrogen boilers to reduce internal cavities. Future trials should be undertaken in flats, particularly high-rises, to assess the risk to those properties.
- There is a theoretical increase in NOx emissions from burning hydrogen compared to natural gas, possibly up to double the NOx emissions. However, testing produced NOx emissions within European eco-design levels, and lower than natural gas boilers at equivalent thermal input levels. Further testing is required to demonstrate if this would be representative of hydrogen-ready boilers post conversion.
- There is uncertainty surrounding the long-term material sensitivities. Hydrogen is known to embrittle metals, such as steel, meaning that current pipework may need to be replaced to avoid embrittlement. In particular, joints, areas in contact with hydrogen, and areas subjected to heat may need upgrading. Polyethylene plastic can reduce this risk, and it is the view of the industry that copper is also likely to be suitable for hydrogen.
- An odorant will need to be added to enable consumers to smell a hydrogen leak and the use of the current natural gas odorant has been proven to be sufficient.
- The lack of a visible hydrogen flame is not an issue in boilers as it is for cookers and fires.

Conclusions

Overall, the study did not identify any major technical obstacles in the roll out of hydrogen boilers. The findings suggest that hydrogen boilers are likely to become technically feasible within timescales that support a net zero transition. The factors which will dictate whether hydrogen is the best option for heating are broader in nature. For example, the relative efficiencies of hydrogen heating compared to other technologies, the relative environmental and resource impacts, the costs to the consumer, the feasibility of a gas network switchover, and other potentially more important uses for green hydrogen.

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1.0

Problem, Context and Objectives

1.1 Problem and Context

Summary

With the adoption of the European Green Deal (EGD), the Commission set EU targets of 55 % greenhouse gas (GHG) reductions from 1990 levels by 2030 and climate neutrality (net zero GHG emissions) by 2050. Buildings are the largest energy consumer in the EU, where they are responsible for approximately 40% of energy use and 36 % of energy-related greenhouse gas emissions. Heating appliances contribute to 12% of the total emissions, with two thirds of energy for domestic appliances coming from fossil fuels. The two frontrunning alternative technologies include heat pumps and hydrogen boilers.

In order to mitigate the threats of climate change, the European Union (EU) has set itself the ambitious target of reducing its greenhouse gas emissions to at least 55% below 1990 levels by 2030, followed by a longer-term goal of reaching climate neutrality by 2050.[3] The European Climate Foundation (ECF) has calculated that 12% of the EU's total annual CO_2 emissions come from space and water heating appliances installed in the built environment.[4] Furthermore, the European Commission has reported that two thirds of the energy used for domestic heating, cooling, and hot water in the EU come from fossil fuels.[5] Therefore, an important contributing factor in the EU's climate efforts must be the decarbonisation of heating systems. This can be achieved by transitioning from fossil gas boilers using lower-carbon systems.

There are various alternatives to fossil fuel-based heating technologies. The most dominant technology is heat pumps. **Heat pumps** use a small amount of electrical energy to transfer a greater amount of thermal energy from a heat source to a heat sink (or vice versa). They have the potential to electrify heating which allows a transition away from gas-based technologies. A recent report from the Regulatory Assistance Project (RAP) stated that:

"Heat pumps are widely seen as the key solution to replace fossil fuel heating systems, either as direct replacements in individual buildings or as part of district heating systems.[6]"

An alternative approach is to use hydrogen fuelled boilers. **Hydrogen gas boilers** work in the same way as fossil fuel natural gas boilers, but with the gas supply to buildings switched from fossil gas to hydrogen gas. If the hydrogen is sourced from low carbon sources, then by replacing gas it can help reduce emissions. Figure 1-1 provides further information about hydrogen boilers.

[3] 2030 Climate Target Plan, European Commission, Europa website: https://ec.europa.eu/clima/eu-action/european-green-deal/2030-climate-target-plan_en
[4] Calculated on the basis of data found in Bertelsen, Nis & Mathiesen, Brian. (2020). EU-28 residential Heat Supply and Consumption: Historical Development and Status. Energies. 13. 1894. 10.3390/en13081894
[5] A Renovation Wave for Europe – greening our buildings, creating jobs, improving lives, European Commission, 14/10/2020, https://ec.europa.eu/energy/sites/ener/files/eu_renovation_wave_strategy.pdf
[6] RAP (2022), The perfect fit: Shaping the Fit for 55 package to drive a climate-compatible heat pump market

Figure 1-1: About Hydrogen Boilers

Hydrogen boilers burn hydrogen gas in a sealed combustion chamber before using a heat exchanger to heat water, that is then pumped to radiators and taps. They are, like modern fossil gas boilers, a type of condensing boiler, meaning that they achieve high energy efficiency by recovering extra heat from water vapour in the exhaust gases they produce.

Hydrogen boilers are seen as a promising means of decarbonising heat because burning hydrogen does not produce carbon emissions, with the main by-product being water. Hydrogen can be produced from a range of different sources, including fossil fuels, biomass, and water electrolysis using electricity, and can be a by-product of industrial processes. In order for hydrogen to be considered a low carbon fuel, it is important to ensure that the zero carbon emissions are released in its production.

The role of hydrogen in the low-carbon heating sector is being actively investigated by a variety of policy makers. For example, a recent UK House of Commons committee concluded that:

> *"Hydrogen could play a role in domestic heating, but the extent of its potential is still uncertain and looks likely to be limited rather than widespread. We are unconvinced its deployment will prove to be economically viable by the time the Government has said it will determine the role of hydrogen boilers, in 2026"*[7]

Table 1-1, outlines several definitions for technical terms and abbreviations in relation to the types of boilers this study focuses on.

Table 1-1: Definitions

Term	Definition
H_2	Hydrogen.
Blending	Integrating a percentage of hydrogen into existing natural gas pipelines to reduce the carbon intensity of methane. Ratios are typically given on a volumetric basis, rather than mass.
Hydrogen Boiler	A boiler which runs entirely (100%) on hydrogen fuel.
Hydrogen-ready Boiler	A hydrogen gas-fired boiler of any type (regular, system or combination) that has been retrofitted to burn 100% natural gas and/or natural gas with a hydrogen blend. Following an in-situ conversion and commissioning process, hydrogen-ready boilers can burn 100% hydrogen.
Conventional Gas Boiler	A boiler which burns natural gas (mostly methane, with small amounts of other naturally occurring fossil gases)*

[7] UK Parliament Committees (2022) - [The role of hydrogen in achieving Net Zero - Committees - UK Parliament]

**In some countries, natural gas has been blended with biomethane. Additionally, in some countries conventional gas boilers have been routinely tested to accommodate hydrogen for many years. For example, in the EU and UK, conventional gas boilers have been tested to accommodate up to 23% hydrogen blends with natural gas since the 1990s, and in more recent trials and demonstrators such as HyDeploy. Conventional gas boilers are not capable of running on 100% hydrogen fuel without significant modification.*

Although hydrogen offers the promise of a low carbon emission fuel, there are significant technical challenges associated with switching the gas supply from natural gas to hydrogen. As noted in the Terms of Reference for this study, safety and maintenance, low energy efficiency, and higher heating costs for householders are all concerns. In addition, the logistical challenge of switching gas distribution networks to hydrogen would be immense. Gas distribution networks deliver the same mix of gas (whether natural gas or hydrogen) to all properties in an area at the same time, meaning that all buildings within a particular area of the distribution network would need to switch their supply and appliances simultaneously from natural gas to hydrogen. This switchover period would presumably take place during the summer when heat demand would be low. This would require an extraordinary amount of coordination on the part of gas network operators. At the same time, this would still cause short-term disruptions to buildings and homes as the gas supply will need to be switched off for one to a maximum of five days[8]. The significance of the disruption would be dependent on the changeover team size.

There is no single obvious technological solution for the transition to low carbon heating in buildings. The future of low carbon heating for buildings is likely to be a mix of technologies. What we know is that decarbonising heat will have profound impacts on people. The change in technologies will require changes in almost every home in the country (including the need for energy efficiency measures). Some householders may be required to change how they engage with their heating system.

1.2 Objectives

1.2.1 Aims and Research Questions

This study aims to provide impartial and accurate information on the technical feasibility of a transition to:

1. 100% hydrogen using a hydrogen boiler; or
2. Hydrogen-ready boilers that are then upgraded to accept 100% hydrogen; or
3. Use of conventional gas boilers to accommodate hydrogen blended with natural gas.

In doing so the research consolidates technical information and presents it in this report for a non-technical audience. This will require answering the main research question:

Is retrofitting gas boilers to accommodate hydrogen, either as blended or 100%, and hydrogen-ready boilers that do not need to be retrofitted, technically possible?

Based on the available literature, this study assesses whether retrofitting existing gas boiler technology to either a 100% hydrogen or hydrogen/fossil gas blend is technically feasible. This includes consideration of the

[8] H21 Leeds City Gate (2022) – H21 North of England Report

technological and economic barriers to converting in terms of sourcing the necessary components and materials for manufacture. It will also include an assessment of the extent to which safety issues associated with hydrogen place limits on the feasibility of retrofitting.

The research questions explored within this study are:

- According to the blending shares and 100% hydrogen configuration, what will the step s for such converting conventional gas boilers and hydrogen-ready boilers be?
- What are the principal obstacles to accommodate hydrogen in conventional gas boilers? What are the main components of a gas boiler affected using hydrogen as a fuel, both as blended and 100% hydrogen?
- Is there a real possibility to have a toolkit to make consumer convert hydrogen-ready boilers to 100% hydrogen?
- What is the maximum blended hydrogen share in conventional gas boilers that would not dramatically affect the operati on of the appliance?
- From the safety point of view, what are the risks with boilers, both as blend ing with conventional gas boilers, hydrogen-ready boilers and hydrogen boilers?
- From the materials of the component's perspective, what are the risks in hydrogen boilers, both as blending with conventional gas boilers, hydrogen-ready boilers and hydrogen boilers?

The UK is leading the way in the development of hydrogen boilers. Many of the advanced trials have taken place in the UK, and as a consequence, much of the findings from this research are UK-centric. These findings have been applied to the rest of Europe where applicable, as well as being supplemented with literature from other European trials and studies.

1.2.2 Scope

This research study concentrates on the technical engineering questions described in Section 1.2.1, concerned with technical matters concerning the implementation and roll-out of hydrogen boilers. It is understood that there are a number of other challenges and concerns regarding the role of hydrogen for heating, including:

- The relative economic and thermodynamic efficiencies of hydrogen heating compared to other technologies (e.g. heat pumps, district heating)
- The relative environmental impact and resource (e.g. scarce mineral) requirements of the hydrogen supply chain (particularly in production) compared to other technologies.
- The relative costs to the consumer for hydrogen heating compared to other technologies.
- The socioeconomic feasibility of a transition of the natural gas network to hydrogen, from production through transmission and distribution, to the home boiler.
- Competition from hydrogen heating with other potential end -uses for green hydrogen (e.g. industry, shipping, aviation, energy storage) where there are fewer alternative technologies available and where hydrogen is likely to make a more viable economic and environmental case, possibly even being vital to the net zero transition in those areas.

Consideration of such external factors are out of scope for this study. Rather, this study focuses solely on the technical feasibility of hydrogen boilers – consideration of whether hydrogen is the best option for heating compared to other options is not under consideration in this piece of work. For consideration of the other factors, the reader is directed to alternative literature available, for example reference [9].

Furthermore, it is important to note that this review has only looked at what happens 'behind the meter', where gas is delivered into the home. Technical considerations, particularly regarding safety, in the wider transmission and distribution network, with its significantly higher pressures and associated risks, has not been considered.

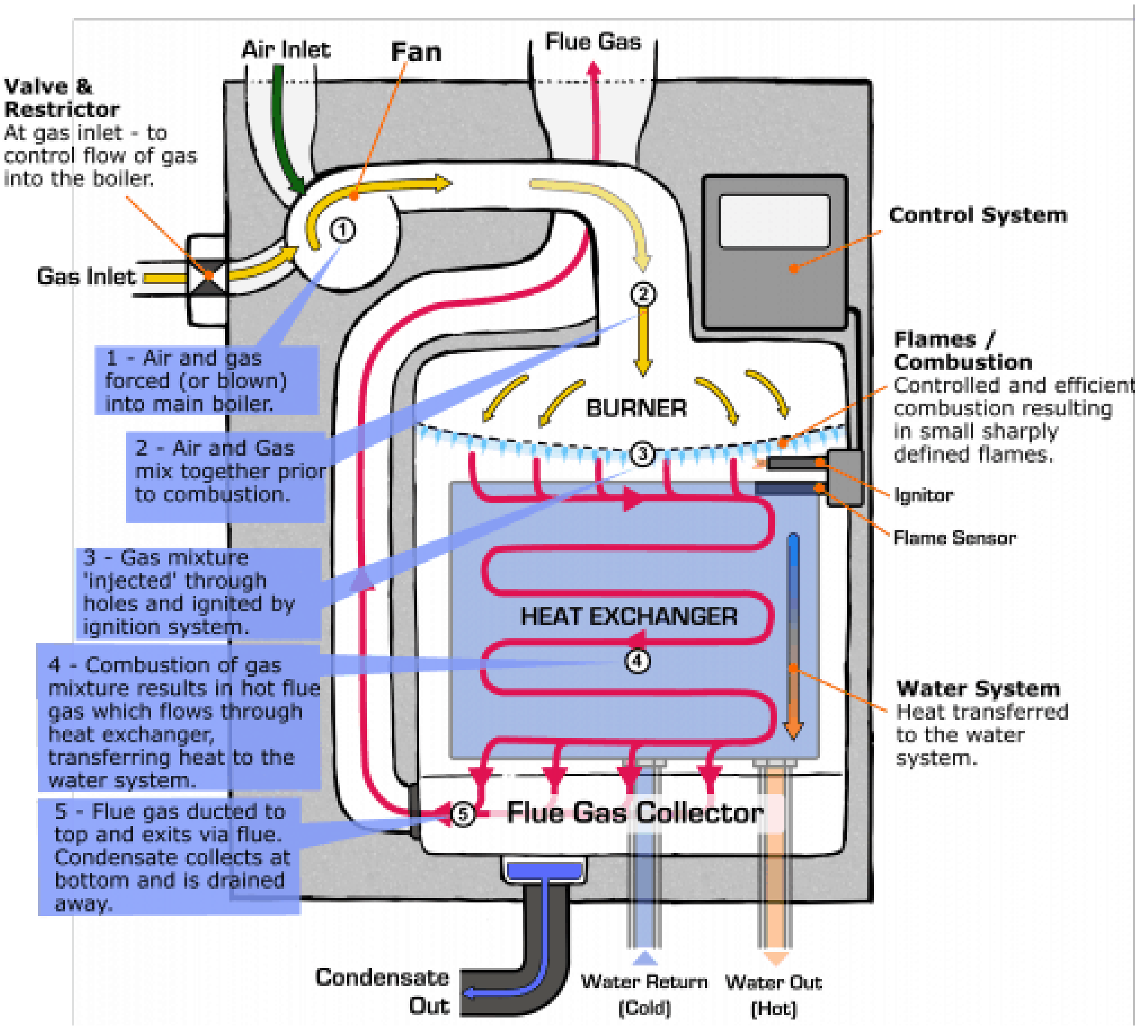
1.3 How a Hydrogen Boiler Works and Key Components

The main components of a common gas boiler, and how they work, are displayed in Figure 1. In summary, the gas enters the chamber via a valve that controls the flow and is then mixed with air before being ignited at the burner. This produces hot flue gases that are forced through the heat exchanger system where the heat transfers to water. Once it reaches the end of the heat exchange process, the flue gas is expelled, and cold water re-enters the system.

