Appraisal of Domestic Hydrogen Appliances

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Executive Summary

This study has explored the engineering challenges of developing domestic gas hobs, ovens, fires and boilers that can run on 100% hydrogen.

It has involved two key steps. Firstly, it has investigated the impact, at a component level, of running appliances designed for natural gas on hydrogen and has identified the key technical issues and the components that will need to be redesigned. Secondly, it has considered the following three options for hydrogen appliances, and in each case evaluated the performance, practical considerations and developmental timescales and costs:

- New appliances developed specifically to run on hydrogen;
- Adaptation of existing natural gas appliances in-situ to run on hydrogen;
- New dual-fuel appliances that can switch from natural gas to hydrogen.

The study has involved a systematic review of the available literature as well as detailed industry engagement involving 1-2-1 conversations and a discussion workshop. The industry engagement has included appliance and component manufacturers, gas testing bodies, maintenance and servicing contract companies, trade associations and consultancies.

Impact of Hydrogen on Existing Appliances

Hydrogen has a significantly higher flame speed, greater flammability range and is likely to burn at a higher temperature than natural gas. These characteristics present significant engineering challenges that particularly affect the burners in all four appliances. Specifically there are concerns with light-back (propagation of flames back through burner), higher NO_x emissions and the potential explosion of unburned gas. To mitigate these effects, it may be necessary to remove the primary aeration, re-size the burner ports (holes) and remove internal cavities where combustible gas mixtures could form. It will also be necessary to select and test materials that are suitable for higher temperature combustion. A number of potential options for new burner technologies have been identified in this study but there is currently no industry-wide consensus on the most feasible burners and further R&D is required.

Another key technical concern is the Flame Failure Device (FFD) which detects the presence of a flame and shuts off the gas supply if it is extinguished. Natural gas boilers use ionisation sensors to detect flames (via the resulting combustion gases) and these cannot be used with hydrogen. Fires, hobs and ovens use thermoelectric FFDs which have a relatively slow reaction time (typically 30 seconds or greater) and this could be a concern for ovens and fires that have enclosed volumes where unburnt gas could build up. Alternatives such as UV and IR sensors are available and used for industrial processes but these will need to be redeveloped to reduce their size and cost. In addition, hydrogen also burns with a pale blue flame that is difficult to see in daylight conditions and this presents aesthetic and safety concerns, particularly for fires and hobs.

Components such as the pipework, heat exchanger and gas valves will require some redevelopment due to the different combustion characteristics of hydrogen but the operational principles will not fundamentally change.

Review of Hydrogen Appliance Options

Overall, the view from stakeholders was that by developing appliances specifically designed for hydrogen (first option), they should be able to match the key features of existing natural gas appliances. This includes appliance efficiency, lifetime, maintenance requirements, size and ease of use.

The main advantage of adapted appliances (second option) is that the cost is only burdened if there is a switchover during the lifetime of the appliances. However, following such a switchover they may suffer reductions in performance compared to a new hydrogen appliance as they contain components that have not been fully optimised for hydrogen. There are also significant differences in the design and makeup of domestic gas appliances. Even within one appliance type, there are variations in current commercially available appliances and even greater variation in the makeup of the existing stock in domestic installations. Adapting existing natural gas hobs, ovens and fires to hydrogen is possible although would require a conversion kit that is sufficiently universal to fit different product variations. Adapting boilers is again, in theory possible, although given the limited space inside the appliances this will be very challenging from a practical perspective.

For all four appliances, a dual-fuel option that can readily interchange between natural gas and hydrogen without replacing components is in theory possible, but is likely to require doubling up various components including the burner system. This will significantly increase the size and is very unlikely to be accepted by occupants. For this reason, this option has been discounted and has not considered in the detailed options appraisal. In the context of a single gas switchover, Hydrogen Ready dual-fuel appliances are potentially more attractive. These would be designed for hydrogen but back-fitted in the factory to run on natural gas up to, and indeed if, switchover occurs. These appliances would be specifically developed to be easily converted and this could significantly lessen the burden of switchover. By developing these appliances with hydrogen in mind, they also should offer the same performance as new hydrogen appliances. In principle, Hydrogen Ready dual-fuel could offer an attractive compromise between rolling out hydrogen only appliances and adapting current natural gas appliances.

Ultimately, the general view of the industry was that the development of domestic hydrogen appliances would be initially led by new hydrogen only appliances and adaption and dual-fuel options would be developed off the back of these. Also, in the short term, new appliances would be based on existing natural gas products as much as possible to minimise the amount of new innovation required. If the industry and market for hydrogen appliances develop, further R&D may mean that the appliance components start diverging from those used in natural gas systems.

Development

The following key technical challenges have been identified in this study and will need to be addressed in order to develop the first generation of hydrogen appliances:

- Hydrogen burner technology – the technical issues associated with hydrogen combustion are generally understood but hydrogen burners suitable for domestic appliances are yet to be developed.
- Flame colouration suitable for hydrogen – hydrogen flames are known to burn with a pale blue flame that is not obvious in daylight. It is necessary to investigate the effect of additives to the hydrogen source and also adding materials at the burner.
- Cooking performance – the differences in flame temperature and humidity from hydrogen combustion could have implications for the performance of ovens in terms of heat uniformity and cooking times.
- Flame Failure Devices (FFD) – fast acting, low cost and reliable sensors suitable for mass manufacture will need to be developed.
- Investigation of leakage and material degradation with hydrogen at low pressures used in domestic properties.

Market Intervention

Development of 100% hydrogen domestic appliances will require government intervention. Initially, this requires target funding to close the innovation gap and develop the first generation of appliances and it is envisaged that the Hydrogen Demonstrator Project will go a long way to achieving this. A market for hydrogen appliances will then only follow with a clear roadmap and regulation from BEIS.

Acknowledgements

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Crosslee

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Embers

Enertek International

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Kiwa Gastec

HHIC

Honeywell

HSL

Nationwide Training Services

Orkli

SIT

Vaillant

Viessmann

Worcester Bosch

Worgas

Webber-Brennertechnik

Glossary

The following terms are used throughout this report:

- **ATEX:** EU Directives that describe the allowable equipment and working conditions in an environment with an explosive atmosphere.
- **Dew point**: Temperature to which air must be cooled to become saturated with water vapour.
- **e.m.f (electromotive force):** Voltage developed by any source of electrical energy such as a battery or dynamo.
- **Flame speed:** Linear rate of expansion of the flame front in a combustion reaction.
- **Flammability range:** The concentration range which a flammable mixture of gas in air can be ignited at a given temperature and pressure. It is usually expressed in volume percentage.
- **Flame Failure Device (FFD):** Device to detect the presence (or lack of presence) of combustion. For hobs, ovens and fires this is typically a thermocouple in the flame, whilst for boilers this is an ionisation sensor.
- **Heat transfer coefficient:** Proportionality constant between the heat flux and the thermodynamic driving force (temperature difference).
- **Hydrogen embrittlement:** Process by which metals such as steel become brittle and fracture due to the introduction and subsequent diffusion of hydrogen into the metal.
- **Light-back:** where the burning gas flows backwards through the burner ports. This occurs when the flame speed is greater than the unburnt gas speed.
- **NO_x:** Generic term for the oxides of nitrogen.
- **Primary Air:** Air that is mixed with fuel gas prior to combustion.
- **Secondary Air:** Additional air that mixes into a combusting gas.
- **Steam methane reformation:** A production process in which high temperature steam is used to produce hydrogen from a methane source, such as natural gas.
- **Town gas:** Flammable gaseous fuel made from coal (also called coal gas). The composition varies according to the type of coal and carbonisation but typically comprises 50% hydrogen, 15% carbon monoxide, 30% methane and small amounts of other gases including carbon dioxide and nitrogen.

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1 Introduction

1.1 Aims and Objectives

This report presents an appraisal of domestic gas appliances and considers how they could be converted to run on 100% hydrogen. It has involved a systematic technical review of the appliances combined with extensive industry engagement.

Initially, the report explores the engineering challenges, at a component level, of running existing domestic natural gas hobs, ovens, fires and boilers on hydrogen. It highlights and discusses potential design solutions and their technological readiness as well as gaps in R&D that will need to be filled in order for hydrogen appliances to be developed.

The report then considers three specific options for hydrogen appliances; developing new designated hydrogen fuelled appliances, adapting existing natural gas appliances to hydrogen and developing new dual-fuel appliances that can burn both natural gas and hydrogen. In each case, it assesses the performance, practical considerations and the development timescales and costs of these options.

1.2 Background

The fast moving energy industry is presenting huge but exciting challenges. The government has signalled its ambitions for affordable low-carbon energy for all through the Industrial Strategy White Paper [1] and Clean Growth Strategy [2], but also is mindful of how this can support a vibrant UK economy. Heat currently accounts for approximately half of UK energy consumption [3] and one third of greenhouse gas emissions [4]. Delivering the government's targets is likely to require almost full decarbonisation of heat in buildings but the most practical and cost-effective manner of achieving this is still in debate.

There has been significant focus on the electrification of heating (for example by heat pumps), substituting traditional fuels with biomass as well as district heating networks combined with decentralised Combined Heat and Power (CHP). However, all these options have their drawbacks and there is currently no consensus on the best approach.

In this context, there has been a growing interest in the role hydrogen could play in decarbonising the UK's heat sector. Studies such as the H2 Hydrogen Leeds City Gate have explored the feasibility of converting the existing gas network to 100% hydrogen and these have concluded that this could be technically and economically feasible. Using Steam Methane Reformation (SMR), carbon dioxide could be captured, sequestered underground and the resulting hydrogen could then be transferred in the national grid pipeline to provide zero carbon heat at the point of end use [5]. Alternatively, and perhaps on a smaller scale, excess electrical energy from renewables can be used to produce hydrogen from the electrolysis of water (Power-to-Gas) [6] and this can be blended with natural gas in the pipeline infrastructure [7]. This provides partial decarbonisation of heat but could be also be used as inter-seasonal energy storage. There are a number of studies considering blended hydrogen both in Europe and the UK including the HyDeploy project in Keele.

This study aims to improve the evidence base for 100% hydrogen as a means of decarbonising heat. It will be used to provide input to BEIS's assessment of decarbonisation pathways and will also feed into the BEIS Hydrogen Demonstrator Project that has recently been commissioned. The Hydrogen Demonstrator Project seeks to develop a safety case for hydrogen, downstream of the meter, in preparation for a future project involving occupied trials. It will look at a hydrogen specification, testing existing internal pipework and developing and testing domestic hydrogen appliances.

Recent studies have highlighted that conversion of domestic gas appliances to 100% hydrogen is feasible but certain design changes will be needed [8]. Following on from these, the next clear step is to understand in greater detail, the technical and commercial challenges of developing hydrogen appliances and what form these appliances may take. BEIS has highlighted three potential options for the appliances:

- New appliances: Development of new hydrogen fuelled appliances;
- Adapted appliances: Adaptation of existing natural gas appliances in-situ to run on hydrogen;
- Dual-fuel: Development of new appliances that are capable of operating on natural gas or hydrogen.

Of these three options, dual-fuel is open to the most interpretation. Dual-fuelling often refers to the ability to interchange between gas types without the need to change over components. However, alternatively and perhaps more relevant to the context of a single gas changeover from natural gas to hydrogen considered here, it could refer to appliances that are designed with hydrogen in mind but initially configured to run on natural gas. These appliances then may require certain components to be changed at the point of switchover but will have been specifically developed to facilitate this process. These different approaches to dual-fuel will be considered in Section 2 and the most feasible definition of dual-fuel will then be taken forward to the options assessment in Section 3.

A new hydrogen appliance offers the freedom of designing and optimising a new technological solution from scratch. However, there are huge challenges associated with rolling out a completely new product which is so ubiquitous and relied upon so universally for domestic comfort and safety. In theory, adapted and dual-fuel options could soften the roll-out but these will have technical and operational issues of their own. Ultimately, the conversion of domestic gas appliances to 100% hydrogen would be a huge undertaking and the challenges extend far beyond the engineering associated directly with the appliances. However, the performance, practical and cost implications of the appliance options are key inputs to the overall picture and this study aims to provide clarity on these three options.

The domestic hydrogen appliance industry is very immature and to date there has only been a small amount of industrial R&D and academic research. This study therefore starts with a systematic review of existing domestic natural gas appliances and considers the technical impact on the constituent components of using 100% hydrogen. It discusses potential solutions to these challenges and assesses their technical maturity using a Technology Readiness Level (TRL) assessment. It also identifies R&D that will need to be undertaken to successfully develop domestic hydrogen appliances.

1.3 Industry Engagement

Alongside a technical review of the available industrial and academic literature, this study has involved detailed industry engagement. The vast majority of the knowledge of the design and optimisation of domestic gas appliances is held directly by appliance and component manufacturers and it has therefore been crucial to canvas their views and opinions on how hydrogen appliances could be developed. The industry engagement involved two elements; detailed 1-2-1 conversations and a general discussion workshop.

1.3.1 Detailed 1-2-1 Conversations

At the outset of the study, BEIS highlighted a series of questions relating to the performance, practicality and development time and cost of the three appliance options. These questions were transferred into a formal questionnaire that was sent out to the industry stakeholders prior to the 1-2-1 conversations. Detailed component matrices for each of the four appliance types (hobs, ovens, fires and boilers) were also produced which aimed to highlight the key constituent components, their function and the predicted impact on the components of switching to 100% hydrogen and these were also sent out prior to the conversations to gain feedback and facilitate discussions. The harmonised Product Standards for the appliances were integral to the development of these matrices. They provided a methodical and auditable method of identifying all the necessary components as well as unique identifiers for the components to aid discussion with the stakeholders who use the Standards extensively. The harmonised standards for hobs, ovens, fires and boilers are presented in Annex A1.

The 1-2-1 conversations were used to discuss the answers to the questionnaire, canvas views on the component matrices, and understand the stakeholders' approach to R&D and how this could be directed towards the development of hydrogen appliances. Overall, over twenty 1-2-1 conversations were undertaken which included the following stakeholder groups:

- Appliance manufacturers;
- Component manufacturers;
- Gas appliance test bodies;
- Gas appliance installation and service providers;
- Trade associations;
- Consultancies.

1.3.2 Workshop

A workshop was held on 7th August 2017 at the Heating and Hotwater Industry Council (HHIC) offices in Kenilworth to discuss both the technical challenges of developing hydrogen appliances and also the key drivers and barriers that industry foresees in realising a hydrogen appliance market. The results of the workshop were combined with the findings of the 1-2-1 conversations and consolidated to form the findings of this report.

