Report for:

DECC Desk study on the development of a hydrogen-fired appliance supply chain

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DECC Desk study on the development of a hydrogen-fired appliance supply chain

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1 Executive Summary

In order to meet international commitments on CO_2 emissions, the UK will need to decarbonise the supply of heat and electricity. Decarbonising heating is substantially more difficult than decarbonising the electricity grid. One option that is attracting significant interest is adoption of hydrogen as a replacement energy vector for natural gas. The use of hydrogen would require the development of a range of hydrogen-fired domestic appliances such as boilers, cookers, hobs, and fires as well as equipment used by industrial, public and commercial operations.

The overall aim of this study was to understand the technical challenges and costs of developing gas appliances to operate using 100% hydrogen, rather than natural gas, and to understand how these barriers might be addressed.

All gas-fired equipment is designed and built for a particular gas specification which includes the range of gas qualities within which the appliance will function correctly. Supply of gases outside this range can lead to problems ranging from poor quality combustion through to equipment damage and ultimately dangerous operation. Therefore, it is essential to ensure that hydrogen fuelled appliances and equipment are designed to function safely and effectively and are tested and certified by independent bodies as is the case with current gas appliances.

This study included a review of the available information about technologies for using hydrogen to supply heat, primarily in domestic settings but also at larger scale in the industrial, public and commercial sectors.

Stakeholder engagement was undertaken with a range of appliance manufacturers and trade bodies.

This report is based on the information collected through these activities. The whole review is included as an appendix.

This report details:

1. **Estimated costs and timescales for manufacture of suitable household and commercial appliances:**

   There is some uncertainty about estimated costs for hydrogen appliances. This is partly due to the new components and materials required, and the fact that some design features are not yet known. However, estimated costs for manufacturing domestic and commercial appliances and fuel cells are presented in Section 6.5. Costings for the catering industry were not available for this report. Catalytic combustion (where the hydrogen is oxidised at low temperature on the surface of a catalyst) has the potential to effectively eliminate NO_x emissions from hydrogen appliances. Whilst catalytic combustion is discussed in the report, most manufacturers assume conventional flame combustion will remain dominant. This is due to the fact that conventional combustion requires simpler burner designs and materials of construction are less costly.

   Discussion on scaling up / manufacturing focused on different manufacturing 'steps' i.e. 1000, 10,000 and 100,000 units. Most UK boiler manufacturers have facilities to scale production up to 100,000 units given that hydrogen appliances could be incorporated into existing production facilities, which have capacity in line with the current UK heating appliance demand. Manufacturers agree that although facilities exist to scale up hydrogen appliance production there may be bottlenecks in the supply of components. High demand / competition for R&D capacity and skills were also regarded as an area of potential concern in scaling up production.

   The timeline for developing hydrogen-fired boilers is dependent on the number of units manufactured. Incorporating a product line of 100,000 units is estimated to take up to 4 to 7 years with the first 1,000 units ready within 2 to 4 years from project start. Product designs would be complete in the lead up to the production of the first batches i.e. comprising the first 2-3 years of the project. Capital costs for the first 1000 units were estimated at four times the cost of equivalent natural gas fired appliances. This could fall to 1.5 times natural gas appliances when production was increased to 100,000 units.

According to fuel cell manufacturers, the technology for using hydrogen in fuel cell appliances is already available with a supply chain generally present for the necessary product components. The majority of components are off-the-shelf and all components outside of the stack already exist at scale. It is estimated that approximately 1-2 years will be necessary for product design, safety architecture and compliance modifications. For scaling stack production, however, additional facilities will need to be built, further details on timescales relating to scale up production are presented in Section 6.5.

2. **An assessment of controllability, usability and aesthetic design (where applicable):**

Most manufacturers agreed that hydrogen as a fuel does not in itself present any problems that prevent the development of safe and efficient appliances. However, it was acknowledged that a range of potential technical challenges existed, mainly relating to differences in the physical and chemical characteristics between natural gas and hydrogen. However, there was common consensus that all these issues could be resolved through redesign, research and development and thorough testing. Some of the challenges raised included higher flame temperature, visibility, odourisation, gas purity and burner design.

Fuel cell manufacturers also agreed that fuel cells will be able to function safely on hydrogen and that there is nothing inherently unsafe in using hydrogen when compared with natural gas, however they emphasised that careful consideration is required if odourants are employed.

3. **The steps required to develop safety standards and training:**

The current complexity of the gas industry is such that these require some consideration. It was agreed that a key aspect for the development of a supply chain for hydrogen-fired appliances is the availability of standards covering:

- Device safety and design;
- Device installation;
- Gas composition e.g. % purity, ppm CO, ppm sulphur, odourant etc.

For the UK, gas supply standards are maintained by the individual GNO's (usually with reference to IGEM standards, whose technical rigour is accepted by the HSE and Gas-Safe). IGEM has been identified as an appropriate organisation to deal with this requirement through the extension of existing standards to cover gases comprising >99% hydrogen. However, whilst IGEM as a recognised industry body could perform this task, some independence from and significant support by the UK gas industry would be required.

It was recognised that current codes of practice and installer training and certification do not deal with hydrogen appliances. This will need to be addressed to facilitate the deployment of hydrogen appliances in domestic and commercial settings. However, engineers and fitters working in the chemical process industries already have experience of dealing with hydrogen equipment and systems, and many of the pipe standards already contain reference to Town Gas, which can be up to 65%v/v hydrogen[1]. In the short term hydrogen appliances can be CE marked and thus placed on the market today using the generic safety requirements contained with the Gas Appliance Regulations.