The basic functioning of a natural gas and hydrogen boiler is largely the same. This study has examined the differences between boilers burning the two fuels, and explores which elements of a natural gas boiler would be different for a hydrogen boiler.

[9] J Rosenow (2022), Is heating homes with hydrogen all but a pipe dream? An evidence review

Figure 1-2: Natural Gas Boiler

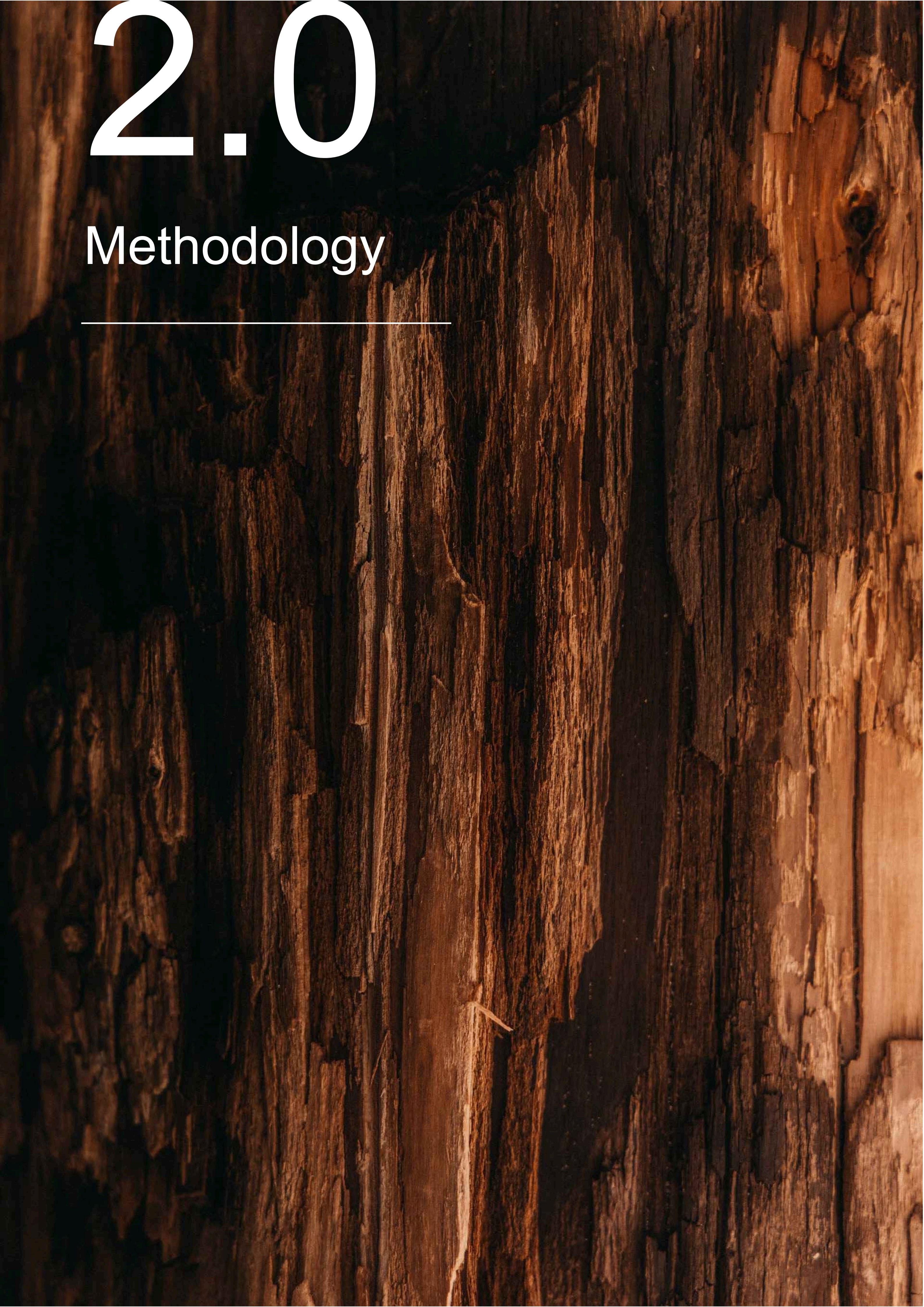


Source: Frazer-Nash Consultancy (2018) [10]

[10] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)

2.0

Methodology



2.1 Research Method

Summary

A literature review was conducted to capture key information and to identify information gaps. The gaps informed the development of the subsequent research and interviews with key stakeholders.

The literature review was conducted to capture useful secondary information related to the research questions. The findings helped the research team to understand where the key information gaps are, and what the key issues are that need to be explored further. This then informed the development of subsequent tasks (e.g. questions for the interviews with stakeholders).

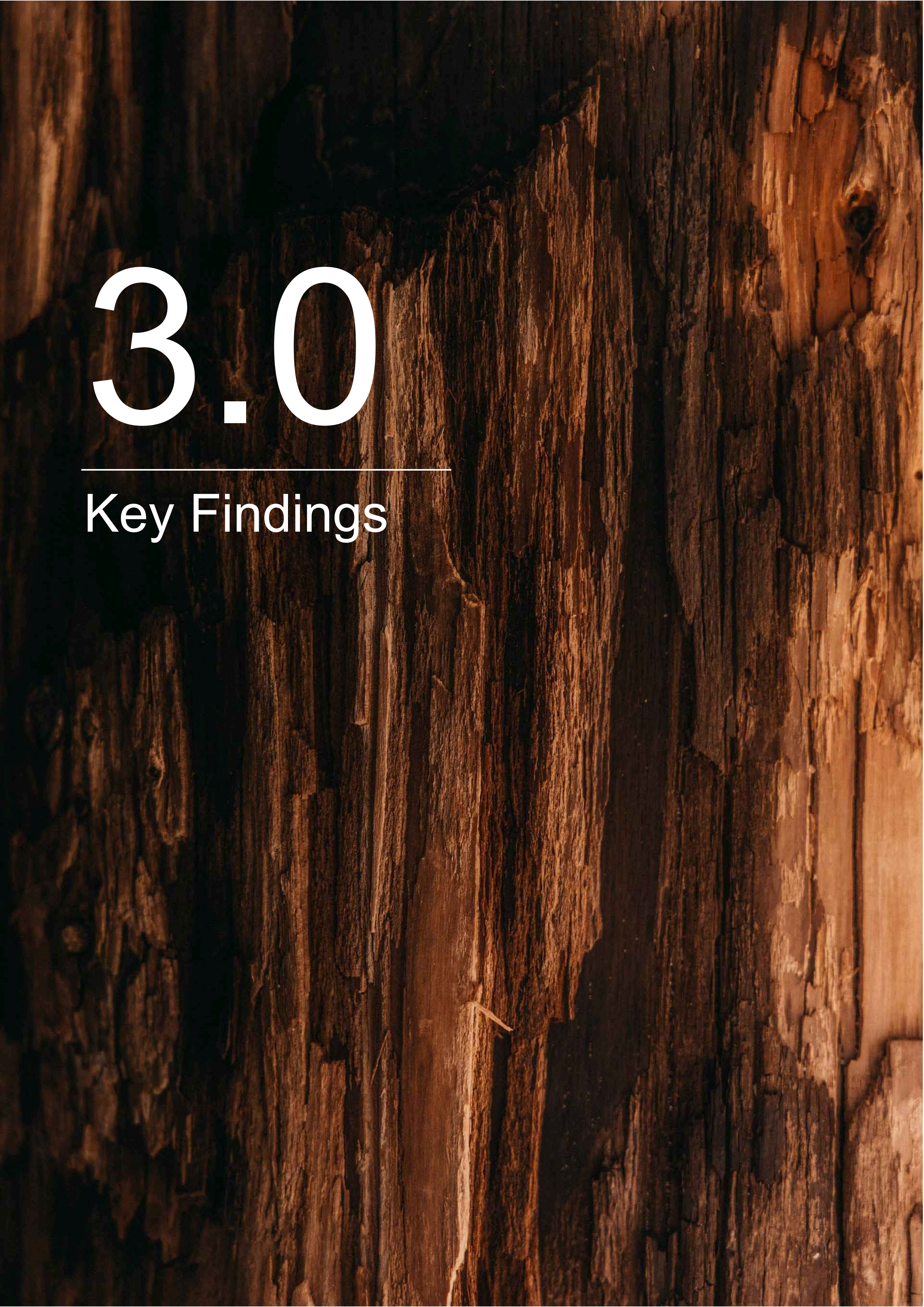
The literature review was conducted in alignment with Eunomia's best practice which aligns with the guidance provided by the UK Government Social Research Service. Several pieces of literature were already known to the research team, and web searches were undertaken to identify additional information. These utilised a series of searchstrings to search electronic databases such as Scopus and Web of Science, and the team also sought to identify literature via Google and any relevant websites.

Examples of literature that was reviewed include:

- Results of trials in EU countries such as Italy, the Netherlands and France;
- Trial documents from UK trials such as Hy4Heat, HyDeploy and H100 Fife;
- Related government documents from the EU and other relevant countries;
- Academic articles;
- Consultancy reports;
- Relevant press releases and media articles; and
- Information provided by manufacturers, trade associations and industry bodies on their websites, prototype documents and research.

A list of key sources reviewed can be found in Appendix A 1.0.

In addition to reviewing literature, the second phase of this research included interviews in November 2022 with key organisations identified throughout the literature. This included boiler manufacturers, technical consultancies, an NGO and a university that worked on the trials. This allowed for views to be gathered on all the research questions that was not covered in the literature, but also specific issues identified to be discussed in detail with the most relevant organisations, as well as filling any gaps. The themes covered in the interviews are outlined in A 2.0. Furthermore, the interviews led to further literature being recommended which was subsequently reviewed.



3.0

Key Findings

This section summaries the findings from the literature review and interview research. The findings are presented by the broad topics of 1) Blended Hydrogen and 2) Pure Hydrogen. The sections cover information relevant to all research questions.

3.1 Blended Hydrogen

3.1.1 Blending Hydrogen in Existing Boilers (20%)

Summary

Most existing gas boilers are capable of burning up to ~20% hydrogen within their standard limits and trials have demonstrated that this is effective and safe with minimal disruption to households. Trials have indicated that boilers do not experience any noticeable damage when fired on a 20/80% blend of hydrogen/natural gas and that their technical performance is not impacted.

Most existing natural gas boilers are capable of burning up to circa 20% hydrogen within their design parameters and within the standard testing limits for natural gas appliances.[11] For example, since the 1996 Gas Appliance Directive all gas appliances sold in the EU and UK have been tested with hydrogen blends of 23% during their production certification.[12] The 20% blend allows the resultant mixture to remain within the HSE's Gas Safety (Management) Regulations 1996 Wobbe Index envelope.

As shown in Table 3-1, the majority of European trials analysed as part of this work utilised a maximum blended share of 20% hydrogen to 80% natural gas. Trial reports suggest that such a blend is effective, safe and minimises disruption to households (in terms of changes to gas appliances and boilers).[13,14,15,16,17] Documents released by boiler manufacturers Baxi, Worcester Bosch and Viessmann corroborated the use of this blended hydrogen share. They state that a 20% blend can be used efficiently and reliably in existing heating appliances.[18,19,20]

[11] HyDeploy., 2020. HyDeploy Gas Safety Webinar. https://www.youtube.com/watch?v=3BGjbcBYmPo
[12] The Chemical Engineer (journal of the Institution of Chemical Engineers), 2019, Heating with Hydrogen
[13] HyDeploy., n.d. Carbon Savings Summary. https://hydeploy.co.uk/app/uploads/2018/02/21063_2PP_HyDeploy_Carbon_Savings_Handout_DIGITAL.pdf
[14] HyDeploy., 2021. Hydrogen blending begins on the public gas network in Winlaton. https://hydeploy.co.uk/about/news/green-light-for-first-hydrogen-blending-on-a-public-gas-network/
[15] Baxi., 2022. Hydrogen. https://www.baxi.co.uk/About%20Us/The%20Future%20of%20Heat/Hydrogen
[16] HyNet., n.d. HyNet North West, unlocking net zero for the UK. https://hynet.co.uk/wp-content/uploads/2020/10/HyNet_NW-Vision-Document-2020_FINAL.pdf
[17] Westküste 100., n.d. https://www.westkueste100.de/en/
[18] Worcester Bosch., 2019. Hy4Heat | Hydrogen-Ready Wall-Mounted Gas Boilers. https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/616d78c680bd847c4efade9a/1634564294494/Bosch+HyLife+.pdf
[19] Viessmann., 2022. Hydrogen boilers: how they work and whether you need one. https://www.viessmann.co.uk/en/heating-advice/boilers/how-do-hydrogen-boilers-work.html
[20] Baxi., 2019. H2. https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/616e91fe9a6a8c132fdc8991/1634684362991/Baxi_Hydrogen_Hy4Heat_DL+.pdf

Table 3-1: European Trial Hydrogen Blends Within Reviewed Literature

Hydrogen Volume Blend	Trial
10%	Italy - Snam
20%	France - GRHYD Germany - Westküste 100 UK - HyDeploy Phase 1 (Keele) UK - HyDeploy Phase 2 (Winlaton) UK - HyNet Northwest
30%	The Netherlands - Ameland

The interviews with manufacturers and an academic institution corroborated these results further. Several interviewees felt that using a 20% blend means that no alterations would be required – both regulatory (e.g., amendments to gas safety regulations) and physical changes to appliances/ boilers.