1.3.3 Summary of Engagement

The majority of the stakeholders consulted have a significant background in natural gas appliances but limited active involvement in hydrogen appliance development. Consequently, their input has been primarily based on their technical background in natural gas appliance development, theoretical knowledge of the physical characteristics of hydrogen and in some cases the conversion of appliances between natural gas and other fuels (propane, butane and town gas). Their input generally therefore comprised expectations based on their professional judgement and most were keen to emphasise that this not been underpinned by analysis or testing. A confidence and sensitivity assessment is provided in Annex A2 along with a list of data limitations and assumptions.

2 Technical Review of Domestic Gas Appliances

This section explores the technical challenges of running existing domestic natural gas appliances on hydrogen. It describes potential design solutions to address these challenges, assesses their technological readiness and proposes areas of additional R&D to assist in the development of domestic hydrogen appliances. This section is distinct from the consideration of the three design options (new product, adapted existing and dual-fuel) which is the emphasis of this study and presents a bottom-up systems engineering review of current natural gas appliances to highlight the technical challenges of hydrogen combustion in domestic appliances. However, by investigating the overall technical challenges it highlights the requirements for the three specific design options and practically what they will need to comprise. This section provides the following:

- Description of the operating principles of the four domestic natural gas appliances, highlighting the key differences and similarities;
- Review of the impact of converting to hydrogen on the appliances, drawing out the key components that will require adaption or redesign;
- Identification of potential design solutions to enable conversion and the Technological Readiness Level (TRL) of these solutions;
- Proposals for R&D to enable hydrogen-fuelled appliances to be developed.

There are significant variations in the design and makeup of domestic gas appliances. Even within one appliance type, there are variations in current commercially available appliances and even greater variation in the makeup of the existing stock in domestic installations. The approach presented here is based on typical modern appliances that are most widely available.

2.1 Description of Domestic Natural Gas Appliances

2.1.1 Domestic Hobs

Of the four appliances considered in this study, the domestic gas hob is the most basic and each ring essentially comprises an atmospheric burner with manual controls and safety gas cut-out. A schematic of a typical domestic gas hob burner arrangement is presented in Figure 1. Natural gas is injected into the base at high speed where it entrains and mixes with air that is drawn into the hob from the underside (primary aeration). This air-fuel gas mixture flows up into the burner head and out of a series of holes (ports) at the sides of burner where it is ignited by a piezo-electric lighter. The primary air generally only provides 40-60% of the oxygen required for complete combustion [10] and the remainder is drawn into the hot combustion gases downstream of the flame front (secondary aeration). The mixing of the fuel gas and air is delivered by the momentum of the gas jet and does not rely on additional mechanical assistance from fans. A detailed explanation of atmospheric burners is given in [11].

A thermoelectric Flame Failure Device (FFD) provides a safety cut-off in the event that the fuel gas is flowing but has not been ignited. The gas burner flame impinges on a thermocouple and induced e.m.f (electromotive force) is used to energise an electromagnet and hold open a spring-loaded valve [10]. If the flame extinguishes, the thermocouple cools, e.m.f is no longer generated and the valve is released and the gas supply is cut off.

Gas flow and hence delivery of heat is regulated manually via a mechanical control knob which regulates the gas supply to the injector. The burner assembly is generally manufactured from cast metal and does not require electrical power input for either the combustion process or safety mechanism which allows the appliance to be manufactured at low cost.

The flue gases (combustion products) are vented directly to the room so gas hobs need to be operated with appropriate ventilation.

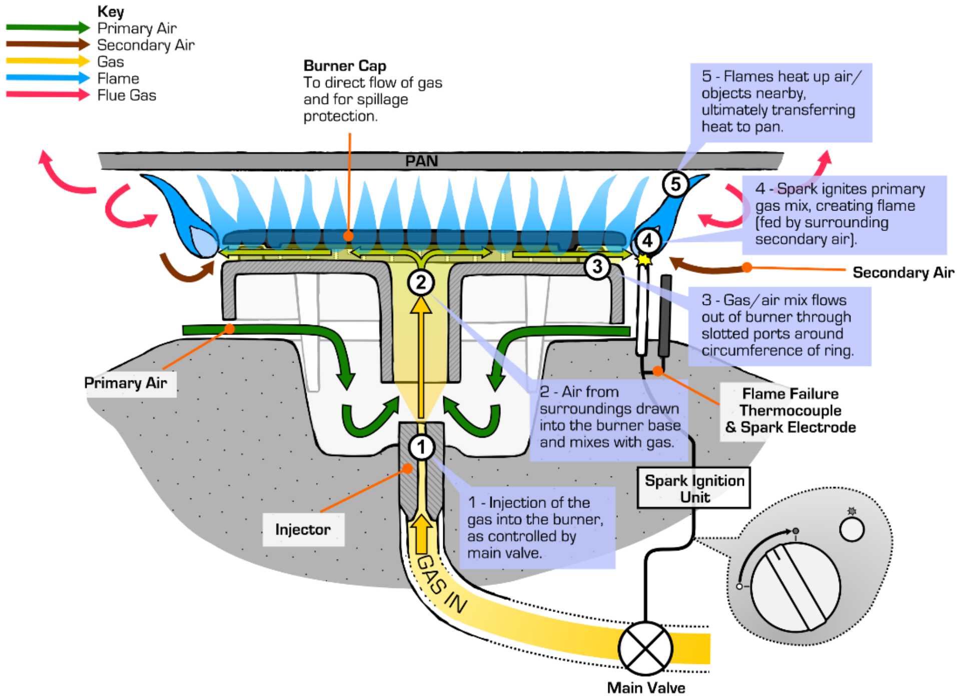

Figure 1: Schematic of a domestic hob showing the principle components

2.1.2 Domestic Gas Ovens

Domestic gas ovens also generally use atmospheric burners and a representation of a typical appliance is shown in Figure 2. Primary air is entrained into a fuel gas jet prior to flowing through ports in the burner head. Secondary air in this case is provided through air inlets to the combustion chamber. The particular design of the combustion air inlets is dependent on the appliance but is chosen to optimise the air flow and heat circulation within the enclosure as well as ensuring complete combustion. Unlike a domestic gas hob, the burner itself is typically a fabricated stainless steel structure with ports distributed in line and with the injector located at one end with the provision for primary aeration [12].

Gas flow and hence heat delivery in ovens is regulated by a thermostat. The safety gas cut-off is generally either by thermoelectric sensor and FFD (similar to gas hob) connected to a manually operated gas valve or solenoid valve on the gas supply. In some appliances, other flame sensors technologies may be used. For example, one manufacturer reported that they have recently moved to an ionisation sensor based system similar to that used for boilers (see Section 2.1.4) in order to reduce flame failure response times. This, however, comes at a premium due to the need for associated electronic controls.

The combustion products are vented directly into the room via a flue at the back of the oven. The flue is designed to create a strong pull within the oven chamber to set up the correct air flow and heat distribution for the cooking process, as well as safe removal of the combustion products.

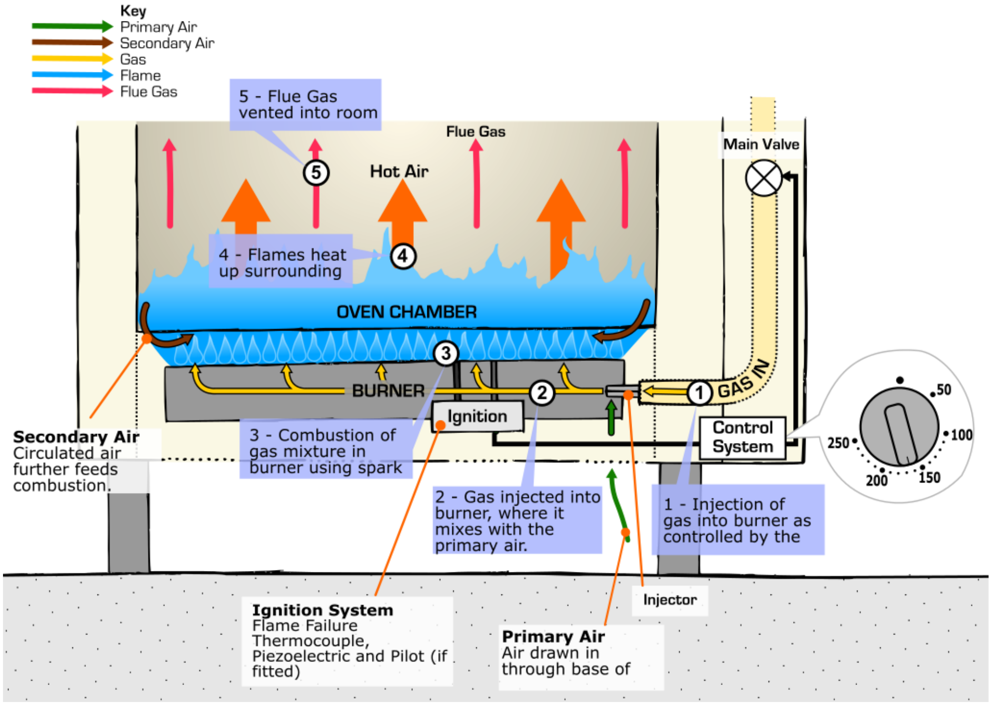

Figure 2: Schematic of a domestic oven showing the principle components

2.1.3 Domestic Gas Fires

Domestic fires also use atmospheric burners and have a similar layout to domestic ovens as shown in Figure 3. Heat delivery of fires is normally via manual control rather than thermostat although some modern appliances are remotely linked to room thermostats or hand-held controls. Primary and secondary air for the burner generally comes from the underside of the fire and further secondary air supply may be drawn in from the surrounding combustion chamber/room environment. The partially aerated burners are generally either the cylindrical sheet metal fabricated type used in ovens or ceramic plaques mounted within a sheet metal box [10].

Relatively low power decorative flame fires often aim to produce long yellow flames and this is typically achieved by a significant reduction in the primary air supply. The flames and flue gases (combustion products) are generally used to heat artificial coals or stones above the burner which, once heated, radiate out to the surrounding room.

The combustion products are typically vented to the exterior of the building by a ducted flue. There are a number of different types but the majority are either open flue (combustion gases flow into an open chimney and rise by buoyancy to the exterior) or room sealed (combustion gases are directly ducted to the outside) (see for example [13] or [14]).

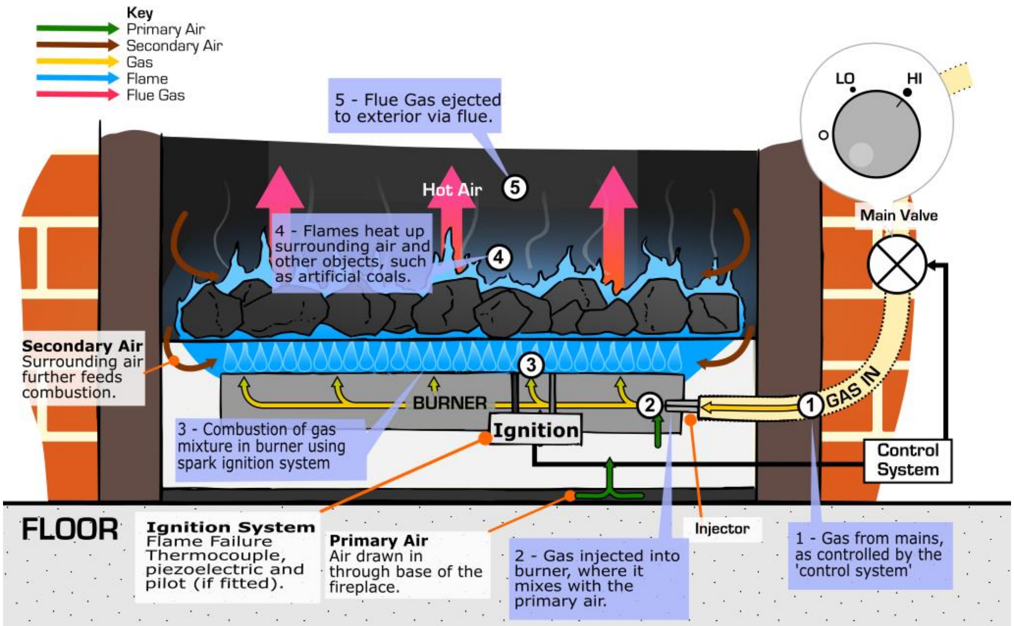

Figure 3: Schematic of a domestic fire showing the principle components

2.1.4 Domestic Gas Boilers

A schematic of a typical domestic condensing natural gas boiler is shown in Figure 4. Unlike the other appliances, condensing domestic boilers use pre-mix burners where the gas is fully aerated at the point of ignition. This enables the burner to operate with lower excess air levels which improves efficiency and reduces NO_x emissions compared to partially aerated combustion [10]. This is required to comply with the requirements of the Energy Related Products (ERP) Directive which is discussed further in Section 2.2.1.4.

In pre-mixed combustion, ambient air is mechanically drawn into the burner and mixed with the fuel gas by a fan (forced draught) to achieve an optimum gas/air mixture for complete combustion without secondary air. Unlike atmospheric burners, the momentum of the incoming fuel gas is not used to entrain air and mix it with the fuel gas; the injector acts as a restrictor to regulate the flow of gas to the appliance. The amount of air mixed with the fuel gas and hence the air-fuel ratio is regulated by the throttle setting and the speed of the mixing fan. This pre-mixed combustion mixture is injected through holes in the burner material where it is ignited producing short, sharply defined flames at the burner surface. The flames and hot combustion gases are passed through a heat exchanger where the heat is transferred to the water system. By using a fan to mechanically force air into, and through, the burner, the flame direction is controlled by fan-induced momentum rather than buoyancy and this allows the burner to be mounted above, and point downwards to the heat exchanger. In turn, this allows the latent heat contained in the exhaust gas to be extracted and the resulting condensation then drains downwards away from the burner. Reclaiming the latent heat by condensation significantly increases the boiler efficiency.

Boilers typically utilise ionisation sensors for flame sensing which detect the presence of ions resulting from hydrocarbon combustion. Hydrocarbon gases are easily ionised and ionised gases conduct an electrical current in proportion to the number of ions present [15]. Ionisation sensors are fast acting, sensitive and have been developed to be manufactured at low cost.