Relevant findings from selected practical trials with boilers using up to 20% hydrogen are described below:

Ameland
Boilers functioned properly and to specification, with no damage occurring as a result of operating appliances with the 20% hydrogen-natural gas blend. Testing also showed a reduction of Carbon Dioxide (CO_2), Carbon Monoxide (CO) and Nitrous Oxides (NO_x) as result of adding hydrogen. The boilers fired up normally and did not suffer from flame damage. During maximum operation with 20% hydrogen, the normally blue flame acquired a red glow. This was a result of flames being closer to the burner and less well mixed with air prior to ignition. Overall, no internal components of the boilers were adversely affected by the hydrogen blend.[21]

[21] Waterstof., n.d. Hydrogen blending with Natural Gas on Ameland. https://www.netbeheernederland.nl/_upload/Files/Waterstof_56_7c0ff368de.pdf

HyDeploy

This study tested eight standard natural gas boilers from four manufacturers (two boilers per manufacturer). One of each manufacturer's boilers burned 100% natural gas, and the other burned a blend of 20% hydrogen. The study used an intensive operational regimeto simulate long-term usage patterns, with some boilers operating continuously at maximum load, some at minimum load and others cycling between the two. During the trial, the boilers consumed fuel volumes equivalent of up to 18 years of normal domestic operations and were observed to perform well.

The boilers were returned to the manufacture rs at the end of the trial for performance testing and component integrity analysis.[22] We interviewed two individuals who were involved in this project. They told us that the manufacturers, when analysing their boilers after the trial, could not tell, from a technical and safety standpoint (e.g., ageing, degradation, embrittlement) which of their boilers had been burning 100% natural gas and which had been burning 20% hydrogen, such was the efficacy of existing natural gas boilers in burning a blended mix. This suggests that the technical performance implications of burning 20% hydrogen in existing natural gas boilers are limited, though noting that a conventional natural gas boiler burning 20% hydrogen will be less efficient than a boiler designed to burn hydrogen.

Following these tests, alongside accompanying trials for the distribution and transmission networks, governments are now moving towards widespread blending of hydrogen in the natural gas network. For example, the UK government is targeting a 2023 policy decision on whether to allow up to 20% hydrogen blending in the gas grid, and has stated that it is "building the necessary evidence base to determine whether blending meets the required safety standards, is feasible, has the desired goal of supporting development of a hydrogen economy, and represents value for money".[23]

3.1.2 Technical, Safety & Performance Implications

Summary

Given that natural gas boilers have not been optimised for burning a hydrogen blend, the performance, efficiency and cost to the consumer is likely to be lower than a brand new 100% hydrogen appliance.

The safety concerns for burning with 20% hydrogen are the same as for a boiler burning 100% natural gas. Technical studies and practical trials have demonstrated that there are no reported increases in gas escapes, CO alarm activations or flammable substance detections. Hydrogen-compensated CO sensors will be required in hydrogen boilers to avoid false-positive activations.

While, theoretically, burning hydrogen may increase NOx emissions, there is mixed evidence on whether or not this is true for domestic boilers, and early trial data indicates that NOx emissions may actually reduce. Further exploration of this topic is required.

[22] HyDeploy (2021): HyDeploy Project Close Down Report.
[23] Department for Business, Energy & Industrial Strategy, Hydrogen Strategy update to the market: December 2022

Natural gas boilers contain components that have not been optimised for hydrogen, and this is likely to result in a reduction in performance to the consumer (e.g., efficiency, cost per unit heat produced) compared to new hydrogen appliances.[24] However, this reduction in performance is likely to be limited to efficiency and cost-effectiveness, as opposed to technical or safety issues.

In many areas, technical and safety considerations for a boiler burning 20% hydrogen are the same as for a boiler burning 100% natural gas. For example, both 100% natural gas and natural gas containing up to 20% hydrogen are considered to be IIA gases[25], meaning any current electrical equipment (i.e., boilers) suitability rated for natural gas exposure are also rated for exposure to blended gas containing up to 20% hydrogen.[26, 27] Whereas, greater than 20% hydrogen would likely classify as an IIC gas, potentially requiring greater requirements to ensure safety.[28]

Whilst it is clear from the literature and interviews that existing natural gas boilers can burn up to 20% hydrogen safely and effectively, there are certain subjects that require particular consideration in order to maintain safe and effective operation.

When discussing safety of boilers, whether gas or hydrogen, common areas of assessment are:

- CO production;
- Material/component failure;
- Explosion risk;
- Flame stability;
- Ignition;
- Overpressure; and
- NO_x

There is consensus within the reports reviewed that blended hydrogen up to 20% can safely be supplied into the home. Along with technical studies, a number of practical trials have been successful in deploying a 20% hydrogen blend to domestic properties. The HyDeploy Keele trial delivered its 20% hydrogen blend to its facilities with no reported increase in gas escapes, CO alarm activations or flammable substance detections.[29]

One challenge encountered in the original HyDeploy trial was the potential for false positive readings on current CO alarms. If not fitted with a hydrogen-compensated sensor, existing alarms will read the presence of hydrogen and mistake this for CO. A modified detector was tested successfully in the trial.[30]

HyDeploy Phase 2 and its Winlaton trial built on the success of the Keele trial, delivering hydrogen to 668 domestic and commercial sites at up to a 20% blend.[31] In the run-up to this trial, 13 burner types were tested

[24] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)
[25] Group IIA: Atmospheres containing propane, or gases and vapours of equivalent hazards D103222X012_Sep19 (emerson.com)
[26] Hazardous area classifications for gases are defined by EU directive 94/9/EC (also known as the ATEX directive), which is used when designing and implementing electrical equipment for use in the presence of gas atmospheres. IIA atmospheres contain propane, acetone, benzene, butane, methane, petrol, hexane, paint solvents or gases and vapours of equivalent hazard. Engineering ToolBox.
[27] HyDeploy (2021): Demonstrating non-disruptive carbon savings through hydrogen blending
[28] Group IIC—Atmospheres containing acetylene or hydrogen, or gases and vapors of equivalent hazard, as per EU directive 94/9/EC.
[29] HyDeploy (2021) Project close down report
[30] HyDeploy (2021) Project close down report
[31] HyDeploy2 (2022) Winlaton Trial Report: September 2022

up to 28.4% hydrogen blends for safety performance. The 8.4% increase above 20% was to account for possible overshoots in supply from the distribution network. The stud y investigated the CO production levels of a malfunctioning device. Two boilers simulated excessively high CO production by reducing the air intake and showed that a boiler with blended hydrogen will produce up to a n 80-90% reduction in CO emissions when malfunctioning, relative to a state of burning natural gas. In a malfunctioning natural gas boiler, a reduction in air intake reduces the stochiometric ratio, hence encouraging increased CO production due to incomplete combustion. However, the presence of blended hydrogen in the natural gas increases the stochiometric ratio, compensating for the reduced air intake and therefore reducing CO emissions by up to 80—90% in a malfunctioning boiler.

While, theoretically, increasing hydrogen blend may increase NO_x emissions, there is mixed evidence on whether or not this is true for domestic boilers operating on a blended mix. Numerous factors are cited to impact the NO_x emissions, beyond the blend of gas, and the impact of age, type and operation of different appliances has a huge impact, limiting the ability to make a clear link between hydrogen blend and NO_x emissions.[32]

To undertake these trials, each participating body had to pass the required certification process. The construction and safety of natural gas boilers is governed by EN 15502-1 covering Europe and the UK.[33] To enable the experimental trials to be carried out, an additional standard, PAS 4444 was created for hydrogen blending trials recently conducted in the UK.[34] For European trials, EN 15502 covers testing with mixtures of up to 20% hydrogen, with work underway to cover mixtures up to 100%.

Going forward within Europe, new gas boilers could be required to meet a 20% hydrogen-ready standard as part of new ecodesign and energy labelling requirements for space and water heaters. [35]

Overall, the technical and safety performance of natural gas boilers burning up to 20% hydrogen has been investigated and has been shown to be satisfactory.

3.1.3 Higher Blending Shares

Summary

The current consensus among manufacturers and independent sources, is that ~20% is the maximum blend for safe limits within domestic use. Above 20% would likely require heavy upgrades and alterations to various components within the natural gas boiler. Instead, manufacturers are focusing on hydrogen-ready boilers that initially run on natural gas and up to 20% hydrogen, but can be later be converted once the distribution network is converted to hydrogen . Conversion of the hydrogen ready boilers is likely to be required for any blended mix of natural gas and hydrogen above 20% hydrogen.

[32] Wright *et al.* (2022) Emissions of NOx from blending of hydrogen and natural gas in space heating boilers
[33] EN 15502, https://www.en -standard.eu/csn-en-15502-2-1-a1-gas-fired-central-heating-boilers-part-2-1-specific-standard-for-type-c-appliances-and-type-b2-b3-and-b5-appliances-of-a-nominal-heat-input-not-exceeding-1-000-kw/
[34] PAS 4444, https://knowledge.bsigroup.com/products/hydrogen -fired-gas-appliances-guide-1/standard
[35] European Commission (2021) Meeting on the review of Ecodesign and Energy labelling requirements for space and water heaters

As explained by an interviewed manufacturer, a blend of 20% has no impact on the combustion process of an existing boiler as the natural gas molecules still dominate the physical properties of the gas mixture. It is only when the overall physical (including combustion) properties become markedly impacted, at higher blends than this, that potential issues arise. Another interviewed manufacturer explained that a 20% blend provides a safety margin to the boiler's true capability of 25-35%. Above the blending limits of 20%, events such as flame-out (where the flame is extinguished) were observed.

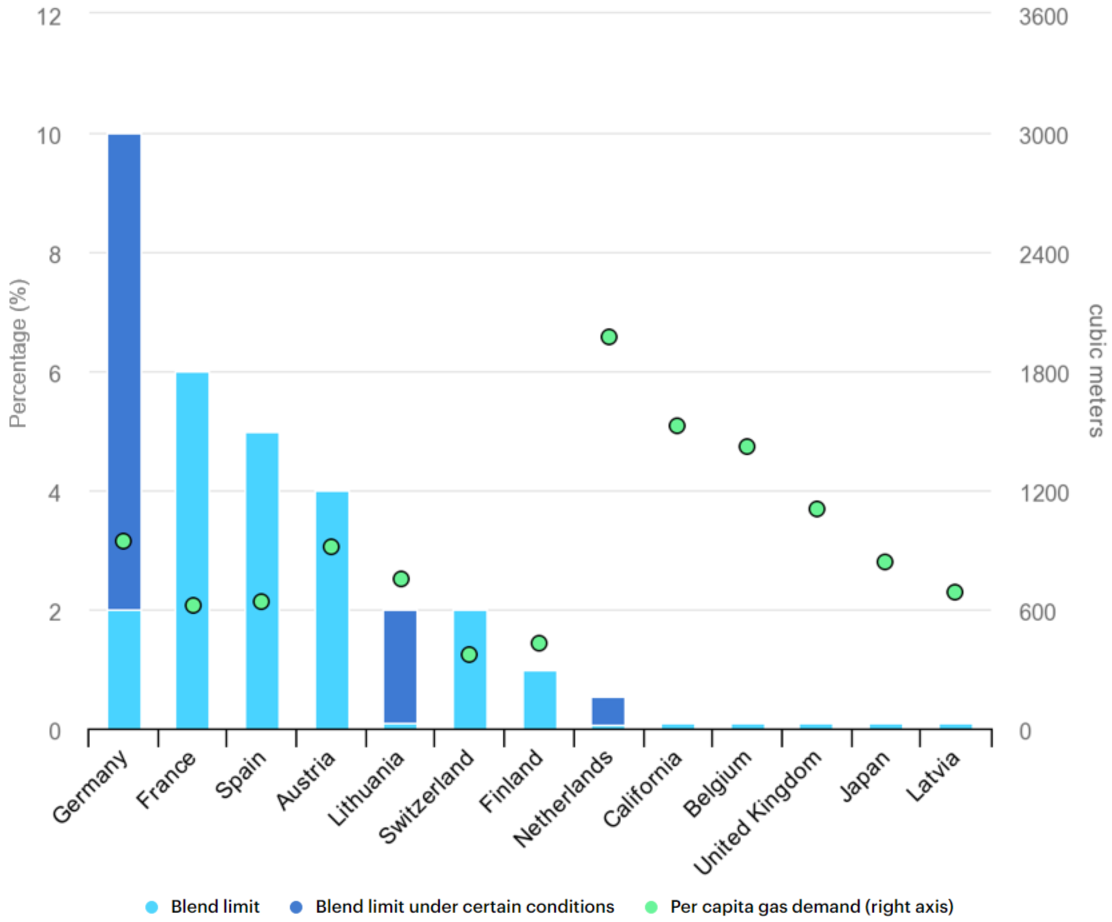
Based on the safety concerns occurring above 20% blend, It is clear blending above 20% would likely require upgrades and alterations to existing natural gas boiler components. As such, manufacturers are instead concentrating on producing "hydrogen-ready" boilers, that are capable of burning 20% hydrogen blend with natural gas (as well as 100% natural gas) and are then converted to 100% hydrogen. Generally, hydrogen-ready boilers will be sold in a configuration for burning 80-100% natural gas, then converted (see Section 3.2.1) to a pure hydrogen configuration when required. This conversion will be necessary for any blended share above circa 20% hydrogen, and is a key reason that manufacturers are concentrating on hydrogen-ready boilers rather than, say, boilers which can burn a higher mix of hydrogen within a natural gas supply, given that the modifications required to a boiler burning such a blend would be the same as (or even greater than) that for 100% hydrogen.

Within the UK, the maximum blended hydrogen share of 20% is based on previous research by the Health and Safety Executive (HSE).[36] The HSE determined that this concentration of hydrogen is unlikely to increase risk from within the gas network or appliances.[37] UK regulations limit the blend to a maximum of 0.1% hydrogen in public gas networks, and up to 23% hydrogen in certain special cases, such as the HyDeploy trials.

Within European countries, different blending limits exist (Figure 3-1), all set by the relevant national governing/regulatory body. Regulations on hydrogen blending today are typically based on natural gas supply specifications, or the tolerance of the most sensitive piece of equipment on the grid. As shown below, very low levels of blending are allowed in the transmission and distribution networks: in many countries, no more than 2% hydrogen blending is currently permitted. One interviewed manufacturer explained that, despite the existing limits, different blending shares were still being trialled – up to 30% in the Netherlands and Germany and as low as 10% in Italy.

[36] HyDeploy., 2020. HyDeploy Webinar: Public Perceptions. https://www.youtube.com/watch?v=VatRX85WGD4&t=3s
[37] HSE., 2015. Injecting hydrogen into the gas network – a literature search. https://www.hse.gov.uk/research/rrpdf/rr1047.pdf

Figure 3-1: Current Limits on Hydrogen Blending in Natural Gas Networks, 2018 [38]



Whilst the reviewed literature stated that the Ameland trial in the Netherlands successfully increased the maximum blended hydrogen share to 30% with all gas appliances effectively operating, findings from another literature source and one interviewee contradicted this.[39,40] The Fraunhofer Institute stated that gas boilers are incapable of handling a blend above 20%. [41] An interviewed manufacturer explained that the trials of up to 30% blend have found that, whilst some appliances continue to operate normally, others do not. The interviewee added that the inability of *some* appliances to operate at a 30% blend was an additional reason for the UK maintaining their blend level at 20%, as 20% ensures that *all* appliances will operate normally.

On the contrary, the work of Jones *et al.* stated that a 30% blend is feasible to supply existing domestic boilers with no required change of the burner (a key component which requires replacement for high hydrogen

[38] IEA, Current limits on hydrogen blending in natural gas networks and gas demand per capita in selected locations, IEA, Paris https://www.iea.org/data-and-statistics/charts/current-limits-on-hydrogen-blending-in-natural-gas-networks-and-gas-demand-per-capita-in-selected-locations, IEA. License: CC BY 4.0

[39] Waterstof., n.d. Hydrogen blending with Natural Gas on Ameland https://www.netbeheernederland.nl/_upload/Files/Waterstof_56_7c0ff368de.pdf

[40] IGRC., 2011. Pilot Project on Hydrogen Injection in Natural Gas on Island of Ameland in the Netherlands. http://members.igu.org/old/IGU%20Events/igrc/igrc2011/igrc-2011-proceedings-and-presentations/poster%20paper-session%201/P1-34_Mathijs%20Kippers.pdf

[41] Fraunhofer Institute for Energy Economics and Energy System Technology., 2022. The limitations of hydrogen blending in the European gas grid. https://www.iee.fraunhofer.de/content/dam/iee/energiesystemtechnik/en/documents/Studies-Reports/FINAL_FraunhoferIEE_ShortStudy_H2_Blending_EU_ECF_Jan22.pdf

percentages – see Section 3.2)[42]. The report states that appliances could operate at this blend continuously as opposed to being the upper limit of a safety buffer. This work and its contents have also been supported by Professor Andrew Barron, Sêr Cymru Chair of Low Carbon Energy and Environment, Swansea University at a recent roundtable. [43]

It is therefore clear that there is no consensus on the upper blending limit, but that it is unlikely to be much higher than 30%.

Going forward, the HyDeploy trial stated that the use of hydrogen blends provides a platform for wider hydrogen adoption alongside enabling a stepping stone to 100% hydrogen use. [44,45]

Research for this project did not reveal any trials where blending exceeded 30%. The Ameland trial validated domestic boilers for use up to 30% in order to allow for a 10% buffer in their blending trial focused on a 20% blend. Further testing and analysis work is therefore clearly required before blending of greater than 20% is implemented.

[42] Jones, D.R *et al.* (2018) – Sustainable Energy Fuels, 2, 710-723
[43] All-Party Parliamentary Group on Air Pollution, 13/12/22
[44] HyDeploy., n.d. Carbon Savings Summary. https://hydeploy.co.uk/app/uploads/2018/02/21063_2PP_HyDeploy_Carbon_Savings_Handout_DIGITAL.pdf
[45] HyDeploy., 2020. HyDeploy Webinar: Public Perceptions. https://www.youtube.com/watch?v=VatRX85WGD4&t=3s

3.2 Pure Hydrogen

3.2.1 Hydrogen-ready Boilers

Summary

Whilst circa 90% of the natural gas boiler and hydrogen boiler components are the same, it would not be economically viable to convert an existing natural gas boiler to burn more than a 20% blend of hydrogen.

Instead, manufacturers are developing hydrogen-ready boilers to prevent homeowners from needing a whole new boiler if the network switches to hydrogen gas. A hydrogen-ready boiler is a boiler that is designed to burn hydrogen, and has then been retrofitted to accommodate natural gas. This means that almost all of the components needed for hydrogen firing are already present, meaning only a small conversion process would be required to convert to hydrogen firing.

Prototype hydrogen-ready boilers have been produced, though none are presently available on the market.

There is one 100% hydrogen-ready boiler – the H_2ydroGEM manufactured by Giacomini, but this is a flameless technology not based on the conventional condensing boiler.[46] Additionally, hydrogen fuel cells, commercially available since the 2000s, can produce heat, electricity and water through a chemical reaction. However, for both devices, the form factor and technical characteristics are substantially different to the condensing boilers considered in this report. Therefore, as such technologies are out of scope, they are not discussed further in this report.

Interviewees indicated that 90% of the natural gas boiler and hydrogen boiler components are the same, and that it could technically be feasible, with a heavy conversion process, to convert already installed natural gas boilers to hydrogen. However, interviewees and sources from the literature confirmed that it would not be economically viable to do so, owing to the difficulty of retrofitting natural gas boilers which had not been designed to burn higher than 20% hydrogen, as their internal configurations and designs are not suitable for burning greater than 20% hydrogen without an extensive and, in the manufacturers' views, uneconomic, conversion.[47]

Instead, the conversion of natural gas-burning boilers to burn greater than 20% hydrogen would take place on specifically manufactured hydrogen-ready boilers, which are hydrogen boilers backfitted to burn natural gas. It

[46] Giacomini, H_2ydroGEM, the hydrogen boiler by Giacomini
[47] Hy4Heat (2020) WP5: Understanding Commercial Appliances for UK hydrogen Heat Demonstration Report (squarespace.com)

is important to note that hydrogen-ready boilers are hydrogen boilers which are modified to burn natural gas, rather than natural gas boilers which are modified to burn hydrogen.

Upon installation, hydrogen ready boilers will be able to burn 100% natural gas and/or natural gas mixed with up to 20% hydrogen. The boilers will then be converted to run on 100% hydrogen, likely at the same time the local gas distribution network is converted. See Section 3.2.2.

When considering conversion of the gas network to hydrogen, there may conceivably be a phase during the transition to 100% hydrogen in which a mostly hydrogen network is supplemented with a small proportion of natural gas. In the same way that an existing, unmodified, natural gas boiler is able to burn up to a 20% blend of hydrogen with 80% natural gas, it is possible that a converted hydrogen boiler will be able to burn a mixture of mostly hydrogen (say, 80%) with some natural gas (say, 20%). However, this is not something that manufacturers or distribution networks have explored at this time.

It is also conceivable that a more even mix of hydrogen and natural gas (say, 50% each) could be implemented during the net zero transition. Such a mix could pose problems for boiler operation, as the burner would need to be able to operate with both fuels, which is likely to present considerable technical challenges (see Section 3.2.3.1), and is unlikely to make economic sense for the manufacturers and consumers.

Manufacturers are concentrating on hydrogen-ready boilers, rather than boilers which can *only* burn hydrogen. This is so the switch from natural gas to hydrogen can be bridged by homeowners without requiring an entirely new boiler, rather only a small proportion of components will need to be replaced/upgraded. The deployment of hydrogen-ready boilers is considered to be the most likely option to facilitate the transition to fully hydrogen boilers.

For the same size and shape as existing boilers, 100% hydrogen-only boilers are currently being developed by manufacturers, but none are presently available on the market.[48,49] Trials are still ongoing, however, Viessmann, Worcester Bosch and Baxi have products in testing. A trial in Lochem, Netherlands is seeing six domestic households having 100% hydrogen boilers installed in their houses.[50] The boilers are supplied by BDR Thermea, who have been conducting feasibility trials since 2019.

3.2.2 Conversion from Natural Gas to Hydrogen

Summary

Hydrogen-ready boilers can be converted to run on hydrogen in approximately 1-2.5 hours by a qualified gas engineer for a cost of circa €200. Due to safety concerns, consumers would not be able to undertake this conversion themselves. It is also unlikely that there would be a universal toolkit for conversion.

[48] HyDeploy., 2020. HyDeploy Gas Safety Webinar. https://www.youtube.com/watch?v=3BGjbcBYmPo
[49] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)
[50] BDR Thermea Group (2022), A world-first as BDR Thermea Group heats historic homes with 100% hydrogen boilers

Hydrogen-ready boilers have been designed to run on hydrogen and have been retrofitted in the factory to burn natural gas (or up to a 20% blend of hydrogen), with the intention that they are later modified in homes to run on 100% hydrogen. This conversion must be done using an approved conversion kit by a qualified gas engineer.

Manufacturers are expecting regulations to be put in place to define hydrogen-ready boilers. For example, the UK heating industry is waiting for the standards and certification framework to be put in place to enable a product to be classified as hydrogen-ready.[51]

In terms of developing a toolkit for the conversion, it is recognised that it would be of great benefit for a standardised toolkit to work across the industry. There is however no evidence to suggest if a tool can be developed that would be sufficiently universal to all variations, owing to the different designs of manufacturers' boilers and considerations such as intellectual property and commercial confidentiality.[52] It is likely that manufacturers will be responsible for the approval and provision of conversion kits and instructions for their own devices, supported by suitable quality plans in place for the suppliers of the components needed.[53]

There has been some suggestion that conversion of hydrogen-ready boilers to run on hydrogen can be undertaken by the resident/homeowner using a consumer kit.[54] However, almost all literature reviewed, and all interviews undertaken, indicated that consumers would *not* be able to undertake the conversion. This is because alteration of key boiler components, such as the burner, would not be safe without the proper training and qualifications.

It is widely recognised in the literature that specialist training is required to perform boiler conversion operations, which mentions the heating engineers performing the work, suggesting that the conversion is not expected or ever envisaged to be performed by consumers. For example, the Heating and Hot Water Industry Council (HHIC), alongside other UK-based organisations, state that the conversion of individual appliances and the whole house gas system to hydrogen must be carried out by an appropriately qualified Gas Safe registered engineer.[55] This is essential to ensure safe conversion and they must hold relevant qualifications in both Natural Gas and Hydrogen Gas. There was also unanimous agreement from interviewees that the conversion process of a hydrogen-ready boiler to burn greater than 20% hydrogen would not be conducted by the consumer; it would need to be conducted by a qualified gas engineer. This is because the process deals with breaking and re-joining the gas connections, which would then need to be tested after the conversion has been completed to ensure it is sound.

The time required for full appliance conversion and testing appears consistent across the literature and is based on trial evidence, this is stated as approximately 1 hour.[56] In terms of costs for converting a hydrogen-ready boiler to burn greater than 20% hydrogen, it is expected to take around an hour of an engineer's time, plus components. Interviewees indicated that this would cost approximately €100 -200, including the components and engineer's time but excluding any time for travel or administration. The Leeds City Gate H21 modelled the

[51] Baxi (2022) Hydrogen - Decarbonisation of the gas grid where practicable through conversion to hydrogen.
[52] Frazer-Nash Consultancy (2020) Logistics of Domestic Hydrogen Conversion Logistics of Domestic Hydrogen Conversion (publishing.service.gov.uk)
[53] HHIC (2022) – Hydrogen Appliances Hydrogen Appliances
[54] European Heating Industry (2021), EHI position paper on the use of green gases for heating
[55] HHIC (2022) – Hydrogen Appliances Hydrogen Appliances
[56] Climate Exchange., 2021. Evidence review for hydrogen for heat in buildings. https://www.climatexchange.org.uk/media/4982/cxc_-evidence-review-for-hydrogen-heat-in-buildings-august-2021.pdf

changeover of 2,500 properties, including travel and administration, and arrived at a cost of £208 per changeover of a traditional combi boiler. It was not clear if parts are included in this cost.

3.2.3 Technical and Performance Considerations

Summary

The majority of components in a natural gas and hydrogen boiler arelikely to be the same, with the boilers showing a similar lifetime and efficiency.

However, some components may need to be redesigned to remove materialsand design configurations unsuitable for use with hydrogen. Furthermore, additional research is required to verify the efficiency and useful operating lifetime of hydrogen boiler s.

The production of boilers designed to burn up to 100% hydrogen will potentially require the redesign of appliance components to remove materials susceptible to hydrogen embrittlement and/or to remove mechanical loading of components.[57] Furthermore, all components will need to be considered, as hydrogen could adversely affect their performance, reliability, and lifetime.[58]

As noted above, interviewees indicated that circa 90% of the components will be the same. Indeed, the understanding that 90% of the components are the same is, according to one manufacturer, a key reason that many manufacturers have committed to producing hydrogen boilers for the same cost, and in the same space envelope, as natural gas boilers.

Furthermore, the efficiency and lifetime of a hydrogen boiler is expected to be similar to that of a natural gas boiler (circa 94% thermal efficiency, circa 12-year lifetime). However, there is currently limited evidence on this as the majority of trials reviewed have had 4- or 5- year lifespans.[59] The Hy4Heat demonstration homes in Gateshead, UK, containing 100% hydrogen boilers, are planned to run for 3 years but could extend to 10. If the extension occurs, it could provide data on hydrogen boiler longevity.

The key components which are likely to need alteration for a hydrogen boiler are discussed below. Working prototypes deployed in various trials have shown that the points below are readily resolvable, with few outstanding issues.

[57] Hy4Heat (2020) WP5: Understanding Commercial Appliances for UK Hydrogen Heat Demonstration Report (squarespace.com)
[58] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)
[59] Climate Exchange., 2021. Evidence review for hydrogen for heat in buildings. https://www.climatexchange.org.uk/media/4982/cxc-evidence-review-for-hydrogen-heat-in-buildings-august-2021.pdf

3.2.3.1 Burner

Summary

The different flame properties of hydrogen and natural gas mean that the burner plate is one of the components that will have to be replaced during the conversion process. This is because 1) the higher flame speed means that the current burner does not provide enough resistance to control the flame, necessitating a resized burner design2) the flame will sit closer to the burner face, increasing the chance of light back, possibly requiring removal of pre-mixing and alteration of the gas valve and 3) the material of current burners may not be heat resistant enough for hydrogen flame temperatures (although further research is needed for this).

Burner systems which can fire both 100% natural gas and 100% hydrogen are technically challenging, though not inconceivable. As such, economic considerations areikely to necessitate replacement of the burner as part of the conversion to 100% hydrogen.

Hydrogen has a higher flame speed, greater flammability range and will burn at higher temperatures than natural gas, which poses engineering challenges that affect the burner.[60]

While burner systems which can fire *both* 100% natural gas *and* 100% hydrogen are technically challenging, new equipment could possibly have two sets of nozzles within the same burner, with the remaining components suitable for both fuel s.[61]

However, in all likelihood and to avoid these technical challenges, the burner will likely be a key component that will need to be replaced in preparing a hydrogen-ready boiler to burn greater than 20% hydrogen (as noted in section 3.1.2, natural gas boilers, their burners included, can burn less than 20% hydrogen with no modification). In particular, interviewees indicated that the burner pl ate, which governs the flame speed and air-fuel mixture, thereby controlling the flame, will need replacing with a one design optimised for hydrogen's higher flame speed. It is crucial to be able to control the flame speed and flame temperature in order to control the boiler output – the burner plate creates a resistance that slows the flame speed down and controls the combustion process. The difference in the combustion process means that the natural gas burner plate will not have the appropriate resistance to control the hydrogen flame due to its higher flame speed, as it would for a natural gas flame. As a burner plate that works for both 100% natural gas and 100% hydrogen is unlikely to be economically feasible, upgrading of the burner plate during conversion will be necessary.