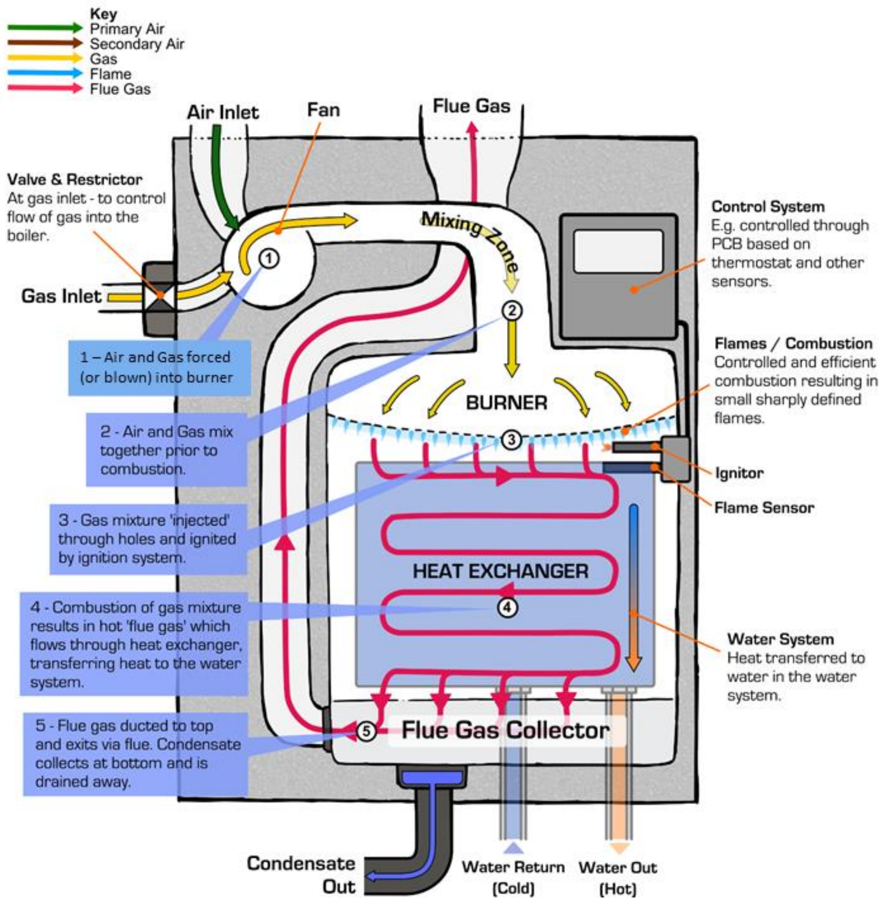

Figure 4: Schematic of a domestic boiler showing the principal components

2.2 Impact on Appliances of Converting to Hydrogen

For the conversion of the four domestic appliances from natural gas to hydrogen, the following key sub-systems have been identified:

- **Combustion** – air and natural gas are brought into, and mixed within the appliance and are ignited in a combustion zone to produce heat. Hobs, ovens and fires use atmospheric burners, whilst modern boilers use pre-mix burners[1].
- **Heat transfer and exhaust** – the heat produced in the combustion zone is transferred to a secondary medium and the exhaust gases are ejected from the appliance.
- **Control** – multifunctional gas controls for controlling appliance heat output. Sensors are used to regulate the functionality and safety of the appliance. For hobs, ovens and fires this is by thermoelectric Flame Failure Device (FFD) whilst for boilers this is achieved by ionisation sensors.
- **Piping, valves and sealed casing** – the gas pipework in the appliance and any outer casing used for room sealing.

[1] There are a considerable number of non-condensing (atmospheric combustion) boilers currently still in service (approximately 30% of the installed boiler base of 21.2M – see Section 4.1), although the number is steadily reducing year on year. These boilers are not considered viable for conversion and have been omitted from this study.

The following sections describe each of these sub-systems in turn and highlight the technical issues related to function, performance and safety of converting to hydrogen and potential design solutions to mitigate these impacts. Many of the technical issues faced are common across the appliances and therefore these sections are largely relevant to all appliances. However, implications for the individual appliances are provided where appropriate.

2.2.1 Combustion System

In any fuel conversion, there are likely to be at least basic changes to reflect the different combustion characteristics of the gases (energy density, flammability range, required ignition energy). For conversions between natural gas, propane and butane in hobs, ovens and fires with atmospheric burners, these typically involve changes to the gas injector, by-pass screw in the gas valve for setting low flow operation gas rate, pressure regulator and burner primary aeration. In general, boilers with pre-mix burners only require basic re-tuning and / or a different gas orifice for hydrocarbon gas conversions.

Hydrogen presents some particular design challenges that specifically affect the combustion system and these are described in this section. In each case, potential solutions are presented and discussed.

2.2.1.1 Light-Back

The flame speed of hydrogen is significantly faster than natural gas (2.7m/s for hydrogen compared to 0.37m/s for natural gas [16]) and using hydrogen in a burner designed for natural gas is likely to cause light-back where the flames propagate back behind the burner surface. This can lead to damage to the burner and surrounding components (which in pre-mixed combustion also includes a fan) as well as safety concerns with incomplete combustion and detonation (Section 2.2.1.3).

Flame Stability and Light-back

Flame stability is the balance between the speed of unburned combustible gases passing through the burner ports to the flame speed (rate of expansion of flame front) of the combusting mixture [11]. If the velocity of the unburnt gas is greater than the flame speed, then the flame will lift off the burner surface and ultimately extinguish. Conversely, if the flame speed is greater than the unburnt gas speed at the opening, then the flame will propagate back through the opening. For appliances with adjustable power output, this balance must be met for the full range of gas flow rates and hence gas port speeds.

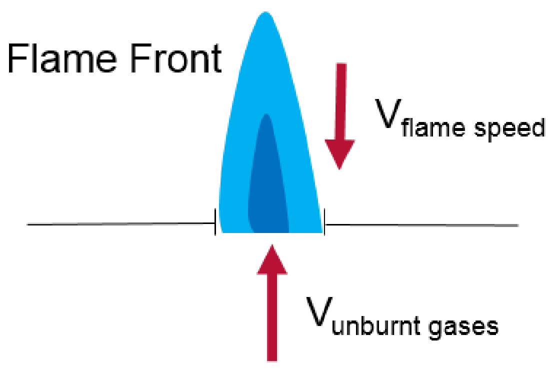

Figure 5: Flame stability is the balance between the speed of the unburned gas through the ports in the burner and the flame speed

Furthermore, as the appliances are turned off, the gas flow and hence speed of the unburned gas through the burner will reduce and this could increase the potential for light-back behind the burner surface. Often a popping sound can be heard with natural gas or LPG.

The concerns of light-back could be avoided by removing the primary aeration to ensure that there is no combustible gas mixture produced prior to the point of ignition. The result is a non-aerated or diffusion flame where pure gas flows from the burner ports and combustion takes place as oxygen from the surrounding atmosphere diffuses into the emerging gas stream (c.f. non-aerated Bunsen burner flame). Even after eliminating primary air, the burner itself will also need to be resized to ensure that the velocity of the pure gas is greater than the flame speed of hydrogen. In addition, the depth of the ports may need to be increased to promote more fully developed flow which reduces the potential for gas backflow and hence light-back [10]. This could have an undesirable effect on combustion temperature, flame profile and thermal efficiency. An alternative option may be to use a gauze (c.f. the Davy lamp principle).

2.2.1.2 Material Degradation

Depending on the level of aeration, hydrogen could burn with a slightly hotter flame temperature than natural gas and this could cause material degradation to the surrounding components. Furthermore, and related to the concerns over light-back, the higher flame speed of hydrogen is likely to mean that the flame sits closer to the burner surface than with natural gas. This presents particular concerns for the burner surface around oxidation and life expectancy. Ceramic burners which offer good temperature resistance could be used although more research is required to understand their reliability and life expectancy when used for hydrogen combustion.

2.2.1.3 Gas Explosion

In the combustion discussed so far, a combustible gas mixture has been ignited in a controlled manner at a burner surface or port. However, if a volume of combustible gas mixture is allowed to develop and then is ignited, it can either deflagrate (sub-sonic combustion which propagates through the combustible gas by heat transfer) or detonate (a combustion wave propagates at supersonic speed through the unburned gas) [17]. Detonation is a particular issue for appliances with confined combustion chambers such as boilers, ovens, and enclosed fires. The internal space behind a pre-mix burner comprises a volume of unburned gas which is a potential risk if ignited but this is mitigated in natural gas systems by careful burner design and light-back protection described previously. However, a gas leak from a valve or joint could allow a volume of unburned gas to develop and this is a particular concern in boilers which have a sealed casing. Ultimately, both of these mechanisms have the potential to cause significant damage to both the appliance and the dwelling but for natural gas, developments in appliance safety and appropriately trained Gas Safe installers and maintainers means that domestic gas explosions are rare [18].

Hydrogen presents the following particular safety concerns that need to be addressed:

- It has a much smaller molecular size than natural gas and is therefore more prone to leakage through joints and valves [19]. Hydrogen leakage is discussed in more detail in Section 2.2.4. However, it is also very buoyant, disperses rapidly and has a low energy per unit volume at atmospheric pressure.
- It has a greater flammability range (4-75% for hydrogen compared to 4-17% for natural gas and lower ignition energy at stoichiometric (complete combustion) conditions [17].

Detonation can cause larger overpressures than deflagration and can result in significant impact and damage with much smaller gas volumes. There are a number of conditions required for detonation to occur but a key parameter is a gas material property known as the detonation cell size. A sustained detonation can only occur if the representative dimension of the gas volume is greater than a multiple of the detonation cell width [17]. For methane (main constituent of natural gas) this is 28cm, whilst for hydrogen this is significantly smaller at 1.5cm. This small amount of hydrogen gas could plausibly build up in appliances and is a particular concern for boilers that have a sealed casing. Ultimately, predicting the exact conditions required for detonation to occur is complex and is also dependent on the strength of the ignition source, the gas temperature and pressure, presence of highly elongated geometry or very high levels of turbulence. In this latter respect, the turbulence produced by a pre-mixing fan in a boiler is of potential concern. The following will need to be considered with respect to hydrogen fuelled appliances:

- The volume of internal cavities that could contain flammable gas mixtures needs to be reduced and if possible eliminated.
- Gas leakage needs to be mitigated by appropriate pipe and joint selection.
- Effective venting of appliance casings should be considered by the use or pre-purge and post-purge.
- The controlled ignition source needs to be reliable – If ignition fails, the region beyond the burner (heat exchanger and flue) could fill with combustible gas.
- Combustion sensing methods need to remain fast acting and the risk of delayed ignition needs to be minimised.

2.2.1.4 NO_x Production

NO_x is formed in high-temperature combustion as nitrogen in the air is oxidised. It has been found to be an environmental pollutant and studies have found that it can have an adverse impact on health for both short and long-term exposure [20], [21]. Gas boilers have been tested for NO_x emissions for a number of years, although in September 2018 the Energy related Products (ErP) Directive will set a maximum emission level of 56mg/kWh. From January 2018, the ErP has set a maximum NO_x emission for gas fires of 130mg/kWh. For hobs and ovens, a reliable measurement of NO_x has so far been difficult to specify.

NO_x

NO_x is the collective term for oxides of nitrogen. Nitric oxide (NO) also known as nitrogen oxide or nitrogen monoxide is a clear gas formed from nitrogen and oxygen at high temperatures. It is a toxic gas at high concentrations and extended exposure will cause difficulty in breathing. Nitrogen dioxide (NO_2) is a reddish-brown reactive gas that has a strong odour and is a major air pollutant. It is also associated with respiratory symptoms [20][22].

The presence of NO_x in combustion exhausts is known to be increased by fuel-rich combustion and increased combustion temperature [10]. Hydrogen has a higher stoichiometric combustion (complete combustion) temperature than natural gas and although many burners are operated below stoichiometric conditions, it is possible that hydrogen burner may run hotter than a natural gas burner and this could cause material oxidation and degradation as well as higher NO_x emissions. In practice, the flame and hence burner temperature is actually dependent on a number of factors:

- Distribution of temperature within the flame;
- Flame size, and any impingement on surrounding surfaces;

- Time individual molecules remain at a high enough temperature for the NO_x reaction to take place (transition time).

In the absence of testing it is difficult to determine whether the burner temperatures will be higher or lower with hydrogen than natural gas and therefore it is difficult to predict the implications for NO_x.

In natural gas appliances, the requirements for low NO_x often have to be balanced with the additional requirements of high thermal efficiency and low carbon monoxide (CO) emissions. Thermal efficiency is increased at high temperatures (hence likely to cause NO_x) and when flames are nearer the surface of the heat exchanger. However, if the flames are sufficiently close that they impinge on the heat exchanger surface this in turn can lead to incomplete combustion and increased CO levels. For hydrogen burners, the CO risks are fully eliminated and this reduces the compliance criteria to only NO_x and efficiency which potentially may make this balance easier to strike.

In anticipation of higher burner temperatures, there could be an industry move from metallic fibres to ceramic fibres which have greater thermal resistance. Elsewhere, some experiments have attempted to lower the burner temperature by covering the burner surface in stainless steel wire-wool which acts as a catalyst and reduces the flame temperature although these burners are already in use especially in commercial pre-mix burners [23].

Ultimately, an increase in NO_x from hydrogen combustion would have particular implications for domestic boilers that have very stringent requirements on NO_x emissions and energy efficiency. The operating temperature of natural gas burners in modern boilers is close to a critical threshold for thermal NO_x and a small change could easily deem the appliances non-compliant under current regulations. However, across all appliances, NO_x level requirements are likely to be key factors in new burner and combustion chamber design.

2.2.1.5 Flame Colour

Natural gas burns with a blue flame under complete combustion [11] whilst hydrogen typically burns with a pale blue flame that is difficult to see in daylight conditions [10]. Where the flame is uncovered then this will have implications for safety as operators may not immediately be visually aware of combustion taking place. This is a particular issue for hobs and fires but is also relevant for some boilers which require flame checks during maintenance and servicing. Furthermore, an important feature of some gas fires is the presence of a decorative flame. Even if the thermal performance of the appliance is not adversely affected, a less visible flame will compromise the aesthetics.

Colourant could either be added to the unburnt gas prior to combustion or added to the combustion zone itself. One potential option could be to consider colourants that are widely used in the pyrotechnics industry, which are generally in the form of metal salts. However, to date there has been minimal research on colouring hydrogen for domestic gas applications. If colourants are to be added to flames there are a number of considerations:

- The additive will need to be food-safe as, in hobs and ovens, as the products of combustion may be direct contact with food.
- If the combustion products are released into the room (hobs and ovens) then the colourant and any chemical reaction products will need to be non-toxic within confined spaces. The wider environmental impact of flue emissions must also be addressed.

- The impact of the colourant on the flame characteristics will need to be investigated – in particular, the flame temperature and stability as these could affect the appliance safety and performance. If the colourant increases the flame temperature then this could increase the amount of NO_x produced.

Other experiments on hydrogen have shown that particulate from metal fibre blankets or vaporised oils located at the burner surface can provide flame colouration where the colour is based on the spectral emission of the particular material used. In the example shown in Figure 6, the solid yellow colour of the hydrogen flame is produced by vaporised oils and fragments of metal carried into the flames.

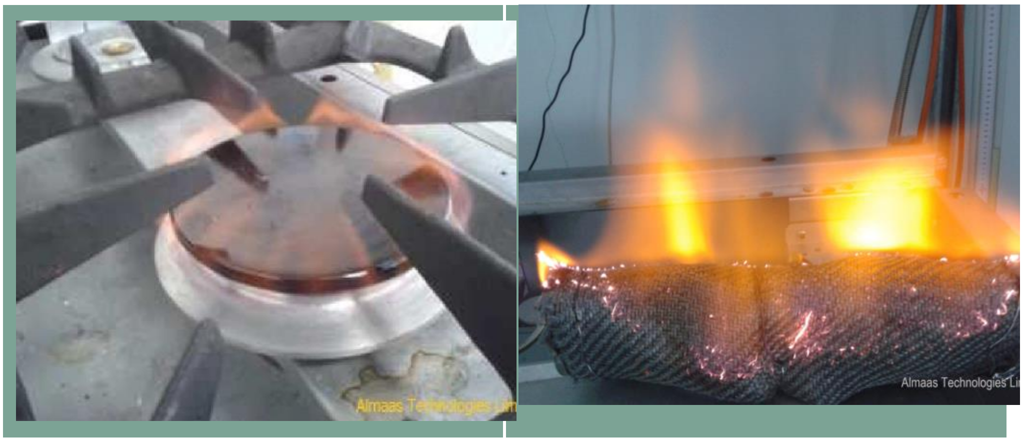

Figure 6: laboratory experiments of hydrogen combustion using standard atmospheric burners; primary air inlet blocked off using proprietary paste (left) and primary air inlet blocked off and wrapped in metal fibre blanket (right)

In addition, black body radiation adds to flame colour appearance. Due to very pale spectral colour for hydrogen the black body radiation becomes much more apparent in hydrogen flames than equivalent hydrocarbon flame.

Ultimately, research into flame colouration should also be combined with hydrogen odourisation to ensure that the solutions obtained are complementary. Hydrogen will require odourising for leak detection, although this is potentially more challenging than for natural gas. If the hydrogen is also to be used for fuel-cells then traditional odours containing sulphur cannot be used as they have a detrimental effect on catalysts.

2.2.1.6 Potential Design Solutions

Non-aerated burners were used extensively with town gas[2] in order to eliminate the risks of light-back caused by gas quality variations. Examples of non-aerated burners that could be applicable for hydrogen are described as follows:

Wedge-cavity (slot) Burner: Thin slots produce a very thin, flat flame with a high surface area to volume ratio. This increases the rate of molecular diffusion into the flame and the rate of combustion, so that the flame is relatively compact [10]. A successful implementation of a flat flame burner was developed by Bray using a suitably shaped cavity on the underside of an orifice plate containing a single hole and this produces a fan-shaped flame. In general, the greater flow rate from a given orifice, the thinner the resulting jet. An example of a hydrogen slot flame burner has been demonstrated by Webber and Haigh and is shown in Figure 7. In principle, as the flames are tight and there is a strong gas velocity at the port, this burner has the

[2] The composition of town gas varies according to the type of coal and carbonisation but typically comprises 50% hydrogen, 15% carbon monoxide, 30% methane and small amounts of other gases including carbon dioxide and nitrogen [24].

potential to provide good flame stability, low NO_x and high energy efficiency, with a performance closer to that of a pre-mix burner than a traditional partially aerated or lazy diffusion flame.

Figure 7: Non-aerated hydrogen slot flame, courtesy of Brent Haigh, Embers Installations Ltd /Webber Brennertechnik GmbH

Matrix (Surface) Burner: This was developed for the combustion of waste hydrocarbon gases, but was found to be capable of burning virtually any gas. Fuel gas discharges from narrow slots or ports adjacent to much larger ports which supply all the air required for complete combustion [10]. The flames produced are generally compact, stable and semi-lifted. In principle, this combines the advantages of a fully aerated burner (short flames and compact combustion chamber) with non-aerated operation (no light-back). In order to maintain the correct air flow and adequate mixing of air and gas, air may be supplied by a fan so this option could, in theory, have similar controllability to a pre-mix burner. The high flame speed of hydrogen is likely to mean that the flames stabilise closer to the burner surface which could cause overheat and material damage and potentially high NO_x. Both of these aspects would need careful consideration in development. This type of burner will require very tight manufacturing tolerances to ensure a compact flame in the correct position. It will also need to be developed for mass production and production at an appropriate price point.

A variation of this principle is the Webber Surface burner which has been designed for industrial applications [25].

Catalytic Burners: Catalysts provide a surface which allow gases to burn ‘flamelessly’ at much lower temperatures but with the same heat release than conventional combustion. Still strictly a non-aerated burner (without primary or secondary airflow), gas is fed to the back of the housing and diffuses through a porous or fibrous pad on which catalyst particles have been evenly distributed. Combustion is not spontaneous but needs to be initiated by pre-heating the pad so this option does require external heat input. Catalytic combustion has the benefits of high radiant efficiency and low NO_x emission. However, there are a number of drawbacks:

- During operation, the catalytic pads remain somewhat drab in appearance and consumers tend to prefer a bright radiant glow for focal point heating.
- It requires an external electrical power supply (unless fitted with a permanent pilot) which adds complication to hobs, ovens and fires.

- Catalytic materials are expensive.

Natural gas is the most difficult gaseous hydrocarbon to burn catalytically and this may explain the lack of R&D in this area for domestic gas applications [10]. This is a potential area that could be explored but because of its complexity and cost the previous methods discussed are likely to be prioritised.

In summary, fundamental research is required to develop a first generation of hydrogen burners. However, any of the above approaches are considered a reasonable starting point for this process.

2.2.2 Heat Transfer and Exhaust

For practical reasons domestic hobs and ovens are not connected to external flues. Similarly, some fires vent combustion products directly into the room although most fire types and all boilers have external flues for removing combustion products from the living environment.

All boilers use a heat exchanger for effective heat transfer to the water circuit. Some fires also have some form of heat-exchanger or heat storage capacity in order to achieve desired heat transfer into the room.

In principle, existing flues and heat exchangers (for boilers) used in natural gas systems should be suitable for hydrogen combustion but may not be optimised. The key technical challenge here concerns the development to take into account the different combustion characteristics:

- Radiation and convection heat transfer are different between hydrogen and natural gas. In particular, hydrogen burns slightly hotter and emits different levels of infrared and ultraviolet emissions.
- Flame length and shape will be different for hydrogen and natural gas due to the different flame speeds and primary/secondary aeration mode.
- Combustion of hydrogen yields 1.6 times the quantity of water vapour than natural gas [8] and this will affect the dew point and heat transfer coefficient.

Ultimately, heat exchangers will have to be redeveloped to achieve maximum thermal performance. If the burner is too close to the heat exchanger, there is a risk of material degradation, whilst if the burner is too far from the heat exchanger and the combustion chamber is not well insulated, the heat losses could reduce the thermal efficiency [10]. This balance could also affect NO_x emission which is dependent on maximum flame temperature and the residence time of the gases within the combustion zone.

Similarly, flame shields and flues will need to be assessed for thermal performance to ensure they maintain integrity and also do not transfer heat to sensitive components. Condensing boilers contain sumps and drains to capture and dispose of the condensate but these should be appropriate as standard size pipe connections are used which are normally oversized for the required volume flow. However, in some cases there may be a need to redesign for the increased water produced from hydrogen combustion.

2.2.3 Controls

Thermoelectric Flame Failure Devices (FFD) currently used in natural gas fires, hobs and ovens can, in principle, be used with hydrogen. However, they have a relatively slow reaction time due to their inherent thermal mass (typically 30 seconds or greater) and in the event that there is a gas leak this could allow hydrogen to collect in confined spaces (particularly in fires and ovens) and present an explosion risk (see Section 2.2.1.3). Consequently, it may be necessary to develop a faster acting FFD to mitigate the potential for hydrogen build-up. Furthermore, combustion temperatures may differ slightly with hydrogen and the different flame length and shape will require consideration.

Ionisation sensors are an effective solution for natural gas boilers but are not suitable for pure hydrogen as it is hydrocarbon ions that are registered by an ionisation sensor [26]. There are various alternatives options that are currently used as hydrogen sensors in other industries although these currently cannot match ionisation sensors in terms of high reliability, small size and low cost [10]. Optical sensors such as infrared (IR) or ultraviolet (UV) cannot detect pure hydrogen gas (e.g. from non-ignition) and are inherently pressure sensitive [15].

Hobs, ovens and fires are modulated manually using the control knobs. Pre-mix boilers are modulated electronically by changing the fan speed. It is possible that a move away from pre-mix fans would necessitate the gas valve to provide the modulation (c.f. non-condensing boilers). This has potential implications for the reliability for gas valves that will need a moving seal in a modulating valve.

2.2.4 Piping, seals and casing

Hydrogen presents some potential concerns to the internal pipework and components. These are discussed as follows:

- **Leakage:** Hydrogen is the smallest molecule and so has a greater propensity to leak through small openings than natural gas. There is a particular concern with leakage through flanged joints and screwed connections and this may mean more welded joints are necessary. However, the appliances will need to be accessible for servicing and this will require further consideration by selecting appropriate quality of fittings for serviceable joints.

- **Material degradation:** Combustion affects materials through a number of damage mechanisms includes blistering, cracking, baking and melting. These issues are generally common to any gas combustion application and are therefore well known to burner and appliance manufacturers.

  Hydrogen is known to reduce the service life of metallic components [27] such as pipework and valves through a number of specific damage mechanisms including embrittlement, blistering, hydrogen attack and cracking [27]. Hydrogen embrittlement, perhaps the most commonly referred to damage mechanism is a process caused by hydrogen atoms diffusing into materials, generating a high pressure and ultimately material cracking. The susceptibility of metals to hydrogen embrittlement in particular varies between materials. Most studies to date have been concerned with embrittlement caused by either high pressure cycle exposure (e.g. vehicle re-fuelling and hydrogen storage at 350-700bar) or hydrogen diffusion during metal forming/welding operations. For domestic gas appliances operating at, or below 20mbar pressure cycle induced embrittlement is unlikely to be a concern. However, hot areas are potentially at 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. Overall, stainless steel (grade 316) is listed as the industry standard for components in hydrogen. Aluminium is known to be highly resistant, and copper is appropriate for low pressure applications [28]. Although various tests have shown that hydrogen blended with natural gas has minimal material degradation [29], testing will need to be undertaken on the internal appliance pipework to ensure adequate reliability and lifetime for low pressure applications using 100% hydrogen.

- **Reverse Joule-Thomson Effect:** When gases are passed through nozzles or leakages they expand. At ambient pressure, natural gas will cool on expansion whilst hydrogen is somewhat unusual as it will heat up on expansion to atmospheric pressure. For low pressure systems, such as those within domestic natural gas appliances this is considered to be negligible [30, 31].

2.2.5 Summary of the Impact of hydrogen on the Key Components

The technical review of the four subsystems presented in Sections 2.2.1 to 2.2.4 is summarised in Table 1. For each component in these systems the following information has been identified:

- The function of the component;
- Whether the component is normally found within each of the four appliance types; hobs (H), oven (O), fire (F) and boiler (B);
- The technical impact of converting from natural gas to hydrogen on the component;
- Potential design change required.

Each component has been assigned a technical risk based on the following colour-coding:

(green)	Green – There is no significant foreseen impact on the component of converting from natural gas to hydrogen. In principle (subject to functional checks) the existing component could be used.
(amber)	Amber – Converting to hydrogen will require the component to be redesigned or resized to optimise performance but the fundamental operating principles of the component will remain the same.
(red)	Red – the component will not work with hydrogen and will require a different technological solution.

Component	Function	H	O	F	B	Impact on component	Design Change
COMBUSTION							
Burner (Atmospheric and pre-mix – including fan)	Site of combustion. Controls safe and efficient combustion and flame picture	✓	✓	✓	✓	Use of hydrogen in current atmospheric or pre-mix burners will cause: • Light-back of combustible gas behind burner surface • Ignition of combustible gas mixture behind burner surface or within appliance if gas leak – leading to deflagration or detonation • Possibly higher NO_x • Hydrogen has very pale blue flame colour is not easy to see in daylight.	• Removal of primary air • Reduce internal volume of burner system (to mitigate gas build up) • Careful design for low NO_x • Add colourants to hydrogen or use gauze or material at combustion surface to emit particles and hence different colours. • Eliminate fans or ATEX rate
Spark Igniter	Ignites gas/air mixture at burner	✓	✓	✓	✓	Hydrogen has a lower ignition energy than natural gas and has a wider flammability range. This will make it easier to ignite.	Possible cross-lighting issues for some specific burners but in general a positive characteristic
Pilot light	Flame to support main burner operation	X	✓	✓	X	Hydrogen has a significantly higher flame speed which will change size and stability of pilot light.	Redesign for new combustion characteristics of hydrogen.
Gas valve	Gas shut-off and throttling	✓	✓	✓	✓	Potential for hydrogen to leak through seals. Different gas flow rate may be required depending on new burner combustion characteristics and changes to overall energy performance.	Seals may need development to mitigate leakage. Adjust for different flow rate by selecting valves with different flow capacity.
HEAT TRANSFER AND EXHAUST							
Heat Exchanger Flame Shield Internal Panels	Transfers heat from combustion zone to provide usable heat output	X	✓	✓	✓	Heat transfer will be different for hydrogen combustion: • Increased flame temperature • Different IR/UV emission characteristics • Different flame length • Increased water vapour in combustion products.	Likely to require re-design to optimise heat transfer (efficiency of appliance) but fundamental operating principle unchanged.
Sump	Collects condensate from heat exchanger	X	X	X	✓	Hydrogen combustion produces 60% more water vapour than natural gas [8]. Amount of condensate collected likely to increase.	Volume of sump or drain may need to be increased.
Flue	Controls release of combustion products to external environment	X	X	✓	✓	Exhaust gas may be hotter and will contain more water vapour. This will increase heat transfer to other components within appliance and potentially to building fabric outside appliance.	With careful design of the heat exchanger the flue gas need not be hotter than a natural gas system
CONTROLS							
Flame Sensor: Thermocouple	Safety device used to regulate gas fuel release to burner	✓	✓	✓	X	Flame temperature may be higher and flame length and shape will be different.	Re-specification of critical position for new combustion characteristics but fundamental operating principle unchanged.
Ionisation sensor		X	X	X	✓	Hydrogen combustion does not produce hydrocarbon ions. Ionisation sensor cannot be used.	Need to change to alternative sensors – e.g. UV or IR.
Automatic and manual controls (e.g. thermostat)	Automatic regulation of appliance heat output	X	✓	X	✓	No significant concerns	No change envisaged
CASING AND PIPEWORK							
Pipework	Distributes fuel gas in appliance	✓	✓	✓	✓	Possible concerns with flow capacity/material/gas tightness issues. There are many seals in gas valves which will need to remain gas tight.	Re-sizing of injector/restrictor if necessary. Check specification of all pipework and fittings and test gas tightness for smaller molecule size.
Outer Casing	Protects components and provides casing which could allow unburnt gases to accumulate	X	✓	✓	✓	Hydrogen has a greater propensity to leak than natural gas. Outer casing could allow a combustible gas mixture to form.	Reducing size of internal cavities that could allow combustible mixtures to form. Incorporate gas sensors inside casing. Pre- and post-purging to ensure there is no combustible mixture prior to ignition.