The conversion may require the replacement of entire burners or only parts of burners, depending on the manufacturer's design.

An additional consideration for the burner is that , due to hydrogen's higher flame speed, the flame sits much closer to the burner face than the flame in a natural gas boiler. This, therefore, presents a higher risk of 'light

[60] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)
[61] Hy4Heat (2019) WP6: Conversion of Industrial Heating Equipment to Hydrogen WP6 Understanding Industrial Appliances Report (squarespace.com)

back' - where the flame velocity could exceed the velocity of gas fed to the burner and travel along the supply pipe, with the resulting safety risk.[62,63,64] One of the key technical advances achieved in hydrogen boiler prototypes are burners that can hold a stable hydrogen flame against the element's high flame speed.[65] Careful design of burners is needed to mitigate the light back risk, as it could lead to damage to the burner and surrounding components, alongside presenting wider safety concerns.[66] To prevent light back, the gas velocity needs to be higher than the flame speed. This could be avoided, for example, by removing the primary aeration and using a non-aerated burner. The burner would need to be resized to ensure the velocity of the gas is greater than the flame speed of hydrogen. There may also be the need to increase the depth of the ports to promote more fully developed flow and reduce the potential flashback, and a gauze could also be used.

Depending on the boiler type, if pre-mixing is removed to combat light back, then the gas valve may have to provide modulation, which has reliability implications as there will be the need for a moving seal.[67]

All burner designs will need changing as a result of increased fuel volume or pressure when delivering hydrogen and the increased thermal loading on the burner tips.[68] Increased flame temperature introduces the risk of internal damage to components and the possibility of increased generation of NO_x in the flue gas, albeit studies and interviews have shown the increase to be well below regulatory levels currently set for natural gas boilers.[69,70] This will be influenced by the burner design. It may be advantageous to switch to ceramic burners that are more heat resistant, but more research is needed on this.[71]

[62] Hy4Heat (2019) WP5: Understanding Commercial Appliances for UK Hydrogen Heat Demonstration Report (squarespace.com)
[63] Worcester Bosch (2021) Engineering the Hydrogen Home
[64] Viessmann (2022) Hydrogen boilers: how they work and whether you need one
[65] CIBSE Journal., 2020. Fuel for thought – prototype hydrogen gas boilers. Fuel for thought – prototype hydrogen gas boilers – CIBSE Journal
[66] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)
[67] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)
[68] Hy4Heat (2019) WP6: Conversion of Industrial Heating Equipment to Hydrogen WP6 Understanding Industrial Appliances Report (squarespace.com)
[69] Hy4Heat (2019) WP5: Understanding Commercial Appliances for UK Hydrogen Heat Demonstration Report (squarespace.com)
[70] DNV-GL (2020) – Development of high performance (Low NOx) domestic hydrogen boilers
[71] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)

3.2.3.2 Flame Detection

Summary

The flame detector systems will need to be adjusted.

Firstly, because hydrogen flames have a shorter flame length so the monitoring apparatus may need to be positioned differently , necessitating a redesign of the pilot dimensions, gas flow rate and flame monitoring sensors.

Secondly, because currentionisation probe-based methods of flame detection used in natural gas boiler will not be suitable for 100% hydrogen. UV, infrared and light sensors are all proven methods for hydrogen flame identification, with light sensors also suitable for natural gas use, meaning that hydrogen-ready boilers can be fitted with light sensors and will not need to be switched in the conversion process.

Faster-acting Flame Failure Devices may also be required, replacing current thermoelectric models with UV or infrared alternatives.

The flame detector is also likely to be affected.[72] Hydrogen flames burning on pilot flames designed for natural gas use is characterised by a reduction in flame length. This reduction then impinges on any flame monitoring apparatus fitted to a differing degree, so affecting how the appliances senses the flame. A redesign of the pilot dimensions, gas flow rate and position of flame monitoring sensors may therefore be required.[73]

Additionally, current methods for flame detection may also not be suitable for 100% hydrogen due to reduced luminosity.[74] The common method for flame detection in natural gas boilers is the use of an ionisation probe which produces a current using the charged ions from the combustion of methane. The combustion of 100% hydrogen does not produce these ions, causing the ionisation probe to become redundant. Alternative technologies include UV, light and infrared detection, all of which are available and technically proven. [75,76,77] One manufacturer interviewed indicated that it will be using light sensors rather than ion sensors, and that the light sensors are also suitable for use in 100% natural gas boilers, meaning that, even in a hydrogen-ready boiler, only a single sensor is required.

Where a second detection system is required, this could be retrofitted at the time of conversion, or it could be built into the boiler. Retrofitting would be slightly more expensive and time-consuming than if it were built into the boiler but would avoid it being redundant if the boiler is not converted to burn hydrogen.

[72] Viessmann (2022) Hydrogen boilers: how they work and whether you need one
[73] Hy4Heat (2019) WP5: Understanding Commercial Appliances for UK Hydrogen Heat Demonstration Report (squarespace.com)
[74] Hy4Heat (2019) WP6: Conversion of Industrial Heating Equipment to Hydrogen WP6 Understanding Industrial Appliances Report (squarespace.com)
[75] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)
[76] Hy4Heat (2019) WP5: Understanding Commercial Appliances for UK Hydrogen Heat Demonstration Report (squarespace.com)
[77] Hy4Heat (2019) WP6: Conversion of Industrial Heating Equipment to Hydrogen WP6 Understanding Industrial Appliances Report (squarespace.com)

Flame Failure Devices (FFDs) currently used in natural gas boilers generally utilise thermoelectric valve technology. This can, in principle, be used with hydrogen, however, thermoelectric FFDs have a relatively slow reaction time (circa 30 seconds) due to their thermal mass. This presents a risk of hydrogen collection and thus explosion in the case of a leak. Faster acting FFDs may therefore be required, for example ultraviolet or infrared sensors. These will need to be low cost, fast acting, and reliable.[78]

3.2.3.3 Valves, Gaskets and Other Smaller Components

Summary

Some of the materials used in the valves, seals and gaskets may need to be replaced with more robust types of material as they come into regular contact with hydrogen. Inlet gas pipes and supply pipes would not need to be modified.

Manufacturers indicated that it might be necessary to change some of the materials used in smaller components such as valves, gaskets and seals. They raised some concerns surrounding the longevity of the materials once they come into regular contact with hydrogen and that, for example, they may need to be made from a more robust type of rubber. Such alternatives are readily available on the market today.

Manufacturers also confirmed that there would not need to be any modifications to the inlet gas pipes or the supply pipes. Even though hydrogen is less energy dense than natural gas, the smaller molecule size and lower resistance means that more hydrogen can be pushed down the pipe with the same amount of pressure, resulting in the same effective output from the same pipework. Furthermore, due to the low pressures involved in domestic gas supply, hydrogen embrittlement and other materials issues such as corrosion would not be a concern for the inlet/supply pipes (though they are an important factor to overcome for distribution and transmission networks, which operate at higher pressures).

3.2.3.4 Code Plug

Summary

The code plug settings will need to be changed so that the boiler is coded to run on hydrogen rather than natural gas. This would be a very simple procedure that would not require any physical changes. It is unlikely that boilers will be able to detect the fuel and automatically switch their settings, necessitating this manual update alongside the other conversion steps (namely the burner).

In addition to changing the burner plate, flame detector and possibly some smaller components on the day of conversion, the other element that will require alteration is the code plug. The code plug settings would need to be changed so that the boiler is coded to run on hydrogen rather than natural gas. This would be built into the hydrogen-ready boiler and would not require any physical changes, only for a USB device or service tool to

[78] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)

be plugged in by the attending technician to change the software. Manufacturers interviewed advised that this is a very simple change that will pose no issues.

Although some manufacturers interviewed indicated that the concept of a boiler being able to detect that is being fed with hydrogen rather than natural gas and then automatically switch over had been considered, it is unlikely that this will happen in the short to medium term, if ever. Not least due to the physical components which require alteration over and above the software.

3.2.3.5 Other Considerations

Summary

There are other technical considerations that will be taken into account but will not pose any obstacles to the feasibility of roll out:

- Heat exchanger designs used in natural gas may not be optimised for hydrogen use so will likely need to be redeveloped for 100% hydrogen. In particular, the potential for flame impingement on the heat exchanger should be carefully considered.
- Current pipework and gas valves may also have to be replaced with the suitable alternatives to reduce concerns over sealing and leakage.
- Given the lack of space inside current boilers, and manufacturers' desire for hydrogen boilers to occupy the same space in homes as existing boilers, any alteration or addition of parts will be challenging. However, the fact that hydrogen has a similar Wobbe number as natural gas, despite its different molecule size, calorific value and density, means that external components and the size of the boiler can largely remain unchanged, and the availability of hydrogen-ready boiler prototypes indicates that design within the current space envelope is feasible.
- Due to the possible increase in NOx emissions when burning hydrogen vs natural gas, there may be the need to install equipment to reduce NOx. Trials have indicated that the current flue gas analysers are suitable for use with a hydrogen blend.
- Minor changes to operating pressures may be required to achieve equality with energy delivery of natural gas.
- Current flue systems may not be adept at removing the increased amount of water vapour produced from hydrogen combustion, compared with natural gas consumption.
- An odorant will need to be added to allow the detection of leakage.
- Due to the volumetric calorific value of hydrogen being lower than that of natural gas, existing gas meters are unlikely to be suitable for hydrogen. Distribution network operators will need to replace meters when converting the local grid.

All other elements of natural gas boilers would already be suitable for hydrogen use in a hydrogen-ready boiler. Therefore, the issues and subcomponents associated with natural gas boilers converting to hydrogen as indicated in the literature review and subsequent briefing note are no longer applicable.[79] For completeness, this section provides an overview of other technical considerations for the roll out of hydrogen/hydrogen-ready boilers. None of these were found to present obstacles to the feasibility of the technology, rather they are considerations which manufacturers, regulators and industry will naturally take into account in developing hydrogen-ready boilers for the market.

It was noted in the interviews that there is presently no codified definition of a hydrogen-ready boiler. This presents challenges for consumers in understanding what the boilers on the market truly offer them. Manufacturers are seeking to update the EN 15502 standard to address this.

A challenge to hydrogen conversion was found to include changes in heat transfer characteristics. The increase in flame temperature impacts on emissions performance, materials selection, and efficiency for combustion devices.[80] Heat exchanger designs used in natural gas boilers should be suitable for hydrogen combustion but may not be optimised and so will likely be redeveloped for optimal performance with hydrogen.[81] Heat exchange is likely to be impacted by the different flame profile of hydrogen compared to natural gas. Due to its low emissivity, hydrogen produces almost no radiant heat, which is normally responsible for a significant amount of the overall heat exchange within the combustion chamber. [82] Hydrogen burns with different radiation/convection properties to natural gas, so optimisation of the new/redesigned heat exchanger will be required to ensure comparable efficiency to a natural gas boiler.[83] In particular, the potential for flame impingement on the heat exchanger should be carefully considered. [84]

In addition to the heat exchanger, the pipework and gas valves will require some redevelopment due to the different combustion characteristics of hydrogen, but the operational principles will not fundamentally change.[85] Nonetheless, several existing components are not suitable for use with hydrogen so will need to be altered compared to current designs.[86] For example, leakage is a risk due to hydrogen's molecular size, particularly with flanged joints and screwed connections, necessitating more welded joints.[87] However, these will need to be serviceable. Similarly, there may be a requirement for different gas valves due to different gas flow rates and concerns over sealing.[88]

Manufacturers are seeking to produce hydrogen/hydrogen-ready boilers that occupy the same volume within a home as existing boilers. Given the lack of space inside current boilers, any alteration or addition of parts will therefore be practically challenging. However, the availability of hydrogen-ready boiler prototypes indicates that design within the current space envelope is feasible. Interviewees advised that this is principally thanks to the Wobbe number (which is a combustion parameter related to the calorific value and density of the gas, which affects flame speed and shape and signifies the amount of energy in a given volume of gas) of hydrogen being almost identical to that of natural gas. Hydrogen has a significantly lower calorific value (heating power)

[79] Such as the pipework, heat exchangers, gas valves and control systems
[80] Hy4Heat (2019) WP6: Conversion of Industrial Heating Equipment to Hydrogen WP6 Understanding Industrial Appliances Report (squarespace.com)
[81] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)
[82] Hy4Heat (2019) WP6: Conversion of Industrial Heating Equipment to Hydrogen WP6 Understanding Industrial Appliances Report (squarespace.com)
[83] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)
[84] Hy4Heat (2019) WP5: Understanding Commercial Appliances for UK Hydrogen Heat Demonstration Report (squarespace.com)
[85] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)
[86] Climate Exchange., 2021. Evidence review for hydrogen for heat in buildings. https://www.climatexchange.org.uk/media/4982/cxc-evidence-review-for-hydrogen-heat-in-buildings-august-2021.pdf
[87] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)
[88] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)

per cubic metre, but also a much lower density, yielding a similar Wobbe Number. This factor has also meant that external components (e.g., the inlet gas pipe and domestic supply pipework) can remain unchanged.

Due to the relative increase in NO_x emissions nominally associated with the burning of hydrogen vs natural gas, there may be the need to install equipment to reduce NO_x, such as flue gas recirculation.[89] Peer-reviewed practical testing has found current flue gas analysers are suitable for use with a hydrogen blend.[90] However, initial field testing indicates that hydrogen boilers may in fact produce *far less* NO_x emissions than natural gas and so such measures may not be required (see Section 3.2.4).

Some minor changes to operating pressures and combustion air supply may be required to achieve equality with energy delivery of natural gas.[91] Adjustments in airflow could be mechanically provided by fans. Alternatively, the supply pressure could be adjusted, but it is understood that network operators generally are not planning on adjusting the supply pressure for hydrogen.[92]

Hydrogen produces 60% more water vapour than natural gas for the same amount of energy, which will impact the boiler design.[93] Current flues may not be suitable for 100% hydrogen due to increased water vapour content in the flue gas. There may be factors that prevent hydrogen, or even hydrogen-ready, boilers being installed in the same flue system as natural gas boilers. This increases the potential of water vapour to condense and corrode parts of the appliance (although modification of the appliance burner could help prevent this).[94]

Furthermore, an odorant will be required, and the choice of this may be a factor in increasing boiler degradation (see Section 3.2.4.4).[95]

Finally, and whilst acknowledging that this research project has only examined "after the meter", the meter itself is an important component that will require an upgrade to handle hydrogen. Due to the volumetric calorific value of hydrogen being lower than that of natural gas, existing installed meters are unlikely to be large enough to meter the flows that will be seen in a hydrogen-heated property.[96] Hy4Heat Work Package 10 involved the development of two meter prototypes which can successfully meter both natural gas and hydrogen, and which have successfully been installed and operated at the Hy4Heat demonstration homes in Gateshead, England.[97] [98] [99] It is expected that conversion/replacement of gas meters will be undertaken by the distribution network operators when the street/neighbourhood is converted to hydrogen.