Table 1: Summary of component review – impact of converting to hydrogen and potential design changes

2.3 Technology Readiness

A Technology Readiness level (TRL) has been undertaken on the key components identified in Section 2.2. TRL assessments quantify the maturity of technologies that form part of a larger system and are a useful way of identifying, and presenting in a consistent manner, components that will need to be developed to produce a complex engineering system.

Technology Readiness Level

Technology Readiness Levels (TRL) are a method of quantifying the technical maturity of products. It was originally conceived by NASA in 1974 [32] for aerospace but has since been adopted widely in other industries and provides a standardised benchmark for assessing technologies. The TRL runs from 1 through 9 where TRL 1 is for scientific research that has taken the first step in being applied practically. At the other end, TRL 9 is one that has been incorporated fully into a larger system and has been proven to work and considered operational [33,34]. The complete TRL scale is shown in Figure 8.

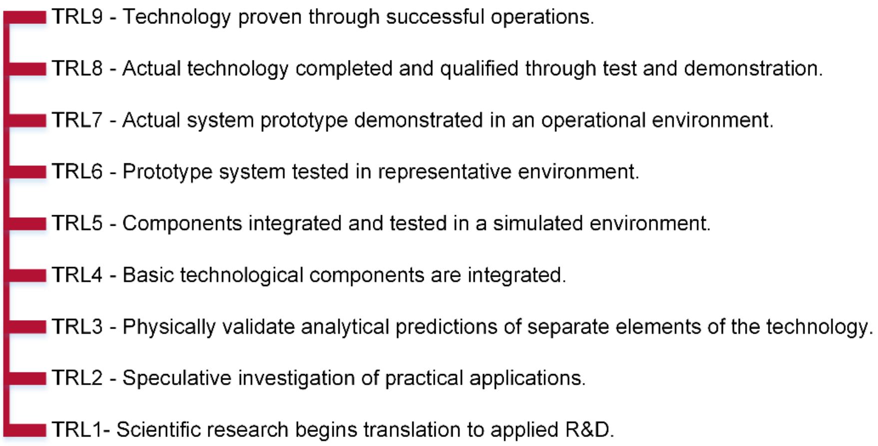

Figure 8: Technology Readiness Level (TRL) scale

The TRL of the key components is presented in Table 2. It is anticipated that some of the components (spark igniter and automatic controls) currently used in natural gas appliances will be applicable to hydrogen and therefore these are judged to have a high TRL of 8-9.

Other components such as the pipework, heat exchanger and flame failure devices used in hobs, ovens and fires will require some redevelopment due to the different combustion characteristics of hydrogen but the operational principles are well understood and essentially unchanged. These therefore have been assigned a TRL of 7-8.

The current ionisation sensors used in boilers will not be applicable for hydrogen and alternatives will need to be found. There are various potential options, including IR and UV sensors that are used in industrial applications but these will need to be developed specifically for domestic appliances. They will need to be reduced in size to fit in boilers and will require extensive reliability and lifetime testing and have therefore been assigned a TRL of 4-5.

Burners suitable for all four appliances will need to be developed. For boilers, some manufacturers have started testing options that they believe may be suitable but to date, there has not been significant testing and there are number of questions to be resolved in performance (light-back, NO_x, colouration as discussed in Section 2.2.1) as well as demonstration of reliability and product lifetime. There is currently no consensus on the best type of burner for hydrogen combustion and this has therefore been assigned a TRL of 2-4. This TRL has been assigned for the burners for hobs, ovens and fires. There has been some preliminary work on the adaptation of atmospheric burners by industrial researchers (e.g. Almaas Technologies) for these appliances but to date there has been minimal development from manufacturers on how these could be implemented. Burners for hobs, ovens and fires have not been the subject of stringent regulations on NO_x and recent development focus has been limited to energy efficiency improvements which are generally controlled by burner application specification within a given appliance configuration. Ultimately, it is envisaged that burners for hobs, ovens and fires will be more technically straightforward than boilers but there has been negligible development from these manufacturers and this is reflected in the similarly low TRL.

TRL	Component	Comment
8-9	Spark ignitor Auto/manual controls	These components currently used within natural gas appliances should be applicable to hydrogen appliances.
7-8	Pipework	Hydrogen pipework is currently in use under significantly higher pressures in other industries. Some work is required to bring affordable low pressure hydrogen fittings applicable to domestic installations to the market.
	Pilot light, heat exchanger, sump, flue and outer casing Flame sensor (hobs, ovens and fires)	The basic principles relevant to these components are well understood but the components will need to be re-optimised in light of different combustion characteristics.
4-5	Flame detection device (boilers only)	Alternative components to ionisation sensors such as IR and UV sensors are in use in other industries. However, these will require development to reduce their size and manufacturing cost to enable them to be applied to domestic appliances.
2-4	Burners: Hobs, ovens and fires	Preliminary work has been undertaken on atmospheric burners which has demonstrated the combustion of hydrogen in atmospheric burners. However, these have not been actively applied and tested on a domestic gas appliance.
	Boilers	Some manufacturers have developed burners that may be suitable for boilers. However, testing of these appliances is at an early stage and is not yet sufficient to demonstrate solutions that demonstrate the required performance, reliability and lifetime.

Table 2: TRL assessment of the components in hydrogen fuelled domestic appliances

2.4 R&D Gaps

A number of technical questions have been identified during this study that will need to be resolved if hydrogen appliances are to be successfully developed. These are summarised, along with potential development options:

- **Burner technology:** For all four appliance options considered in this study the burner technology presents possibly the largest challenge. The general technical issues of hydrogen combustion are well known but the most effective way of developing a safe and effective hydrogen burner is yet to be determined. This issue could be progressed by a cross-industry research study that aims to develop and test burner options at a sufficiently general level that the results would be relevant to all appliances and manufacturers. To avoid concerns over IP, ideally this would be government led with optional input from appliance and component manufacturers.
- **Flame colouration and impact:** Hydrogen flames are known to burn with a pale blue flame that is not very obvious in daylight. It would be beneficial to investigate options for changing the flame colour through additives in the source hydrogen and by adding materials at the burner.

  Furthermore, it is known that hydrogen flames emit significant UV and it would be beneficial to investigate the safety implications of this to the occupants – particularly for fires where the flames will be visible, but also potentially hobs.
- **Cooking performance:** The differences in flame temperature and humidity from hydrogen combustion could have implications for the performance of cooker ovens in terms of heat uniformity and cooking times. The type of burner could also have implications on the cooking performance and on the venting of the combustion gases.
- **Flame sensing:** Ionisation sensors used in boilers are not suitable for hydrogen combustion. It would be beneficial to undertake research on flame sensing technologies with the aim of developing fast acting, low cost and reliable solutions suitable for mass manufacture. This is particularly relevant to boiler manufacturers but could benefit the other appliances too, as well as those outside this study (e.g. tumble dryers, water heaters and commercial appliances). Thermocouples used in hobs, ovens and fires have a relatively long reaction time and this could pose a risk of passing unburnt hydrogen for several seconds in a confined area.
- **Pipework:** There are potential concerns over leakage and material degradation of existing appliance pipework subjected to hydrogen. Hydrogen is used extensively in industry at high pressures, however, the body of knowledge of the material impact of hydrogen at low pressures (e.g. 20 mbar) is less well documented. The safety concerns of pipework in domestic buildings is being considered in one of the work packages for the Hydrogen Demonstrator Project and given that the gas pressure within appliances is very similar to that within domestic pipework downstream of the gas meter, the results of this work package should also be relevant to the appliances.

2.5 Summary of Appliance Technical Review

The technical review described in this section has highlighted that there are parts of the four appliances that will need to be fundamentally redesigned (burner), some that operate by the same principles (e.g. heat exchanger) but will require re-optimisation for hydrogen and some components that can, subject to testing and approval, essentially be used as they are. These findings have implications for the appliance options that are discussed in Section 3, in particular for the adaptation of existing natural gas appliances and dual-fuel appliances. These are discussed as follows:

Option 1: New Hydrogen Appliances

For hobs, ovens and fires that use atmospheric burners for natural gas, certain fundamental changes will be required. The primary airflow will need to be completely removed and the internal volume significantly reduced, if not totally eliminated. The burner ports will also need to be adapted based on the higher flame speed of hydrogen. Thermoelectric Flame Detection Devices used in fires, hobs and ovens may be appropriate for hydrogen, but they have a relatively slow reaction time (typically 30 seconds or greater) and consequently it may be necessary to develop faster acting sensors.

Ultimately, hobs are likely to require a re-designed burner assembly. Ovens and fires differ slightly in that the key components that need to be changed are generally all integrated into a burner tray (burner, flame detection device (including pilot) and control valve) and it may be possible to confine re-development to this tray.

For boilers it is unlikely that pre-mix burners will be suitable for hydrogen, so a new burner will need to be developed. The heat exchanger will most likely require some consideration based on the different heat transfer characteristics of hydrogen, although it is possible that it will not require complete re-design. A new Flame Detection Device will also be required for hydrogen as ionisation sensors currently used with natural gas are not appropriate for hydrogen.

The hydrogen appliances may require different gas valves due to different gas flow rates and concerns over sealing.

Option 2: Adaptation of current natural gas appliances to run on hydrogen

Adapting current natural gas hobs, ovens and fires is possible but will require a conversion kit for the burner assembly. For hobs this will require, at a minimum, a new burner base and gas cap that can be readily removed. However, if it is found that this is not safe (for example, due to incorrect positioning by users and hence inadvertent introduction of primary air) the whole burner assembly may require replacement. Ovens and fires will require the burner tray to be replaced. As with new hydrogen appliances described above, adapted hobs, ovens and fires may require the flame detection device to be replaced.

Adapting boilers is, in theory, possible although given the lack of space inside the appliances this will be practically challenging. Boilers will also require replacement flame detection devices.

Ultimately, in adapting any of the four appliances that were originally designed only for natural gas, consideration will need to be given to the effect of the changeover on the other components that are not replaced (see for example Table 1). Switching to hydrogen could adversely affect their performance, reliability and lifetime.

Option 3: Dual-Fuel Appliances

As discussed in Section 1.2, dual-fuel typically refers to appliances that are interchangeable between two gas types without the need to replace components. However, in the context of a single gas changeover from natural gas to hydrogen, such interchangeability is not so relevant and appliances that are designed with a hydrogen switchover in mind, but require some components to be replaced at that point are potentially more appropriate. Given the findings of this section, the implications for these two definitions of dual-fuel are as follows:

- Pure Dual-Fuel

  It is likely that pure dual-fuel appliances that are capable of readily interchanging between natural gas and hydrogen will require doubling up of the burner system. For all four appliances, the burner assembly is a significant proportion of the total size and pure dual-fuel appliances will be larger and considerably more expensive than current natural gas appliances.

  For hobs, ovens and fires, if a faster acting Flame Failure Device is developed for hydrogen then this could also be used for natural gas although this is likely to require adjustment for the different flame size. For boilers, if a replacement to the ionisation sensor is developed for hydrogen then in principle this could be appropriate for natural gas too.

- Hydrogen Ready Dual-Fuel

  These appliances will require components to be replaced but it should be possible to design them to fit within the same size envelope as current natural gas appliances. By developing these appliances with hydrogen in mind, it should also be possible to ensure that the necessary components can be readily removed and replaced.

Overall, pure dual-fuel appliances that are significantly larger and more expensive than current natural gas appliances are unlikely to be accepted by occupants. For this reason, pure dual-fuel appliances have been discounted and only Hydrogen-Ready dual-fuel appliances will be considered in the options appraisal in Section 3.

3 Appliance Development Options

This section discusses the feasibility of three potential options for the four types of hydrogen appliances (hobs, ovens, fires and boilers):

- New Hydrogen Appliances – newly developed hydrogen appliances designed specifically to run on hydrogen.
- Adaptation of Natural Gas Appliances - existing natural gas appliances will remain in place and key components will be replaced in-situ by a Gas Safe engineer to allow them to run on hydrogen.
- Dual Fuel Appliances – newly developed Hydrogen Ready appliances that are designed to run on hydrogen but have been back-fitted in the factory to run on natural gas. These would require key components to be replaced by a Gas-Safe engineer at the point of switchover but the appliances will be developed to facilitate this process.

The findings of the appliance analysis in Section 2 have highlighted some practical implications for the adapted and dual-fuel options. For the purposes of this section, both adapted and dual-fuel appliances will require replacement of combustion systems and flame detection devices. The key difference between these options is that dual-fuel appliances will have been designed to facilitate the replacement of components and also that the remaining components will have been designed to perform with hydrogen.

Each of the options have been assessed in terms of the performance, practicality, costs and timescales associated with the four types of domestic appliances; hobs, ovens, fires and boilers. Where appropriate, options are benchmarked against natural gas.

3.1 Performance

The key metrics that contribute towards the appliance performance include the expected operational lifetime, efficiency, maintenance requirements and reliability. As described in Section 2, there are significant differences in the combustion characteristics between natural gas and hydrogen and the ability of the design options to deal with this depend on compromises in performance, cost and size.

3.1.1 Operational Lifetime

The predicted operational life of hydrogen appliance variations is summarised in Table 3 along with the natural gas equivalent, which is between 10 and 15 years for boilers, hobs and ovens and up to 25 years for fires.

For new hydrogen appliances, manufacturers stated that they would aspire to achieve a similar operational life for hydrogen appliances to that currently achieved for natural gas. Despite the technical challenges raised in Section 2, with sufficient R&D this is considered to be a feasible expectation. By developing a completely new hydrogen appliance all components would be designed and optimised specifically for hydrogen which should provide a high level of confidence in the components, and therefore the appliance as whole. There are concerns regarding the lifetime of some of the new components and in particular new burner materials which have not had extensive lifetime testing. In the short term it is likely that these components will be replaced more regularly to maintain the overall appliance lifetimes.

Adapted appliances are likely to suffer from reduced lifetimes as the components that are not replaced will not be designed for hydrogen and will be used outside their design conditions.

Dual-fuel appliances should have a similar lifetime to new hydrogen appliances. Even though only the key components would be replaced at the point of switchover the remaining components will have been designed with hydrogen in mind. In practice, hydrogen is likely to present greater engineering challenges (higher temperatures, sealing and material degradation) than natural gas so by designing for hydrogen they should also be appropriate for natural gas.

The predicted operational life of the three hydrogen appliance variations is consistent across the four appliance types considered.