[89] Hy4Heat (2019) WP6: Conversion of Industrial Heating Equipment to Hydrogen WP6 Understanding Industrial Appliances Report (squarespace.com)
[90] HyDeploy., 2020. Project Report Fourth. https://hydeploy.co.uk/app/uploads/2018/02/HYDEPLOY-FOURTH-OFGEM-PPR.pdf
[91] Hy4Heat (2019) WP5: Understanding Commercial Appliances for UK Hydrogen Heat Demonstration Report (squarespace.com)
[92] Frazer-Nash Consultancy (2018) Logistics of Domestic Hydrogen Conversion Logistics of Domestic Hydrogen Conversion (publishing.service.gov.uk)
[93] Frazer-Nash Consultancy (2018) Logistics of Domestic Hydrogen Conversion Logistics of Domestic Hydrogen Conversion (publishing.service.gov.uk)
[94] Hy4Heat (2019) WP5: Understanding Commercial Appliances for UK Hydrogen Heat Demonstration Report (squarespace.com)
[95] Hy4Heat (2019) WP2: Hydrogen Purity & Colourant Microsoft Word - WP2 Report final .docx (squarespace.com)
[96] Scottish Gas Networks, H100 NIA: Domestic Metering Solution
[97] Hy4Heat (2019) WP10: Metering https://www.hy4heat.info/wp10
[98] Pietro Fiorentini, H2-SSM leaflet
[99] SIT, Domusnext® 2.0 MMU6 meter

3.2.3.6 Next Steps

Summary

Manufacturers are confident in their development of hydrogen-ready boilers. Large scale trials will be the next steps to prove its real-world feasibility, and these are planned in the UK with the UK government planning for a potential pilot hydrogen town. For manufacturers, the next steps will be scale up and commercialisation of their hydrogen-ready boilers. Manufactures are waiting for policy support before this begins that will enable them to make investment decisions.

When questioned in the interviews as to whether any of these technical/performance implications represented insurmountable challenges to hydrogen boiler technology, all interviewees were of the view that the issues will be, or have already been, resolved. Indeed, one manufacturer noted that they have ceased further development of their hydrogen-ready boilers altogether, as they are confident that the technology will work safely, effectively and for the correct cost, rather they are waiting for government policy backing for hydrogen before they can make the business case to move to mass production.

Existing trials have focused on a small number of boilers and homes. The next step to prove real-world feasibility of hydrogen boilers will be larger scale trials. There are several such trials planned, such as H100 and the Hydrogen Village in the UK.[100] [101] Within the EU, there are several planned trials such as Hoogeveen, Netherlands which is planned to see domestic households supplied with a 100% hydrogen boiler.[102] Lochem, Netherlands is also undertaking a similar trial.[103] Given the successes shown in trials to date, industry stakeholders are confident that these future larger scale trials will be similarly successful. A key focus for these trials will be to understand whether there are any further technical/safety issues not already under consideration, and to examine the use of hydrogen boilers at scale.

Following village/neighbourhood scale trials, town-sized trials will then follow. For example, the UK government is planning for a potential pilot hydrogen town and has recently invited gas distribution networks to submit proposals.[104]

For all major manufacturers with proven hydrogen and hydrogen-ready boiler prototypes, the next steps towards full rollout are industrialisation, commercialisation and mass production. One interviewed manufacturer noted that it has a production line producing hydrogen boilers already, but that this is still a relatively bespoke, hand-made, production line making boilers for test purposes, rather than a full-scale production line with modern automation.

Before progressing to mass production, by and large, manufacturers are waiting for governments to make policy decisions or directions that will enable them to take investment decisions. Interviewees observed that the rest of the nascent hydrogen industry (production, transmission and distribution) is much further behind

[100] H100 Trial https://www.h100fife.co.uk/
[101] Department for Business, Energy & Industrial Strategy, Hydrogen Strategy update to the market: December 2022
[102] Waterstoft Tiny House https://waterstoftinyhouse.nl
[103] BDR Thermea Group (2022), A world-first as BDR Thermea Group heats historic homes with 100% hydrogen boilers
[104] Department for Business, Energy & Industrial Strategy, Hydrogen Strategy update to the market: December 2022

than appliance manufacturers in terms of readiness for conversion of the gas network to hydrogen, and it will be these elements that are more likely to encounter policy, economic, technical and safety challenges.

3.2.4 Safety

Summary

There are broadly the same safety concerns for pure hydrogen burning compared to blended, but there is less evidence surrounding safety concerns for 100% hydrogen.

Broadly, the same risks for 20% blended hydrogen also apply to pure hydrogen, as covered in Section 3.1.2. However, with the increase from blended to 100% hydrogen in supply, there is less evidence and agreement within documentation regarding hydrogen's safety. Key issues are explored below.

3.2.4.1 Leakage and Explosion

Summary

Even though hydrogen demonstrated a higher leak rate (circa 50% higher) than natural gas, its concentration was lower, meaning it is still below the Lower Flammability Level. This means the risk is no greater than with natural gas in small leaks.

In larger leaks, there is a greater explosive risk (circa double) with hydrogen than natural gas, with greater likelihood of an explosion causing significant structural damage. Trials have indicated that incorporating additional Emergency Flow Valves, or installing ventilation ducts in the ceilings of rooms where hydrogen is present, could reduce the risk. Hydrogen boilers should also be designed so that internal cavities are reduced.

Future trials should be undertaken in flats, particularly high-rises, to assess the risk to those properties.

The density of natural gas relative to that of air is 0.68, meaning it rises quickly in air, but can still accumulate in rooms and present a safety hazard. Hydrogen's density relative to air is 0.0696 – a tenth of that of natural gas. This, plus the fact that it is a tiny molecule, means that hydrogen gas can readily escape through small voids and even through opaque materials (like ceilings), which reduces the accumulation risk in the event of a leak.

Despite this reduced risk of accumulation, the very fact that hydrogen's small molecule size means it can readily escape through materials is a key reason why leakage of hydrogen, with its famously high flammability, is a concern within buildings.

An analytical assessment of hydrogen in the home was undertaken in the HyDelta project.[105] For a small kitchen area, hydrogen will have a higher leak rate by a factor of 1.2-1.6 times higher than natural gas flowing from the same damage site/hole. This is in fair agreement with the Hy4Heat model of a 1.3-1.8 times higher leak rate. [106] However, even with the higher leak rate, the concentration of hydrogen is still below its Lower Flammability Limit (LFL) as shown in Table 3-2. [107] Therefore, the risk is no greater risk for hydrogen in small leaks relative to natural gas. This was confirmed in the Hy4Heat report where small leaks (<2 *mm*) do not present a risk above that associated with natural gas [87].

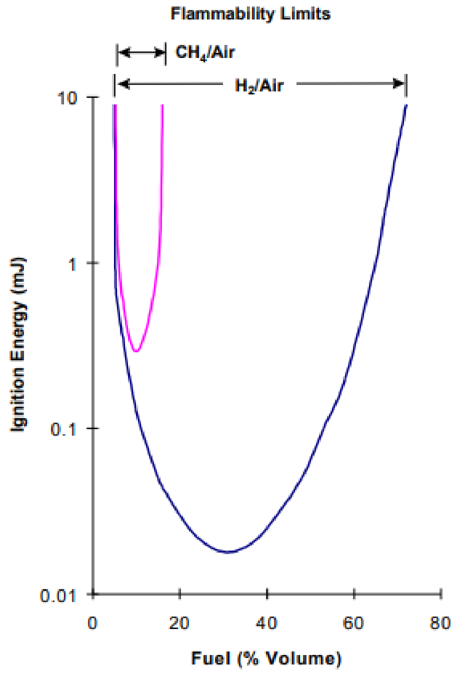
Table 3-2: Parameters Associated with the Safety of Hydrogen Relative to other Common Gases[108]

		Hydrogen	Methane	Propane	Gasoline
Detonation limits (%vol in air)	Lower	11 – 18	6.3	3.1	1.1
	Upper	59	13.5	7	3.3
Adiabatic Flame Temperature (°C)		2318	2158	2198	2470
Flammability Limit (%)	Lower	4	5.3	2.1	1
	Upper	75	15	9.5	7.8

At larger leak rates, caused by accidentally drilled holes for example, the HyHouse study concluded that there is a greater explosive risk from hydrogen compared to natural gas. It has been shown that the likelihood of a large leak causing an explosion resulting in significant structural damage to a building is twice as high for hydrogen than natural gas[109]. This is due to the higher ignition bandwidth, lower minimum explosive energy, and high over-pressures on explosion of hydrogen relative to natural gas. The larger bandwidth for flammability of hydrogen in air against methane in air is highlighted in Figure 3-3. Every point on the curve represents an explosive event, with varying severity. A notable omission from analyses and trials is the consideration of varying building types. High-rise flats have not been considered in analytical appraisal or field trials and could be a logical next step.

Figure 3-2: Minimum Ignition Energies of Hydrogen and Methane in Air

[105] HyDelta (2020) WP 1C: Pipes and indoor installations – risks involved in the use of hydrogen instead of natural gas
[106] Hy4Heat (2021) WP7: Safety assessment: Precis
[107] Shell (2001) Compilation of Existing Safety Data on Hydrogen and Comparative Fuels
[108] Shell (2001) Compilation of Existing Safety Data on Hydrogen and Comparative Fuels
[109] Mouli-Castillo *et al.* (2021) A quantitative risk assessment of a domestic property connected to a hydrogen distribution network



Measures to mitigate the increasing explosive risk of hydrogen have been investigated. The Hy4Heat project recommended incorporating one Emergency Flow Valve (EFV) upstream of the meter and one within the smart meter. In doing so, the number of explosion events and physical injuries per year would reduce by 75% and 33%, respectively, against no EFVs being installed, with data shown in Table 3-3. However, even with the valves, the number of events modelled by Hy4Heat would still be larger than for natural gas. Further risk mitigation studies have been qualitatively discussed. Risk mitigation strategies include the installation of ventilation ducts in the ceilings of rooms where hydrogen is present.

The Hy4Heat programme recommended a vent area of 10,000 mm^2 at ceiling height for rooms with significant pipework or appliances, to reduce the hydrogen concentration in homes. This was tested at HyStreet – run by DNV GL – in a kitchen with leaks originating from 3-7 mm holes.[110] For all hole sizes, the maximum concentration recorded was reduced by installation of vents, However, in all cases the concentration remained above the lower flammability limit of hydrogen (4%), presenting a risk of ignition. This risk was not quantified in the Hy4Heat and should be investigated further. It was recommended that the vents be non-closable. Including vents was also recommended by the HyHouse project, although no quantification of vent size was made. A further recommendation was hydrogen boilers being installed on the outside of domestic buildings. However, no solutions have been field tested at the time of writing.

[110] Hy4Heat (2021) Comparative Safety Assessment Report (inc. QRA)

Table 3-3: Hy4 Heat Natural Gas Base Case Compared with Different Hydrogen Scenarios[111]

Scenario	Predicted number of events per year	Predicted number of individuals injured per year
Natural Gas	9	17
100% Hydrogen	39	65
100% Hydrogen with risk mitigation measures in place	26	16

From a design perspective, pure hydrogen boilers should be designed so that internal cavities are reduced. There is likely be a need to remove primary aeration, re-size the burner ports and remove internal cavities where combustible gas mixtures could form.[112] They should also mitigate potential leakage through pipe and joint selection, they should have vent appliance casings, a reliable controlled ignition source and fast acting, reliable, combustion sensing.

3.2.4.2 Nitrous Oxides

Summary

There is a theoretical increase in NO_x emissions from burning hydrogen compared to natural gas, possibly up to double the NO_x emissions.

However, tested prototype 100% hydrogen boilers produced NO_x emissions within European eco-design levels and *lower* than natural gas boilers at equivalent thermal input levels. Further testing is required to demonstrate if this would be representative of hydrogen-ready boilers post conversion. Long-term field testing should also be undertaken.

NO_x emissions have been an area of concern for hydrogen boilers. The theoretical increase in NO_x is attributed to the larger adiabatic flame temperature of a 100% hydrogen flame relative to pure methane [113]. Hy4Heat modelling showed that, in the worst case, at the same equivalence ratio, hydrogen boilers could produce approximately double the NO_X emissions of natural gas boilers.

Worcester-Bosch [114] and DNV-GL[115] have each stated that 100% hydrogen-ready boilers are producing NO_x levels lower than European eco-design levels and *lower* than natural gas boilers at equivalent thermal input levels. These findings were echoed by interviewees.

[111] Hy4Heat (2019) Safety Assessment Conclusions Report Comparative Safety Assessment Report (inc. QRA) (squarespace.com)
[112] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)
[113] Wright *et al.* (2022) Emissions of NOx from blending of hydrogen and natural gas in space heating boilers
[114] Worcester Bosch (2022) – Hydrogen-Ready wall Mounted gas boilers
[115] DNV-GL (2020) – Development of high performance (Low NOx) domestic hydrogen boilers

These lower NO_x levels are achieved through design features such as shortening gas residence time or flue-gas recirculation. The emissions scale linearly with thermal input, highlighting the trade-off between emissions and thermal efficiency. Hydrogen boilers do have the advantage over natural gas boilers whereby there is no need to trade-off with CO production levels. However, it is not clear if the boilers tested would be representative of existing gas boilers, post conversion. Furthermore, long-term field testing does not appear to have been undertaken yet.

3.2.4.3 Materials

Summary

There is uncertainty surrounding the long term material sensitivities in the presence of hydrogen. Hydrogen is known to embrittle metals, such as steel, meaning that current pipework may need to be replaced to avoid embrittlement. Joints in particular may need upgrading. Polyethylene plastic can reduce this risk, and it is the view of the industry that copper is also likely to be suitable for hydrogen.

For domestic gas appliances operating at low pressures, hydrogen embrittlement is unlikely to be a concern, even for non-stainless steels. However, hot areas are potentially at increased risk, particularly any material that is in direct contact with the flame (approximately 200°C hotter than natural gas) and where hydrogen atoms will transitionally be present. The impact on pipework joints should also be considered.

Additionally, depending on the level of aeration, hydrogen could burn hotter than natural gas, causing material degradation.

The vast majority of literature in relation to hydrogen and its impact on materials is concerned with mains distribution and transmission of hydrogen, rather than within domestic appliances. Nonetheless, there is some literature which does deal with the topic.

Overall, there are still many uncertainties regarding long term material sensitivities (in pipes, devices etc.), in particular with regard to a reduced lifetime when hydrogen is present, which requires further investigation as hydrogen becomes a fuel actively used in society.[116]

Hydrogen is known to reduce the service life of metals, and particularly steels, through embrittlement, blistering, hydrogen attack and cracking.[117] Hydrogen is absorbed by some containment and piping materials, which can result in loss of ductility or embrittlement, and is accelerated at elevated temperatures and pressures.[118] Material embrittlement by hydrogen for metallic components may be high for hydrogen pipework

[116] Fraunhofer Institute for Energy Economics and Energy System Technology., 2022. The limitations of hydrogen blending in the European gas grid. https://www.iee.fraunhofer.de/content/dam/iee/energiesystemtechnik/en/documents/Studies-Reports/FINAL_FraunhoferIEE_ShortStudy_H2_Blending_EU_ECF_Jan22.pdf
[117] Frazer-Nash Consultancy (2018) Logistics of Domestic Hydrogen Conversion Logistics of Domestic Hydrogen Conversion (publishing.service.gov.uk)
[118] Hy4Heat (2019) WP6: Conversion of Industrial Heating Equipment to Hydrogen WP6 Understanding Industrial Appliances Report (squarespace.com)

compared to natural gas (generally where metallic components are under physical loading).[119] As such, certain items like piping will highly likely need replacement to avoid the risk of embrittlement.[120] Pipework joints, in particular, may require upgrading.

Stainless steel is generally used as the industry standard for components in contact with hydrogen.[121,122] Replacing non-stainless steel with polyethylene pipes (not currently used with natural gas due to fire safety concerns) can also drastically reduce the likelihood of a risk arising from a service pipe.[123] Welded copper is widely used presently with natural gas, and it is the view of the industry that copper is likely to be suitable for hydrogen, but further studies will be needed to confirm this. Alternative materials also include aluminium, which is highly resistant to hydrogen. Cast iron and lead have been recommended to not be used with hydrogen, and for any cast iron or lead components within households to be removed. [124]

For domestic gas appliances operating at low pressures (at or below a 20mbar pressure cycle), hydrogen embrittlement is unlikely to be a concern, even for non-stainless steels. This conclusion was reinforced through findings from trials such as HyDeploy, which observed no embrittlement or corrosion, and through discussion during the interviews. Therefore, it is unlikely that the piping into individual homes will require alteration, rather the transmission and distribution networks will be where replacement of non-stainless steels is required.

However, hot areas are potentially at increased risk as the solubility of hydrogen increases at higher temperatures and this applies to any material that is in direct contact with the flame and where hydrogen atoms will transitionally be present.[125] The potential for increased flame length with hydrogen compared to natural gas has important implications on potential flame impingement here, and on material selection for the burner and combustor.[126] Depending on the level of aeration, hydrogen could burn hotter than natural gas, causing material degradation. Hydrogen has an approximately 200˚C hotter flame than natural gas, as shown in Table 3-2. Also, the higher flame speed means that the flame sits closer to the burner surface than with natural gas, presenting concerns for oxidation and life expectancy of the burner. A number of steps could be taken to mitigate this risk, for example through ceramic burners. These are being considered by manufacturers. Flame shields and flues will also need to be assessed for thermal performance to ensure they maintain integrity and also do not transfer heat to sensitive components.[127]

[119] Hy4Heat (2019) WP5: Understanding Commercial Appliances for UK Hydrogen Heat Demonstration Report (squarespace.com)
[120] Climate Exchange., 2021. Evidence review for hydrogen for heat in buildings. https://www.climatexchange.org.uk/media/4982/cxc-evidence-review-for-hydrogen-heat-in-buildings-august-2021.pdf
[121] Frazer-Nash Consultancy (2018) Logistics of Domestic Hydrogen Conversion Logistics of Domestic Hydrogen Conversion (publishing.service.gov.uk)
[122] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)
[123] Hy4Heat (2019) Safety Assessment Conclusions Report Comparative Safety Assessment Report (inc. QRA) (squarespace.com)
[124] Hy4Heat (2019) Safety Assessment Conclusions Report Comparative Safety Assessment Report (inc. QRA) (squarespace.com)

[125] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)
[126] Hy4Heat (2019) WP6: Conversion of Industrial Heating Equipment to Hydrogen WP6 Understanding Industrial Appliances Report (squarespace.com)
[127] Frazer-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances FNC Complex Proposal (publishing.service.gov.uk)

3.2.4.4 Other Safety Considerations

Summary

Other safety concerns include:

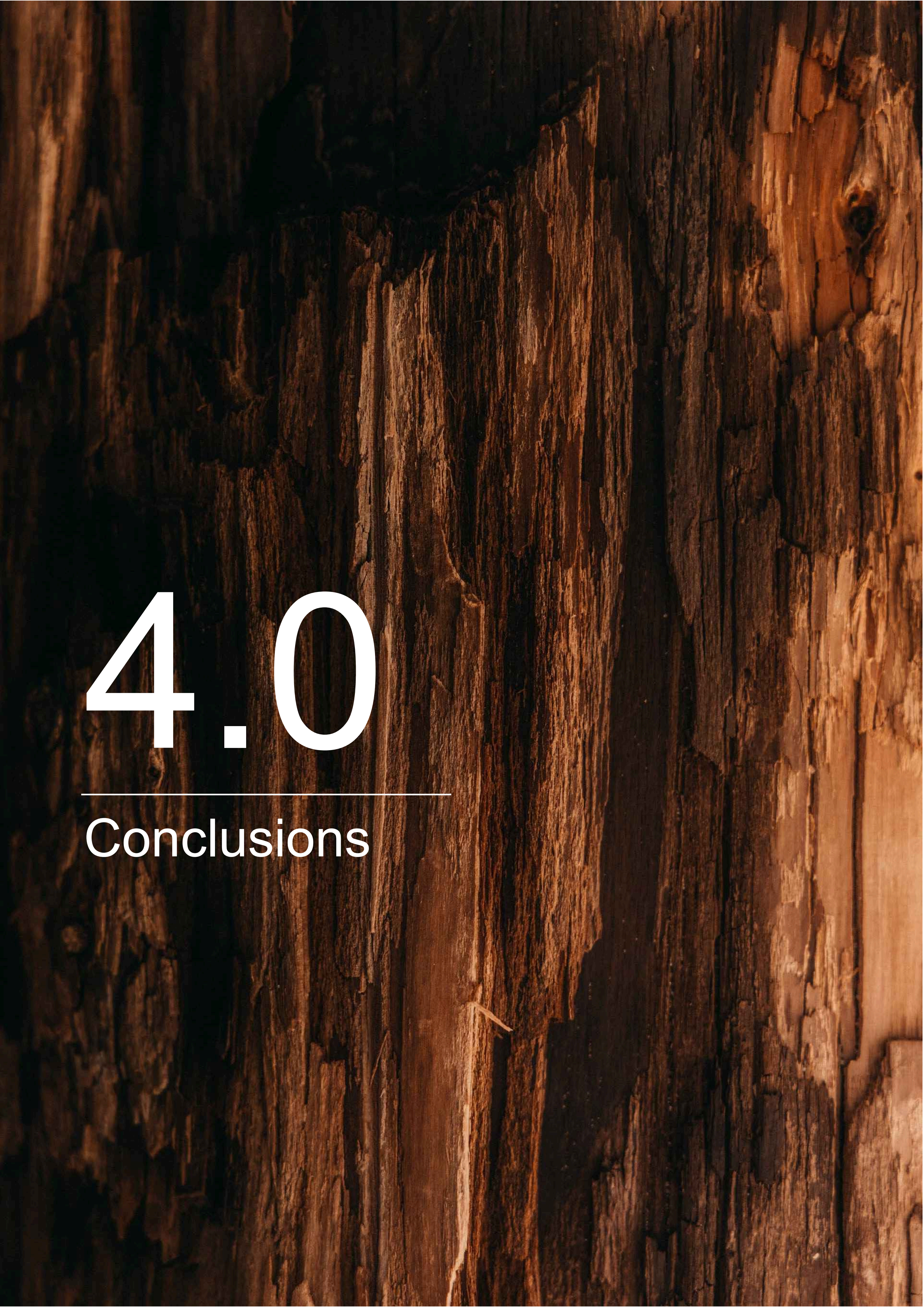
- An odorant will need to be added to enable consumers to smell a leak and the use of the current natural gas odorant has been proven to be sufficient.
- The lack of a visible flame is not an issue in boilers as it is for cookers and fires.

Like methane, hydrogen is odourless by nature. Whilst it is not toxic, as with any gas, it can be an asphyxiant if present in sufficient quantities. Of more concern is the need for consumers to smell a leak of hydrogen and undertake an associated action, in this case informing emergency services of a leak. Natural gas in the UK network has, since its introduction, been laced with quantities of NB (a blend of t-butyl mercaptan and dimethyl sulfide). In the Netherlands and France, TetraHydro Thiophene (THT) is used as a standard odrant whilst in Germany a mix of acrylates (methyl acrylate and ethyl acrylate) and methyl ethyl pyrazine is used by several grid owners.[128] The Hy4Heat package concluded that odorants would be required for pure hydrogen supply in the UK. In areas where the odorant cannot be smelt by residents, it was recommended a hydrogen detection alarm be installed. The current choice of NB within the UK was concluded as acceptable. Whilst NB has a sulphuric component and could induce corrosion in exhaust-flues, it was found to be no more significant than what is currently observed with natural gas.[129] As such, no additional steps beyond what is already practiced with natural gas would be required if a switch to 100% hydrogen is made. Degradation due to the presence of sulphur in the odorant is comparable between hydrogen and natural gas boilers.[130]

A hydrogen flame is not detectable on the visible spectrum by a human eye. Of the literature reviewed, this does not appear to be an issue for domestic boilers as the flame is contained within the boiler unit.[131] As such, this item does not need further consideration for boilers (though it remains an issue for other hydrogen appliances such as cookers and fires, where the flame is open and unenclosed).

Finally, it will be important to convince the public and regulators of the safety and practicability of domestic hydrogen appliances. They will need to offer similar performance and safety to existing natural gas appliances. For a successful rollout, it will be important to ensure that public perception is positive and that the perceived benefits of hydrogen are clearly articulated.[132]

128 DNV.GL (2020). Odour assessment of selected odorants in hydrogen and natural gas-hydrogen mixtures
129 Hy4Heat (2020) WP2: Hydrogen odorant
130 HyDelta (2022) WP2 – Odorisation of Hydrogen, D2.5 – Advice on odorant choice
131 Frazer-Nash Consultancy (2020) Logistics of Domestic Hydrogen Conversion Logistics of Domestic Hydrogen Conversion (publishing.service.gov.uk)
132 Frazer-Nash Consultancy (2018) Logistics of Domestic Hydrogen Conversion Logistics of Domestic Hydrogen Conversion (publishing.service.gov.uk)



4.0

Conclusions

Summary

There are no major foreseeable technical obstacles toa roll out of hydrogen boilers. The potential obstacles found are:

- Lack of government backing of the technical feasibility of hydrogen for heating.
- Size and cost. Hydrogen-ready boilers are the same size as natural gas boilers with the same output. Similarly, because the majority of components are likely to be the same, they can be manufactured at the same cost.
- Parts sourcing. Due to fact that the majority of components are likely to be the same, the majority of the components are already manufactured globally, only a small number of components would need to be manufactured on a large scale.
- Lack of a codified definition means some elements surrounding design and testing are still undetermined. This would need to be confirmed before hydrogen-ready boilers could be scaled up to a commercial scale.
- Workforce skills and creating a conversion workforce. Hydrogen gas can easily be added to the gas training certification that gas engineers need to get.

NGOs have accused boiler manufacturers and the gas industry of neglecting or downplaying the problems associated with a transition to hydrogen gas in their lobbying efforts to make hydrogen boilers the dominant technology for decarbonising heating in the built environment.[133]

The general consensus from interview participants was that there are no major foreseeable barriers to the large scale roll out of hydrogen boilers, as long as the industry receives government backing.

Governments are yet to make a decision on the strategic role of hydrogen in heating, as they are conducting further assessment of the technical feasibility, costs, benefits and other impacts being required. Nonetheless, many governments continue to acknowledge the potential for hydrogen to offer a strategic option for decarbonising heat in buildings. For example, the UK government is targeting 2026 for decisions on the role of low carbon hydrogen in heating, with the hydrogen town pilot (see Section 3.2.3.6) planned for the late 2020s/early 2030s.

In the nearer term, hydrogen is likely to be blended into the natural gas network. The safe limit for this has been identified as 20%, and the safety concerns for burning natural gas 20% hydrogen are the same as for a boiler burning 100% natural gas. However, given that natural gas boilers have not been optimised for burning a hydrogen blend, the performance, efficiency and cost to the consumer is likely to be lower than a brand new 100% hydrogen appliance.

In the longer term, a roll-out of boilers which can burn hydrogen will be required to support a 100% hydrogen grid. As mentioned by one manufacturer, if the government were to mandate that every boiler sold, from a certain date, had to be a hydrogen-ready boiler then the household stock would gradually be pre-populated

133 https://www.e3g.org/news/climate-groups-warn-fossil-fuel-lobby-trying-to-capture-government-hydrogen-policy/

with hydrogen-ready boilers prior to transition. This is something that is beginning to be considered by the UK government, for example, although with no guarantee of the use of hydrogen gas.[134]

Whilst circa 90% of the natural gas boiler and hydrogen boiler components are the same, it would not be economically viable to convert an existing natural gas boiler to burn more than a 20% blend of hydrogen. Instead, manufacturers are concentrating on producing hydrogen-ready boilers.

Due to the fact that hydrogen-ready boilers are expected to be made up of 90% of the same components as gas boilers, boiler manufacturers state they can produce hydrogen-ready boilers at the same cost and place them on the market at broadly the same cost for the consumer. In addition, they are the same size with the same output, so they can fit into existing boiler locations within the household. Manufacturers believe that the decision to roll out only hydrogen-ready boilers would be inconsequential (a "no regrets" option) if it was decided *not* to roll out hydrogen, as the hydrogen-ready boilers can operate on natural gas for their full lifecycle. At present, prototype hydrogen-ready boilers have been produced, though none are available on the market, and research is required to verify the efficiency and useful operating lifetime of hydrogen boilers.

As mentioned, the majority of components in a hydrogen boiler are likely to be the same as a natural gas boiler. From a component readiness perspective, this means that the majority of the components are already commercialised and are manufactured globally at reduced costs. Some components may need to be redesigned to remove materials and design configurations unsuitable for use with hydrogen.