Appliance Type (B/F/H/O)	Natural Gas Benchmark	New Hydrogen Appliance	Adapted Appliance	Dual Fuel Appliance
B/H/O	10-15 years	Aspire to meet the natural gas benchmark.	Decrease from the natural gas benchmark	Aspire to meet the natural gas benchmark.
F	15-25 years			

Table 3: Operational lifetime of hydrogen appliance variations compared with the natural gas benchmark.

3.1.2 Efficiency

The expected efficiency for each of the appliance variations is presented along with the natural gas benchmark in Table 4. Manufacturers stated that they would aspire for new hydrogen appliances to offer similar efficiency compared with current standard natural gas equivalents.

The type of burner and combustion system within an appliance is an important factor in its overall efficiency. Pre-mix burners in boilers provide efficient combustion with low NO_x emissions. However, there is often a balance between maximising appliance efficiency and minimising carbon monoxide and NO_x emissions. Although hydrogen combustion does not produce carbon monoxide, NO_x emissions are a significant concern and if pre-mix burners are not feasible (for example due to concerns with light-back and explosion safety) then appliance efficiency may be limited by the need to keep NO_x emissions low. Furthermore, pre and post-purging is likely to be required, particularly for boilers, and this will reduce the efficiency slightly depending on the characteristics of the start-up and shut-down cycle.

Adapted appliances are expected to offer reduced efficiency compared with current natural gas appliances. This is mainly due to the compromises required in converting the key components from natural gas to hydrogen. The size of the appliance being adapted is a limiting factor and this will determine the internal space available for the new components. Gas appliances (particularly boilers) are typically designed with very little empty space so new components must be the same size. This potentially means that the components are designed for size rather than performance, therefore resulting in reduced appliance performance. This is consistent over all four appliance types.

For dual-fuel appliances, manufacturers stated that they would aspire to meet the efficiency currently achieved with natural gas appliances. In practice, it is possible that there may be a slight reduction in efficiency as it will be difficult to optimise the components that are not replaced for the two gas types. However, there is currently insufficient knowledge to quantify this at present. By designing for both gases at the outset, this efficiency reduction should be minimised as far as practicable.

Ultimately, efficiency is a key performance attribute for gas appliances and quantifying the reduction for each of the three options (and appliance types) would be a significant benefit in determining which approach to take.

Appliance Type (B/F/H/O)	Natural Gas Benchmark	New Hydrogen Appliance	Adapted Appliance	Dual Fuel Appliance
B	85-90% [35]	Aspire to meet the natural gas benchmark.	Decrease from natural gas benchmark.	Aspire to meet the natural gas benchmark. Potentially slight decrease from natural gas benchmark as difficult to optimise non-replaced components for both gases.
F	Varies from 20-25% for decorative open flued fires up to almost 100% for efficient flueless designs [36]			
H	>50% [37]			
O	No standard definition			

Table 4: Efficiency of hydrogen appliance variations compared with the natural gas benchmark.

3.1.3 Maintenance and Availability

Guidance from manufacturers is that all domestic gas appliances should undergo an annual maintenance check to ensure safe and efficient operation. The consensus from the engagement was that the frequency of maintenance on all new hydrogen appliance variations should remain as an annual inspection but that the duration and costs of the maintenance checks for hydrogen appliances is likely to be higher. This is due to the need to replace key components more frequently. Components in new hydrogen appliances that have been carried across from natural gas may be used in a different operating environment. New components that are developed specifically for hydrogen will not, in the short term, have detailed operational data required to plan maintenance schedules. Consequently, it is envisaged that certain components will require replacement more regularly for hydrogen than in with natural gas.

Adapted appliances will include components that are not intended for use with hydrogen and this will increase the cost and duration of annual maintenance. Dual-fuel appliances will be designed to work with hydrogen so these appliances are expected to have similar lifetimes to new hydrogen appliances. All three appliance options, when operating on hydrogen, may require personnel to have a particular skillset which could potentially increase the cost of the annual maintenance. An overview of the maintenance frequency for the three options compared to natural gas is presented in Table 5.

Appliance Type (B/F/H/O)	Natural Gas Benchmark	New Hydrogen Appliance	Adapted Appliance	Dual Fuel Appliance
B	Annual service is recommended and includes examination of the physical condition and safe functioning of the appliance, pipework, ventilation and flue.	Annual inspections with increased costs and duration compared with the natural gas to proactively replace consumable components.	Annual inspection with increased costs and durations over those expected for a new hydrogen appliance to replace increased number of consumable	Annual inspection with similar costs and durations expected for a new hydrogen appliance
F				

Appliance Type (B/F/H/O)	Natural Gas Benchmark	New Hydrogen Appliance	Adapted Appliance	Dual Fuel Appliance
	Typically costs around £80 for 1 hour inspection		components from original design.	
H	Typically costs around £50 for a 30 minute inspection			
O				

Table 5: Maintenance requirements for hydrogen appliance variations compared with the natural gas benchmark.

3.1.4 Reliability

Natural gas appliances have been developed over many years to be very reliable and manufacturers stated that they would aspire to maintain this for new hydrogen appliances. There are, however, potential concerns with the reliability of new components - burner materials that may suffer heat degradation and (for boilers) new flame detection devices, e.g. IR and UV that may not currently offer the reliability of ionisation sensors. The reliability of the hydrogen appliance variations is summarised in Table 6 which also outlines the components that typically fail in natural gas appliances. There is not currently sufficient data of the failure cycles of new components to quantify the reliability but the knowledge base on this is likely to improve as the first generation of appliances are developed.

Adapted appliances will contain some components that are designed exclusively for natural gas and this is likely to reduce their reliability compared to new purpose-built hydrogen appliances.

Dual-fuel appliances that have been designed with hydrogen in mind should be able to offer the same reliability as new hydrogen appliances.

Appliance Type (B/F/H/O)	Natural Gas Benchmark	New Hydrogen Appliance	Adapted Appliance	Dual Fuel Appliance
B	Burner, valves, control system, sensors, pump, fan.	Aspire to offer the same reliability as the natural gas benchmark through proactive maintenance regime.	Reduced reliability compared to a new hydrogen appliance due to using components designed for natural gas on hydrogen (outside of design intent)	Aspire to offer the same reliability as the natural gas benchmark through proactive maintenance regime.
F	Burner, fan, thermocouple			
H	Burner, thermocouple			
O	Burner, fan, thermocouple			

Table 6: Reliability of hydrogen appliance variations compared with the natural gas benchmark.

3.2 Practicality

The practicality of each of the appliance variations has been assessed in terms of its size, control, noise, warm up and cool down time, system complexity and disruption caused by installing the appliances in the domestic environment.

3.2.1 Size of Appliances

Manufacturers stated that they would aspire to develop new hydrogen appliances that are similar in size to the current natural gas appliances. Some of the components required for hydrogen combustion have been developed for industrial applications (e.g. IR flame sensors) but the intention would be to redevelop these for domestic applications. Whilst, the manufacturers did not foresee any concerns in meeting the current envelope, ultimately the appliances sizes will depend on this development.

Adapted appliances would need to fit within the existing housing of the appliance as any enlargements would be extremely unpopular with the occupants. This requirement would likely require compromises in component design as current appliances lack free space. The trade-off is likely to be between appliance performance and the cost required to develop the appropriately sized components.

Manufacturers stated that they would aim to produce dual-fuel appliances at the same sizes as existing natural gas and new hydrogen appliances. The typical sizes for hobs, ovens, fires and boilers are presented in Table 7 along with the predicted sizes of the three appliance variations.

Appliance Type (B/F/H/O)	Natural Gas Benchmark (mm)	New Hydrogen Appliance	Adapted Appliance	Dual Fuel Appliance
B	750 x 500 x 300	Aspire to the natural gas benchmark.	Designed to fit existing appliance housing (natural gas benchmark).	Aspire to the natural gas benchmark.
F	650 x 500 x 150			
H	550 x 550 x 50			
O	900 x 550 x 550			

Table 7: Size of hydrogen appliance variations compared with the natural gas benchmark.

3.2.2 User Controls

End user controls for natural gas appliances are typically in the form of analogue dials or digital control panels (Table 8). Similar mechanisms would be employed to operate the new appliance variations and manufacturers would look to maintain similar control systems for hydrogen appliances.

Appliance Type (B/F/H/O)	Natural Gas Benchmark	New Hydrogen Appliance	Adapted Appliance	Dual Fuel Appliance
B	Dials, thermostats or digital control interface.	Aspire to use the same controls as the natural gas benchmark.		
F				
H				
O				

Table 8: User controls for hydrogen appliance variations compared to the natural gas benchmark.

3.2.3 Internal Control System

Natural gas appliances contain well-established control systems to detect poor gas supply and quality and lack of ignition.

- Thermoelectric Flame Failure Devices (FFD) used throughout the appliances may be appropriate for use with hydrogen, although there is a concern regarding their relatively slow reaction time. They will also need to be adapted for the different combustion characteristics of hydrogen; flame size, shape and temperature (Section 2.2.3).
- Ionisation sensors used in boilers are not suitable for hydrogen combustion and this will require alternative solutions (such as IR or UV sensors) to be developed (Section 2.2.3).

The potential for a gas explosion due to unreliable ignition is greater with hydrogen and so not only do the appliances require reliable ignition but also fast-acting sensors that can detect when ignition has not occurred.

An assessment of the complexity of the internal control systems required in the hydrogen appliance variations compared with the natural gas benchmark is provided in Table 9.

Appliance Type (B/F/H/O)	Natural Gas Benchmark	New Hydrogen Appliance	Adapted Appliance	Dual Fuel Appliance
B	Ionisation flame sensor	Different flame detection device appropriate to hydrogen (e.g. IR or UV)		
F				
H	Thermoelectric FFD	Fast acting FFD		
O				

Table 9: Internal control systems for hydrogen appliance variations compared to the natural gas benchmark.

3.2.4 Noise

The noise produced by current natural gas appliances is typically in the range of 40 – 55 dB, which is categorised as moderate to quiet for human hearing. Potentially, this could increase slightly for all hydrogen appliance variations due to the increased gas flow through the jets. For boilers, this may be offset by a reduction in fan noise if pre-mixed burners are not found to be viable.

Any increase in noise level is not expected to be significant and is likely to go un-noticed in boilers, hobs and ovens which are generally located in kitchens. However, the noise may be more noticeable for domestic fires as these are generally located in a quieter living space.

The new appliance and dual-fuel options offer the best opportunity to reduce any additional noise through efficient design of the combustion system and inclusion of acoustic damping. It is unlikely that adapted appliances will have sufficient room for acoustic damping.

A summary of the anticipated noise from the appliance variations is provided in Table 10. Prior to the development and testing of hydrogen appliances, only qualitative predictions are possible as the resulting noise levels will depend on both the noise generated and the acoustic damping, which in turn will depend on the available space.

<table>
<tr><th>Appliance Type (B/F/H/O)</th><th>Natural Gas Benchmark</th><th>New Hydrogen Appliance</th><th>Adapted Appliance</th><th>Dual Fuel Appliance</th></tr>
<tr><td>B</td><td rowspan="4">40 – 55dB</td><td rowspan="4">Slight increase and frequency shift of noise compared with the natural gas benchmark.</td><td rowspan="4">Limited ability to damp noise.
Increase in noise over that expected for a new hydrogen appliance.</td><td rowspan="4">Similar to new hydrogen appliances.
Slight increase and frequency shift of noise compared with the natural gas benchmark.</td></tr>
<tr><td>F</td></tr>
<tr><td>H</td></tr>
<tr><td>O</td></tr>
</table>

Table 10: Noise produced by hydrogen appliance variations compared with the natural gas benchmark

3.2.5 Warm up/Cool down Period

The warm up and cool down periods of gas appliances are largely determined by the burner and heat exchanger. Similar periods are expected for a new hydrogen appliance through optimisation of the combustion system. There could be a slight increase in warm up/cool down periods for the adapted and dual-fuel appliances if compromises in the combustion system design are required although this is not expected to be noticeable except in non-storage combination boilers without a pre-heat function. In addition, it may be necessary to purge air through boilers (as these have sealed containment) to ensure there is no combustible gas mixture prior to ignition. This should not add significant warm-up time but is likely to affect the appliance efficiency (Section 3.1.2). An overview is presented in Table 11.

<table>
<tr><th>Appliance Type (B/F/H/O)</th><th>Natural Gas Benchmark</th><th>New Hydrogen Appliance</th><th>Adapted Appliance</th><th>Dual Fuel Appliance</th></tr>
<tr><td>B</td><td>Approximately 0.5 hours</td><td colspan="3" rowspan="4">Aspire to offer similar to the natural gas benchmark or no noticeable difference.</td></tr>
<tr><td>F</td><td rowspan="3">Almost instantaneous</td></tr>
<tr><td>H</td></tr>
<tr><td>O</td></tr>
</table>

Table 11: Warm/Cool period of hydrogen appliances compared to the natural gas benchmark.

3.2.6 Flame Aesthetics (Colour)

Flame aesthetics are the major selling point of gas fires and a visible flame is essential for the safety of hobs and also to a certain extent ovens. A visible flame colour is also beneficial for some boilers to highlight effective combustion during maintenance and servicing. Hydrogen burns with a pale blue flame [10] and there are concerns that it will not be suitable for domestic fires.

Flame colouration for domestic hydrogen combustion requires further research and development and this is discussed in Section 2.2.1.5. This could involve additives to the gas at the point of injection into the gas main and therefore completely disassociated from the appliances or potentially materials at the burner to produce and enhance flame colour.

The challenges and requirements for flame colouration apply to new, adapted and dual fuel hydrogen appliances as summarised in Table 12. Any impact of colouration to flame temperature and heat transfer characteristics needs to be investigated as they could affect other performance characteristics.

Appliance Type (B/F/H/O)	Natural Gas Benchmark	New Hydrogen Appliance	Adapted Appliance	Dual Fuel Appliance
B/H/O	Blue visible flame	Required for safe use, installation and maintenance.		
F	Blue, yellow or orange flame picture	Manufacturer's stated that this is a key feature of fires and ideally would like the flame to be similar to natural gas or a colour that can be shown to be equally desirable.		

Table 12: Flame aesthetic considerations for hydrogen appliance variations compared with the natural gas benchmark

3.3 Costs and Timescales

The costs and timescales involved in realising the three domestic hydrogen appliance variations have been categorised into development, production, retail, installation and ancillary work. These are considered separately in this section along with an estimate of how these costs and timescales may evolve towards a mass market.

3.3.1 Development

An estimate of the development costs and timescales associated with the three domestic hydrogen appliance variations is presented in Table 13. In general, the development cost is a reflection of the appliance's complexity with hobs and ovens being the simplest and requiring the lowest development cost, fires in the middle and boilers the most complex and requiring the greatest investment. However, this is complicated by the variation in the sizes of the companies producing the appliances, in particular with hobs, ovens and boilers where there are both small companies with low production volumes and also some very large companies focussing on mass-manufacture:

- Smaller, low volume manufacturers tend to operate with more basic manufacturing techniques that are cheaper to adapt for new products but which lead to higher per unit production costs.
- Larger manufacturers will tend to invest heavily at the outset and develop expensive tooling that can then mass-manufacture new products at low marginal cost.