Key components that may need redesign/replacement include the burner (due to the higher flame speed, flame position and material concerns with hydrogen), the flame detector (due to ionisation probes being unsuitable for hydrogen), the code plug settings and materials used in valves, seals, gaskets, etc. Other technical considerations include the heat exchanger designs, pipework, gas valves, space constraints, flue gas analysers, operating pressures, flue design, and metering.

The small number of new components that would be required in a hydrogen-ready boiler would need to be scaled up. However, manufacturers claim that they are already working along the supply chain with established partners and have confidence that the components can be scaled up quickly.

For safety reasons, conversion of hydrogen ready boilers to run on hydrogen cannot be undertaken by the consumer and must be undertaken by a qualified gas engineer. The conversion would take approximately 1-2.5 hours and would cost circa €200.

From a safety perspective, while, theoretically, burning hydrogen (whether blended or 100%) may increase NOx emissions, there is mixed evidence on whether or not this is true for domestic boilers, and further research is required. To avoid leakage and explosion, hydrogen boilers should be designed to reduce internal cavities. Changes to dwellings with hydrogen boilers may also be required. For example, to avert significant risks of fire or explosion, modifications such as non-closable vent installation may be required. Such modifications may present issues for listed buildings due to regulations. Further research is also required into ventilation for flat blocks or pre-fabricated buildings. Furthermore, there is uncertainty surrounding long term

[134] The Guardian (2022) UK minister float plan for 'hydrogen-ready' domestic boilers from 2026 UK ministers float plan for 'hydrogen-ready' domestic boilers from 2026 | Hydrogen power | The Guardian

material sensitivities in the presence of hydrogen, particularly in areas subjected to heat and/or where hydrogen atoms will be present.

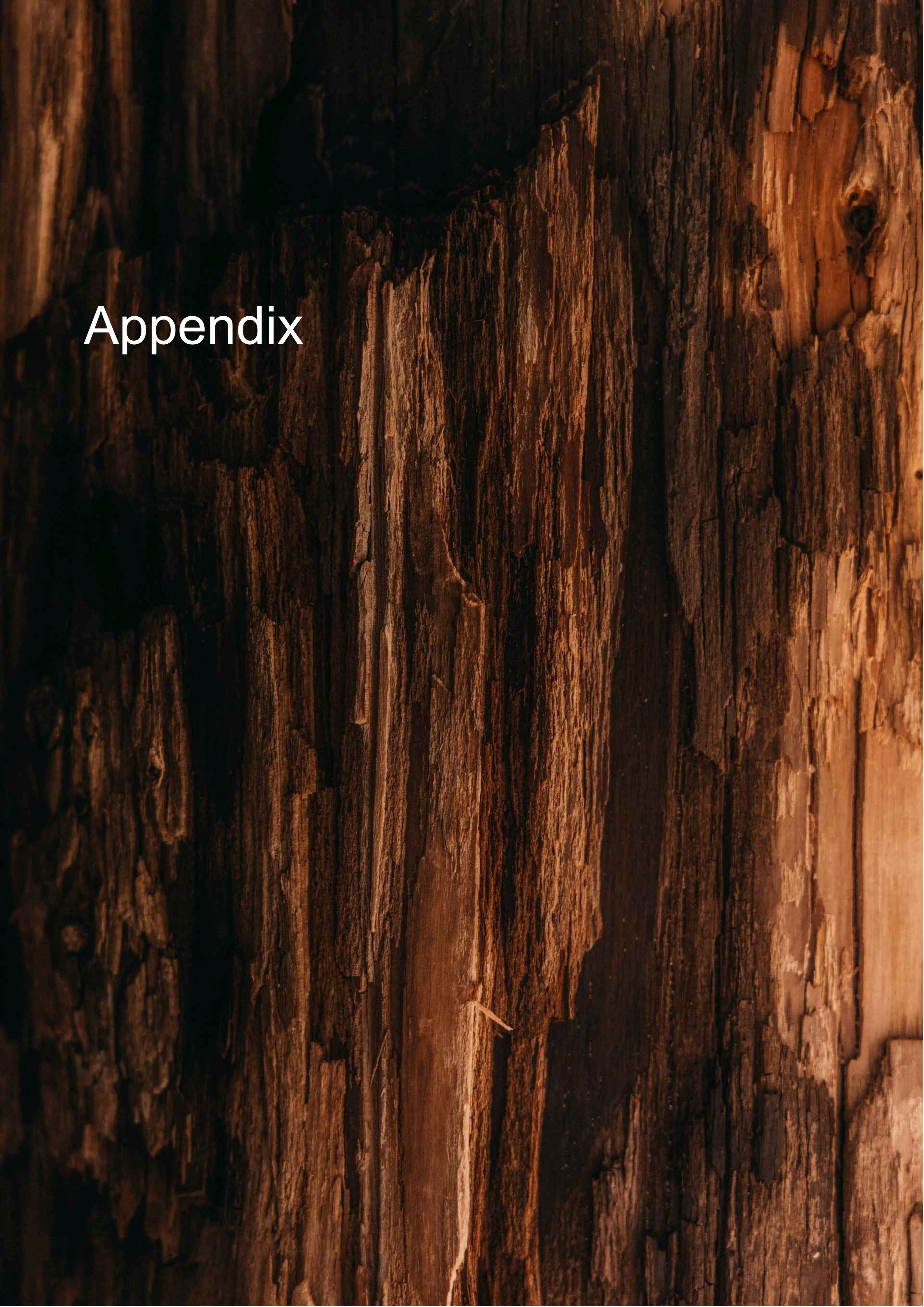
Another issue mentioned was that of developing standards and a codified definition, particularly for design and testing. Stakeholders in the industry believe that they are at the stage where they could roll out hydrogen-ready boilers fairly quickly and have an industry standard for what a hydrogen-ready boiler means. However, there is currently no codified European standard for a hydrogen-ready boiler and, therefore, no specification of what a hydrogen-ready boiler would mean from a consumer point of view. Manufacturers are working with governments and standards bodies to update the EN15502 standard to address this, which would need to be confirmed before the manufacture of hydrogen-ready boilers could be scaled up for mass roll out. In the UK, the UK government intends to sponsor the British Standards Institution to ensure that hydrogen -ready industrial-sized boiler equipment is covered the UK equivalent of EN 15502, BS 15502.[135] The final codified definition may require manufacturers to slightly alter the design of their boilers, meaning that manufacturers are currently apprehensive over finalising their models. However, this is not seen as a significant obstacle to scaling up, rather a time-dependent factor that manufacturers can react to and finalise once the codified definition is announced. This will also level the competitive playing field among the different manufacturers.

The final potential obstacle to large scale roll out would be upskilling current operatives and creating a conversion workforce.[136] However, just as gas technicians currently need to get Gas ICS Certification, they would have to complete an additional hydrogen module or element of this training to gain their certification to work with hydrogen gas. This is not seen as a major obstacle by the stakeholders in the industry, though some interviewed did express concern at a perceived gap between the theoretical and real-world standards of gas technician training and application thereof.

Overall, the literature reviewed, and industry stakeholders interviewed, did not identify any major technical obstacles in the roll out of hydrogen-ready boilers, with the main issue at present being the lack of definitive policy support from governments. That being said, the opinions presented here are biased towards encouraging successful roll out. and there is still debate within the scientific and political communities as to the efficiency and suitability of hydrogen to heat homes.

In conclusion, this study has indicated that hydrogen boilers are likely to be technically feasible on timescales that support a net zero transition. Instead, the factors which will dictate whether hydrogen is the best option for heating are the matters outside of the scope of this study, summarised in Section 1.2.2. These include the relative efficiencies of hydrogen heating compared to other technologies, the relative environmental and resource impacts, the costs to the consumer, the feasibility of a gas network switchover, and other potential more important uses for green hydrogen. All of these topics were out of scope of this study, but resolution of the issues they present will be vital to define hydrogen's future role in heating.

[135] Department for Business, Energy & Industrial Strategy, Hydrogen Strategy update to the market: December 2022
[136] Imperial College London (2022) The future of Home Heating Imperial+Research+-+Decarbonising+the+domestic+heat+industry+briefing+paper.pdf (squarespace.com)



Appendix

A 1.0 List of Sources

Source Type	Documents Reviewed
Trial Documents	Hy4Heat Trial: • WP2: Hydrogen • WP2: Hydrogen Colourant • WP2: Hydrogen Purity & Colourant Final Report • WP4: Domestic hydrogen gas appliance development • WP5: Understanding Commercial Appliances for UK Hydrogen Heat Demonstration • WP6: Conversion of Industrial Heating Equipment to Hydrogen • Safety Assessment Precis & Conclusions Report • Final Progress Report
	HyDeploy Trial: • Carbon Savings Summary • Demonstrating non-disruptive carbon savings through hydrogen blending • HyDeploy: The UK's First Hydrogen Blending Deployment Project • Project Report Second • Project Report Third • Project Report Fourth • Project Report 17/18 • HyDeploy hydrogen blending trial at Pilkington UK (video) • HyDeploy Keele (video) • HyDeploy Webinar - Public Perceptions (webinar) • HyDeploy: Gas safety webinar (webinar) • Hydrogen blending begins on the public gas network in Winlaton • HyDeploy2 Project
	HyNet: • HyNet Industrial Fuel Switching Feasibility Study • HyNet Northwest, unlocking net zero for the UK
	H100 Fife: • A world-first green hydrogen gas network in the heart of Fife • Network Innovation Competition: H100 Fife

	Engie: • The GRHYD Demonstration Project • 'Hydrogen and natural gas : a new energy field: The French government supports the GRHYD demonstration project
	GRHYD: • GRHYD: A successful demonstration for the new gas H2NG
	Westküste 100 • Complete sector coupling: Green hydrogen and decarbonisation on an industrial scale
	Snam: • Snam and Hydrogen
	DNV: • Heating Dutch homes with hydrogen
	Stedin: • Hydrogen in Rozenburg with Power2Gas
	Waterstof: • Hydrogen blending with Natural Gas on Ameland
	IGRC: • Pilot project on hydrogen injection in natural gas on island of Ameland in the Netherlands
	BDR Therma • BDR Thermea joins pioneering test of hydrogen energy in Germany
	Vaillant: • Vaillant's Second Certified 100% Hydrogen Boiler Moves in at Hystreet Spadeadam Trial
	H21: • H21 Phase 1 Technical Summary Report
Government Documents	Response to consultation: • Hydrogen for heat Facilitating a ‘grid conversion’ hydrogen heating trial European Commission: • European Clean Hydrogen Alliance All Party Parliamentary Group: • Non-Verbatim Minutes – The role of hydrogen in decarbonising heat in homes

Academic Papers	• A quantitative risk assessment of a domestic property connected to a hydrogen distribution network • An overview on safety issues related to hydrogen and methane blend applications in domestic and industrial use • Hydrogen-enriched natural gas as a domestic fuel: an analysis based on flash-back and blow-off limits for domestic natural gas appliances within the UK
Articles and Press Releases	• The Guardian • Cadent Gas • The Engineer • Recharge • Smart Energy International • CIBSE Journal
Consultancy Reports	Frazer-Nash Consultancy: • Logistics of Domestic Hydrogen Conversion • Appraisal of Domestic Hydrogen Appliances
	Climate Exchange: • Evidence review for hydrogen for heat in buildings
	Fraunhofer Institute for Energy Economics and Energy Systems Technology • The limitations of hydrogen blending in the European gas grid
	Imperial Consultants (ICL): • The Future of Home Heating
	Institute of Economic Affairs: • The Future of Hydrogen
Manufacturer and industry reports and websites	• Worcester Bosch: • Baxi • EON • HHIC • Viessmann • Boiler guide • Hydrogen UK • Northern Gas Network • H2GO

A 2.0 Interview Topic Guides

1. Background Questions	
No.	Question
1.1	Nature of Business/Organisation? Briefly describe your business/organisation? Are you a subsidiary of a large organisation? What is the main product or service you provide? What sector or sub-sector are you in?
1.2	Participant's role in the organisation? What department do you work in? What are your main responsibilities?
1.3	What geographical locations do you cover? Local, regional, national, international
2. Converting conventional gas boiler technology to hydrogen	
No.	Question
2.1a	We understand the converting a boiler design to operate on hydrogen rather than natural gas requires some changes to components, plus the burning of hydrogen generates nitrogen oxides (NOx) as well as more steam. In your view, what are the major components affected by a conversion of gas boiler technology from natural gas to *blended* hydrogen?
2.1b	What do you think are the major components affected by a conversion from natural gas to *100%* hydrogen?

2.2	Are the steps to convert conventional gas boiler technology to hydrogen the same for all blend shares?
2.3	Do the steps for conversion vary across different countries?
2.4	How scalable is the roll-out of hydrogen boilers?
3. Obstacles to accommodating hydrogen in existing gas boiler technology	
No.	Question
3.1	What do you think are the main technical obstacles to accommodating hydrogen in gas boilers?
3.2a	How resolvable are the issues and obstacles identified to using hydrogen in gas boilers?
3.2b	Are there any technical issues that could present insurmountable obstacles to the development of hydrogen boilers?
3.3	Are you planning/aware of anyone planning to conduct further hydrogen boiler trials?
4. Hydrogen conversion toolkit	
No.	Question
4.1	A number of organisations have suggested the concept of a hydrogen conversion kit, which can allow consumers or technicians to convert boilers to 100% hydrogen. Were such a conversion kit available, what specific parts and procedures would be involved in making the switch?
4.2	Who would undertake this conversion and what skills would they need?
4.3	Do you think consumers be able to undertake the switch themselves, or would a technician be required?
4.4	Would it be possible to produce a standard kit and procedure that works across different brands/types?

4.5	Would there be an impact on manufacturers' warranties when making the switch?
4.6	Are you aware of any indicative costs of the conversion kit? And installers time?
4.7	Would there be a safety risk of switching/using a switched boiler?
5. Blending share	
No.	Question
5.1	In a hydrogen-natural gas blend, what maximum hydrogen share would you envisage?
5.2	Do you foresee any variances in maximum share by country?
6. Safety	
No.	Question
6.1a	What do you think are the main safety risks for boilers using a natural gas-hydrogen blend?
6.1b	What are the main safety risks for boilers using 100% hydrogen?
6.2a	How resolvable are the safety risks identified?
6.2b	Are there any safety risks that could present insurmountable obstacles to the deployment of hydrogen boilers?
6.3	Do you view public perception of hydrogen boilers' safety as a barrier to their successful deployment? And if so, what measures could be taken to address this?
7. Materials Risks	
No.	Question
7.1	What materials risks are likely to occur in boilers using mixed or 100% hydrogen?
7.2a	How might these risks be resolved, and how feasible are the possible solutions?

7.2b	Are there any material issues that could present insurmountable obstacles to the development/deployment of hydrogen boilers?
7.3	Are you planning/aware of anyone planning to conduct trials examining the materials issues?

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