This has implications for new development as smaller companies may be more able and willing to develop new products on a shorter timeframe.

It is anticipated that both the development of conversions kits for adapting existing natural gas appliances and also the development of dual-fuel appliances would be commenced only once viable new hydrogen appliances have been developed. The development timescale for adapted and dual-fuel appliances is therefore slightly longer than new appliances but the marginal cost should be relatively low. The development cost of dual-fuel appliances is expected to be 10-25% greater than the development of new hydrogen appliances, partly as a result of the additional tests required.

The development timescales for all three options are longer than for typical development times for natural gas products which is a reflection of the performance and safety challenges of operating with hydrogen.

Overall, the appliance manufacturers stated that significant hydrogen appliance development would require diverting resource away from their existing R&D and this will need strong and positive signalling from the government.

Appliance Type (B/F/H/O)	Natural Gas Benchmark	New Hydrogen Appliance	Adapted Appliances	Dual Fuel Appliance
Costs				
B	Current natural gas appliances have been developed incrementally over many years and it is not possible to provide an accurate comparative development cost	£750k (low volume) - £5 million* (high volume)	Difficult to quantify at this stage	Increase of 10-25% from new hydrogen appliance development
F		£250k (low volume) - £450k (high volume)		
H		£200k (low volume) - £1million (high volume)		
O				
Timescales				
ALL	18 months - 2 years	Best: 1.5 years Mid: 2.5 years Worst: 5 years+	Best: 2 years Mid: 3 years Worst: 5 years+	

Table 13: Development costs and timescales associated with the domestic hydrogen appliance variations (*if a new heat exchanger is required this could increase the development cost by up to £20 million).

3.3.2 Production

The costs and timescales associated with producing manufactured units of domestic hydrogen appliances are summarised in Table 14. Production costs are volume sensitive and also dependent on the level of the manufacturing process development undertaken (Section 3.3.1). However, for simplicity the figures presented here are considered to be typical of average industry production rates and development and also based on a relative mature market (similar to the nature gas benchmark).

The production of new and dual-fuel hydrogen appliances is likely to be more expensive and potentially more time consuming than natural gas for a number of reasons:

- They may contain more complex components in order to run on hydrogen (e.g. more expensive flame detection devices for boilers)
- They may require more safety and performance tests prior to dispatch.
- For at least the foreseeable future, they are likely to have to compete with natural gas appliances on the production line. Diversity in production is likely to increase costs and potentially slow manufacture.

The production cost of dual-fuel appliances is dependent on whether the conversion kit is manufactured with the appliance or whether it is produced separately at the point of switchover. For the purpose of this study, the latter has been assumed and the conversion kit has not been included. However, dual-fuel appliances are anticipated to be up to 20% more expensive to produce than new hydrogen appliances as they are likely to require more complex components and increased testing.

For adapted appliances, the production cost of the conversion kit as a proportion of the appliance production cost varies between the appliances. For fires the burner assembly (burner, pilot and sensor) is approximately 50% of the total production cost whilst for boilers the burner and sensor only represent approximately 10-15% of the total appliance cost. For boilers the most expensive component is the heat exchanger and manufacturers would look to maintain this component if at all possible. For hobs and ovens, adaption kits are estimated to be 20-40% of the cost of a new hydrogen appliance.

Ultimately, until the first generation of hydrogen appliances are developed these costs and timescales are considered to be very approximate.

<table>
<tr><th>Appliance Type (B/F/H/O)</th><th>Natural Gas Benchmark</th><th>New Hydrogen Appliance</th><th>Adapted Appliances</th><th>Dual Fuel Appliance</th></tr>
<tr><td colspan="5">Production Cost</td></tr>
<tr><td>B</td><td>£650</td><td rowspan="4">Up to 20% greater than natural gas appliances</td><td>10-15% of new hydrogen appliance</td><td rowspan="4">Up to 20% greater than new hydrogen appliances</td></tr>
<tr><td>F</td><td>£280</td><td>Up to 50% of new hydrogen appliance</td></tr>
<tr><td>H</td><td>£120</td><td>20-40% of new hydrogen appliance</td></tr>
<tr><td>O</td><td>£150</td><td>20-40% of new hydrogen appliance</td></tr>
<tr><td colspan="5">Production Timescale</td></tr>
<tr><td>B</td><td rowspan="4">Less than 1 day</td><td rowspan="4">Up to 20% greater than natural gas appliances</td><td rowspan="4">Currently difficult to quantify</td><td rowspan="4">Up to 20% greater than new hydrogen appliances</td></tr>
<tr><td>F</td></tr>
<tr><td>H</td></tr>
<tr><td>O</td></tr>
</table>

Table 14: Costs and timescales associated with the production of domestic hydrogen appliance variations.

3.3.3 Retail

Typical retail prices of current natural gas appliances are presented in Table 15 along with estimates of the retail prices of the hydrogen appliance options.

In general, the anticipated costs of the development phase are reflected in the retail prices of the hydrogen options. The retail price of new hydrogen appliances and dual-fuel appliances is anticipated to be 10-20% higher than natural gas appliances.

At this stage it is difficult to quantify the retail costs for adapted appliances as this cost may not be burdened by the occupants. However, simple scaling of the production costs may be used as an initial estimate.

Appliance Type (B/F/H/O)	Natural Gas Benchmark	New Hydrogen Appliance	Adapted Appliance	Dual Fuel Appliance
B	£500 - £1000	£550-£1200	Currently difficult to predict the retail price of adapted appliances	£550-£1200
F	£200 - £500	£220-£600		£220-£600
H	£100 - £200	£110-£240		£110-£240
O	£200 - £400	£220-£480		£220-£480

Table 15: Estimated retail costs of the domestic hydrogen appliance variations.

3.3.4 Domestic Installation

Assuming a gas supply already exists and no additional ancillary works are required then the costs and timescales for installing existing natural gas appliances varies from 1 hour for hobs and ovens (approximately £80) to two days for boilers (approximately £1000).

A summary of the costs and timescales associated with installing the hydrogen appliance variations compared with natural gas is presented in Table 16. The installation duration is determined by its complexity. A like-for-like replacement is generally relatively easy to perform as the connections are already in place. Conversely, if the appliance is being installed for the first time, or it has to be relocated, then the installation is more complex and this translates to longer timescales and higher costs.

Installing a new hydrogen appliance or dual-fuel appliance is considered to be similar in complexity to replacing a like-for-like natural gas appliance.

Adapting an installed appliance could be relatively simple if the internal components are accessible and can be easily replaced. It is also easy to imagine some appliances that are integrated into the building structure and for these adaption could be significantly easier than replacement. However, in some instances the appliance itself may be accessible but accessing the relevant components inside may be difficult. In this case, appliance replacement may be more straightforward. Ultimately, the cost and timescale will depend on the particular appliances but it is likely that devices that are difficult to adapt will be highlighted early on and replaced instead of adapted.

Overall, if the appliances need to be moved due to concerns with exhaust emissions (e.g. NO_x) or the potential for hydrogen leakage then this could cause considerable disruption for all options.

Appliance Type (B/F/H/O)	Natural Gas Benchmark	New Hydrogen Appliance	Adapted Appliance	Dual Fuel Appliance
Costs				
B	£500 - £1000.	Similar to the natural gas benchmark	Costs will be appliance specific. Key issues are accessibility, availability of internal space and number of components to change	Similar to the natural gas benchmark
F	£200 - £500.			
H	£80 - £150			
O				

Timescales		
B	1-2 days	As detailed for costs
F/H/O	1-4 hours	

Table 16: Costs and timescales associated with installing the domestic hydrogen appliance variations

3.3.5 Ancillary Works

The ancillary works such as pipework and power cable routing required for domestic gas appliances is generally completed at build stage and retrofitting is rarely performed. For natural gas this typically takes up to a week and costs in the region of £2000. The costs and timescales involved vary with complexity of work, including distance from the meter and access to, and within the property. The complexity of the work is also increased significantly when the dwelling is occupied and furnished.

There are a number of technical challenges associated with using natural gas pipework for hydrogen and this is one of the topics being considered in the BEIS Hydrogen Demonstrator Project. This will consider hydrogen leakage from joints and connections as well as the suitability of different pipe materials. The type of pipework in the domestic environment varies; in modern properties this is generally copper whilst older properties can have cast iron or mild steel pipework.

Currently, the considerations for hydrogen ancillary works are estimated to be similar to those for performing ancillary works retrospectively for natural gas; the complexity and disruption increases with the extent of pipework that requires upgrading. An overview of the expected ancillary costs and timescales is detailed in Table 17.

Appliance Type (B/F/H/O)	Natural Gas Benchmark	New Hydrogen Appliance	Adapted Appliance	Dual Fuel Appliance
Costs				
B	Approx. £2000.	Minimal costs are involved if new regulations allow the current natural gas pipework to be used to deliver hydrogen. Costs equivalent to the natural gas benchmark are expected if the pipework needs to be replaced, or a new supply is required.		
F				
H				
O				
Timescales				
B	2 – 5 days	As detailed for costs.		
F				
H				
O				

Table 17: Costs and timescales associated with the ancillary works for hydrogen appliances compared with natural gas.

3.4 Summary of Appliance Options Review

The general view of the industry is that the development of domestic hydrogen appliances would be led by new hydrogen only appliances and adaption and dual-fuel options would only be developed on the back of these.

For new hydrogen appliances, manufacturers stated that they would aim to match the key attributes of existing natural gas appliances. Given the opportunity to develop a specific hydrogen appliance from scratch they consider this generally could be achieved. In their view, reductions to the lifetime, reliability and efficiency as well as compromises in size and appearance would be undesirable for consumers and new hydrogen appliances would need to match or better the performance of existing natural gas appliances in order to be accepted.

Adapting appliances offers the key advantage over new hydrogen and dual-fuel appliances that the cost is only burdened if the switchover to hydrogen occurs during the lifetime of the appliance. Adapted appliances will most likely deliver reduced performance compared to new hydrogen appliance as they will not be optimised specifically for hydrogen. The increasingly stringent regulations on efficiency and NO_x may be challenging to meet for adapted appliances and this may require some concessions.

Dual-fuel appliances offer the benefits in reliability and lifetime that come with a new appliance, but should be significantly easier to switchover than adapting current natural gas appliances. The current view of the manufacturers is that they should be able to offer similar performance to new hydrogen appliances and if this is found to be the case, dual-fuel appliances may offer an attractive compromise between rolling out hydrogen only appliances and adapting current natural gas appliances which both present challenges for switchover.

Given the limited state of development of domestic hydrogen appliance technology, it is not currently possible to state which of these is preferable from an engineering perspective. In the short term, it is necessary to develop first generation hydrogen appliances and determine solutions to the key technical challenges discussed in Section 2. It will only then be possible to explore where existing components can be used for both natural gas and hydrogen appliances, or where new components are required, and then use this to investigate the feasibility of adaptation and dual-fuel options.

4 Market Development

4.1 Gas Appliance Market

In the UK approximately 84% of households rely on natural gas for their space heating [38, 39, 40]. The total installed base of hobs, ovens, fires and boilers in the UK is presented in Table 18, along with the annual purchases and appliance lifetimes. An indication of the current market demand for the appliances can be obtained by dividing the installed appliance base by the number of annual purchases. For example, for boilers, 21.2M/1.6M/yr =13.3 yr replacement cycle, which is consistent with the notional appliance lifetime and suggests that the boiler market is (albeit very approximately) constant. For fires, the same calculation gives a replacement cycle of 52 years, suggesting that the gas fire market is reducing, perhaps due to competition from electric fires. For hobs and ovens the replacement cycle is 12.7 years, below the lifetime, and suggests that demand for these appliances is slightly increasing.

Gas Appliance Type	Estimated installed appliance base [29]	Appliance purchases/ year	Notional Appliance Lifetime
Boilers	21.2M Appliances	1.6M	10-15 years
Fires	10.4M Appliances	0.2M	20+ years
Hobs	12.7M Cookers	1M	20 years
Ovens			15 years

Table 18: Estimated installed and purchased appliances and typical lifetimes

Case Study, Condensing boilers

Part L1 of the Building Regulations for England & Wales stipulates that gas-fired boilers installed after 1 April 2005 must be condensing boilers, whether they are replacements or new installations. Prior to this date, despite being available since the late 1980s and offering significantly improved efficiency and hence running cost, there was not a significant installed base of condensing boilers.

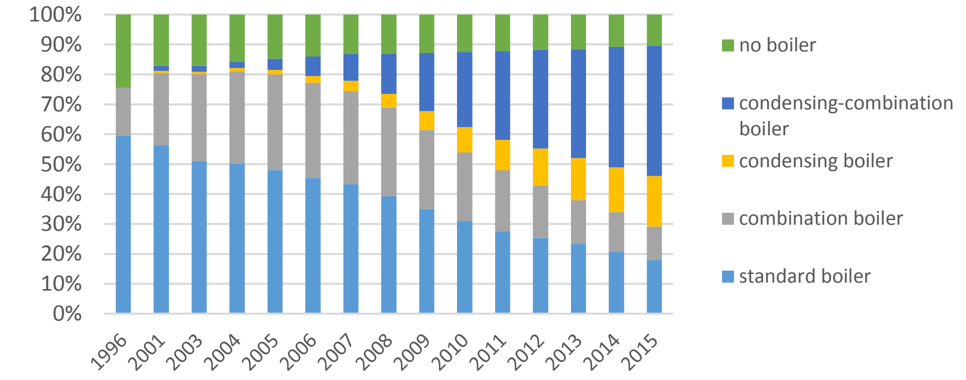

Figure 9: Boiler installed stock, 1996 to 2015, per 2015-16 [38]

The regulatory change in 2005 has had a significant effect on the proportion of condensing boilers. The installed base increased from less than 5% in 2005 to more than 60% in 2015.

The natural gas appliance market has developed over the last fifty or so years based on incremental technical improvements and regulatory change but apart from the town gas conversion in the 1970s there have not been requirements for major change. One of the most significant technical developments has been the introduction of condensing boilers and this is described in the Case Study. Prior to the introduction of regulations for condensing boilers, there had been a very low uptake but this changed significantly following regulation.

In practice, hydrogen appliances present particular technical challenges and direct parallels between condensing boilers and hydrogen appliances are limited. However, the clear success of the policy demonstrates the ability of appliance manufacturers, sales people, purchasers and maintainers to respond to a regulatory driven change so long as they suffer minimal inconvenience, it is clearly signalled and adequate guidance and support is provided.

4.2 Potential Market for Hydrogen Appliances

There are two key mechanisms for innovation:

- Internal (technology-driven) 'push factors', and;
- External (market-driven) 'pull factors'.

Internal factors include an appliance's technical sophistication, manufacturing supply chain, and research base and these have been discussed in the previous sections. Comparison to other industries which manufacture technical products suggests that the research base is less developed than might be expected. The general view from stakeholders suggested that appliance testing is a major part of appliance development and there is less design and optimisation modelling than in some industries. Indeed, a 2008 research thesis was found during the course of this study on the fundamental theory of atmospheric burners used in hobs, ovens and fire [11]. This sought to further the fundamental understanding of how the burners operate even though they have been successfully in use for many years.

Factors affecting the external mechanisms or market pull include regulation, sales volume, customer purchasing decisions and appliance refresh rate. The following sections explore the external factors in more detail.

Enablers for Technology Development

Component level manufacturers appear to have mature relationships with the appliance manufacturers. Where research and development is undertaken, it tends to be at the component level aiming to improve the performance of a component or sensor without affecting the way that it interacts with a wider appliance. The development work undertaken tends to be small incremental iteration of existing components with limited application to 'whole-appliance' level development. An example is that the development of low cost condensing boilers was restricted until reliable fan speed controllers were available.

The industry has an active lobbying, public and media relations community organised through several trade bodies. They serve as a good source of information dissemination and engagement focal points for the wider industry.

Drivers for Technology Development

With the exception of certain premium products, the key drivers for gas appliances and therefore also hydrogen appliances is capital cost. A point made repeatedly by stakeholders was that the majority of domestic appliance purchasing decisions are made on a 'distress' basis. Consumers buy new heating appliances when they are forced through the failure or obsolescence of their existing appliance. This means that, for the majority of customers, the most important differentiator between different heating appliances is capital cost; other features such as efficiency, reliability, flexibility or usability are minor considerations in any purchase. At the bottom end of the market in particular, there are significant numbers of ‘badged’ appliances, where a homeware retailer or DIY puts their brand on a generic, mass produced appliance. This feature allows limited differentiation between individual brands and reinforces consumers decision making based on price.

Altering or changing regulation of appliances is a key driver of change within the industry. The condensing boiler case study demonstrates that the market responds to changes in regulation and prompts the technical innovation required to improve efficiency and achieve NO_x targets. The level of regulatory change required to enable a hydrogen economy is obviously much more comprehensive with all elements of the gas transmission and distribution system affected. However, the systemic structural change must be driven from a systematic regulatory change with alignment between the different areas and a clear roadmap on the ultimate objectives.

Inhibitors for Technology Development

Treatment of Intellectual Property (IP) and how it may act as an inhibitor to collaborative working was not raised by many of the interviewees. This may reflect the lack of experience of running new technology development programmes and means that the IP considerations may come into development later on.

There is widely held understanding that the transition to using hydrogen as a source of fuel within domestic homes requires a whole system change. However organisations within the industry are unclear about the timeline for such a change and also about how certain it is to occur.

Barriers for Technology Development

A number of stakeholders contrasted the attitude of appliance purchasers in the UK with the situation in continental Europe, where ‘investing’ capital in appliance upgrades to gain the benefits of fuel efficiency is seen as a driving factor for customer purchases and therefore technology development.

The research undertaken suggests that there is currently a funding gap for the development of novel or revolutionary domestic gas devices. The existing research and development relationships within the industry should be sufficient to achieve component development. They will drive development through from TRL1 to 3 establishing the theoretical and practical technical considerations. The hydrogen projects that have been conducted and are planned (Oban and Leeds H21 projects etc.) will accomplish actual technology testing and demonstration i.e. TRL7-9.

Funding should therefore focus on the current innovation funding gap within the sector, TRL 4-7: the integration, development and testing of whole device mock-ups and prototypes. It is envisaged that the BEIS Hydrogen Demonstrator Project will go a long way to achieving this. However, it is important that the fundamental technical challenges raised in this study (e.g. combustion system, flame colouration etc.) are addressed as these will underpin the development of appliance development.

Development funding could also assist manufacturers hedge the risk from competing technologies such as electrical heating. For boilers, there is a large installed base and currently a lack of cost-effective competing technologies. Consequently, in the event that the grid is converted to hydrogen the opportunities for boiler heating are good. However, for hobs, ovens and fires there is a real threat from electric appliances that are widely available and in many cases (capital) cost attractive. If hydrogen appliances are less attractive, reliable, effective or more expensive than current natural gas appliances there is a risk that consumers will switch and manufacturers may not recoup their development cost.

4.3 Intervention

As the condensing boiler case study demonstrates, governmental intervention has been necessary in the past and, given the lack of either significant industry push or customer pull, is likely to be essential in the future if new hydrogen appliances are to be developed. Overall, the following proposals have been identified

- **Enthusiasm Towards Hydrogen Across Different Appliances Types:** The enthusiasm towards hydrogen development varies significantly between the four appliance types and BEIS needs to ensure that their approach is designed to take forward the whole gas appliance industry. In the UK there is a large competitive market for boilers and manufacturers may see hydrogen as a way to innovate. On the other hand, fires are a significantly smaller industry than boilers and manufacturers are deeply worried about the aesthetics of hydrogen flames. Hobs and ovens are typically developed by large international organisations who would be prepared to innovate in hydrogen but only if other countries are following suit in 100% hydrogen option, rather than say blended hydrogen.

- **Whole System View:** None of the stakeholders engaged during this study has the ability to drive the system wide changes required to enable and exploit domestic hydrogen appliances, connected to a 100% hydrogen gas grid. The market is not going to deliver this transition on its own; it will need significant regulatory and legislative help and guidance in order to achieve decarbonisation.

  BEIS are currently the only organisation with a systemic view of the whole industry (gas transfer and storage, transmission, distribution and consumption) and therefore the only organisation who can coordinate the system wide transformation required for a hydrogen grid. The work being undertaken by Ofgem and the Institution of Engineering and Technology to promote the concept of future system architecture for the electricity transmission and distribution industry might form a useful template for this role.

- **Target Funding to Close the Innovation Gap:** It is clear from the engagement that industry representatives believe that additional funding will be required in order to encourage the development of the first generation of domestic hydrogen appliances. Sections 2.3 and 2.4 outline the nature of the funding gap that needs to be closed and this is illustrated in Figure 10.

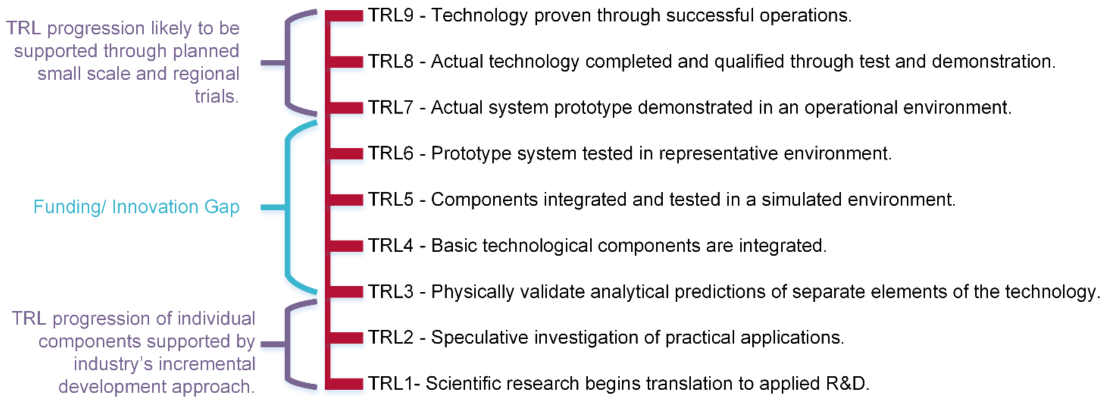

Figure 10: Technology Readiness Level (TRL) highlighting the funding gaps in R&D.

The interviewees were particularly keen on funding streams which would encourage collaboration between different parties within the industry.

- **Provide a Roadmap:** A consistent theme during discussions with the manufacturing community was their lack of certainty about the development of the whole hydrogen sector. Appliance manufacturers, their suppliers and representatives are not going to take significant steps or make investments in new plant and processes until they are convinced that a market for the new products exists. The interviewees consistently requested a reduction in uncertainty in this area through a clear, early and consistent signalling of the government's intentions for the de-carbonisation of heat.

  BEIS have commissioned a number of roadmaps and studies into the whole system transformation which would be required to enable the hydrogen economy.

5 Conclusions and Recommendations

The combustion characteristics of hydrogen present a number of engineering challenges for domestic appliances. For all four appliances considered in this study, hobs, ovens, fires and boilers, the burner and combustion system is a key concern, both in safety and performance and this will require further R&D. Other components will require redevelopment based on the different combustion characteristics of hydrogen but it is envisaged that fundamental principles of these components will remain the same.

Overall, manufacturers stated that they would strive to develop new hydrogen specific appliances that offer similar performance to existing natural gas appliances. This includes appliance efficiency, lifetime, maintenance requirements as well as size and ease of use.

Adapting existing natural gas appliances to hydrogen is possible although it is uncertain whether a conversion kit for the burner can be developed that is sufficiently universal to fit different product variations. It is likely that the performance of these appliances will be reduced when running on hydrogen as many of the remaining components will not be optimised for hydrogen.

Dual-fuel appliances that can interchange between natural gas and hydrogen without the need to replace components are not considered practical. However, in the context of a single gas changeover, Hydrogen Ready dual-fuel appliances may be appropriate. By designing the appliances with hydrogen in mind, they should share many of the performance attributes with new hydrogen appliances but could be designed to facilitate a smooth switchover. In principle, these could offer an attractive compromise between rolling out hydrogen only appliances and adapting current natural gas appliances which will both have huge challenges at the point of gas changeover.

Ultimately, however, before there can be any significant consensus on the appliance options, it is important to address the fundamental technical questions raised in this study:

- Burner technology;
- Flame colouration;
- Cooking performance;
- Flame sensors;
- Pipework.

For hydrogen appliances to be realised, government intervention will be required. In the short to medium term it will be necessary to bridge the innovation gap in order to develop the first generation of hydrogen appliances and it is envisaged that the Hydrogen Demonstrator Project will go a long way to progressing this. However, it is important for the industry that there is progress on the fundamental technical areas highlighted as this will ultimately be needed to underpin hydrogen appliance development.

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A1 Product Standards for Domestic Natural Gas Appliances

Appliance	Reference	Title	Category
Cookers (hobs and ovens)	BS EN 30-1-1:2008+A3:2013	Domestic cooking appliances burning gas.	Cooking ranges, working tables, ovens and similar appliances
Boilers	BS EN 15502-1:2012+A1:2015	Gas-fired heating boilers. General requirements and tests	Boilers and heat exchangers Central heating
Fires and Space Heating	BS EN 613:2001	Independent gas-fired convection heaters	Heaters. Gas
	BS EN 509:2000	Specification for decorative fuel effect gas appliances	Installations in buildings Heaters. Gas
	BS EN 14829:2007	Independent gas-fired flueless space heaters for nominal heat input not exceeding 6 kW	Heaters. Gas
	BS EN 14438:2006	Gas-fired insets for heating more than one room	Heaters. Gas
	BS EN 13278:2013	Open fronted gas-fired independent space heaters	Heaters. Gas
	BS EN 1266:2002	Independent gas-fired convection heaters incorporating a fan to assist transportation of combustion air and/or flue gases	Heaters. Gas
	BS 7977-2:2003	Specification for safety and rational use of energy of domestic gas appliances. Combined appliances. Gas fire/back boiler	Central heating Water heating Heaters, Gas
	BS 7977-1:2009+A1:2013	Specification for safety and rational use of energy of domestic gas appliances. Radiant/convectors	Heaters. Gas
	BS EN 1266:2002	Independent gas-fired convection heaters incorporating a fan to assist transportation of combustion air and/or flue gases	Heaters. Gas
	BSEN1266 : 2002	Independent gas-fired convection heaters incorporating a fan to assist transportation of combustion air and/or flue gases	Heaters. Gas
	BSEN509 : 2000	Decorative fuel-effect gas appliances	Heaters. Gas

A2 Confidence and Sensitivity Assessment, Assumptions Log and Data Limitations

Confidence and Sensitivity Assessment

The stakeholders consulted in the study had a significant background in natural gas appliances but many have had limited active involvement in hydrogen appliance development. Consequently, their input has been primarily based on their technical background in natural gas appliance development, theoretical knowledge of the physical characteristics of hydrogen and in some cases the conversion of appliances between natural gas and other fuels (propane, LNG and town gas). Their input generally therefore comprised expectations based on their professional judgement and were keen to emphasise that this has not been underpinned by detailed analysis or testing.

For the appliance options considered in this study, the information provided on the performance, practical considerations and development timescales and costs has largely been qualitative but comparisons between the options have been provided and where possible, natural gas examples have been used to benchmark the information. Furthermore, where possible bounds have been provided on the evidence to give some indication of the level of certainty and sensitivity to external factors.

Given the lack of market ready appliances available, it is judged that the level of detail provided is appropriate.

Data Limitations

There have been a number of limitations in the data collected as part of the stakeholder engagement and these are summarised as follows:

- The information collected has been based on multiple, consolidated opinions with expertise in natural gas appliances but little or no direct involvement with hydrogen appliances. As a result it should be considered to be semi-qualitative.
- The stakeholder engagement profile was biased towards boiler manufacturers which represents the largest portion of gas appliance. Hobs, and ovens are particularly underrepresented.
- Stakeholders were not asked to share commercially sensitive information.
- The industry is not used to innovation or radical change and therefore has limited experience to draw from.

Assumptions

This study has involved the following assumptions:

- It has been limited to the production of heat from conventional combustion and has not considered fuel cells or other technologies.
- The analysis has concentrated on a hydrogen concentration of 100%. The feasibility of using hydrogen in lower concentrations blended with natural gas has not been considered.

- Only domestic appliances have been considered. Industrial and commercial combustion appliances have been omitted from this present study.
- Furthermore, only hobs, ovens, fire and boilers have been considered. It is acknowledged that there are other domestic appliances that operate on gas (water heaters and tumble dryers) but these have not been included. It is envisaged that many of the technical issues raised in the report are, however, relevant to these other appliances.
- There are significant variations in the design and makeup of domestic gas appliances. Even within one appliance type, there are variations in current commercially available appliances and even greater in the variation in the makeup of the existing stock in current in domestic installations. The approach presented here is based on typical modern appliances that are most widely available. In particular, non-condensing (atmospheric combustion) boilers would not be considered for adaption or conversion as they are considered obsolete.
- The energy market for domestic natural gas appliances is assumed to stay relatively constant in the short to medium term (up to 2030). The impact of radical changes in the market such as electric heating or heat pumps has not been considered.

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