4. **The barriers to development and measures to reduce or overcome these barriers:**

Key technical and market barriers have been identified and are presented together with comments and mitigations in Section 8. No barriers found were considered insuperable. In summary:

- The majority of technical barriers raised by boiler manufacturers are likely to be resolved through a comprehensive research and development programme leading to redesign and the use of new components and materials suitable for use with hydrogen. By way of example however a hydrogen

[1] http://www.citygas.com.sg/pdf/City_Gas_Handbook_on_Gas_Supply_Nov13.pdf

combi boiler is expected to look like, and operate very similarly to an existing combi boiler. Manufacturers agree that thorough testing and approval procedures are essential in bringing safe products to market.

- Fuel cell manufacturers did not see any fundamental technical barriers to development although increasing stack lifetime should be an R&D priority going forward. However, a barrier to large-scale deployment is importantly cost which in turn relates to technology development, field trials, scale of production and data collection. It was also recognised that until the technology is fit for purpose many of these issues cannot easily be resolved.

In the view of the manufacturers interviewed, the single most important factor in the development of the hydrogen appliance market is an agreed and signed off plan for the local deployment of bulk pipeline hydrogen through the existing NG network. One suggestion by manufacturers was that the bulk of these appliances would be purchased by the converting organisation, in which case, it would be necessary for the contractual approach to be carefully considered to ensure the development of a competitive hydrogen appliance industry. Market barriers for all technologies will be challenging, and considerable investment and commitment will be required to establish the required infrastructure and engineering capacity. Market requirements must be understood in order to meet consumer and policymaker needs and financing mechanisms for appliance development / conversion and roll-out must be established. Management of timescales in preparing standards / codes of practice and training for installation and maintenance personnel are essential and must be co-ordinated to allow timely roll-out of products.

2 Glossary

Term	Description
H_2	*Hydrogen*
CO_2	*Carbon Dioxide*
CO	*Carbon Monoxide*
NO_x	*Nitrogen Oxides*
LPG	*Liquefied Petroleum Gas*
LNG	*Liquefied Natural Gas*
mCHP	*Micro Combined Heat and Power*
GAD	*Gas Appliance Directive*
GT	*Gas Turbine*
CCS	*Caron Capture and Storage*
IGCC	*Integrated Gasification Combined Cycle*
DHW	*Domestic Hot Water*
HICE	*Hydrogen Internal Combustion Engine*
PEMFC	*Proton Exchange Membrane Fuel Cell*
SOFC	*Solid Oxide Fuel Cell*
kW	*Kilo Watts*
MW	*Mega Watts*
m/s	*Meters per Second*
°C	*Degrees Centigrade*
Hz	*Hertz*
Nm^3	*Volume at Normal Temperature and Pressure (293.15 K, and 1 atm or 101.325 kPa)*
15/15	*Denotes ISO standard reference conditions of 15 °C (288,15 K) and 1013,25 mbar (101,325 kPa)*
Calorific value or CV	*The amount of heat energy released by combustion of a fuel*
Heating value	*Synonym of CV*
%v/v	*Volume percent*
IGEM	*Institute of Gas Engineers and Managers*
OEM	*Original equipment manufacturer*

Term	Description
light-back	*See 'flashback'*
flashback	*The flame burns back into the equipment or supply line, also referred to as 'lightback'.*
flashback arrestor	*Gas safety device to stop the flame burning back into the equipment or supply line, also known as 'flash arrestors'*
deflagration	*subsonic flame propagating by heat transfer; hot burning material heats the next layer of cold material and it ignites*
detonation	*flame propagation involving a supersonic exothermic front accelerating through a medium that eventually produces a shock front propagating in front of it*
stoichiometric	*amounts of reactants match exactly – so that they are entirely consumed if the reaction is completed, in the case of combustion this means the amount of oxygen (air) available is just sufficient for all the fuel to burn completely*
flame speed	*the measured rate of expansion of the flame front in a combustion reaction*
auto-ignition	*the ignition of fuel without the need for an external ignition source such as a spark. It occurs at specific temperatures for ignitable fuel:air mixtures and this is the 'auto-ignition temperature'.*
fuel mixture	*A description of the amount of air mixed with the fuel. Richer mixtures contain higher proportions of fuel and leaner mixtures higher proportions of air. These terms are relative and qualitative.*
Pt	*platinum*

3 Background and scope

Decarbonising heating is substantially more difficult than decarbonising the electricity grid.

One option that is attracting significant interest is adoption of hydrogen as a replacement energy vector for natural gas. A number of projects are being undertaken supported by various interested parties.

H21 Leeds City Gate Project (Northern Gas Networks)
An engineering study investigating the conversion of Leeds to 100% hydrogen has been undertaken concentrating on the potential practicalities and costs of replacing the current natural gas supplies to Leeds with hydrogen. This is due for publication July 2016.
Repurposing the Gas Networks (Energy Networks Association)
The ENA - Gas Futures Group have placed a contract with KPMG to investigate the relative economics and practicalities for the whole of the UK meeting its 2050 climate change obligations (80% reduction from 1990) by investigating four routes: 1) Greening the gas - The conversion of much of the gas network to hydrogen with supporting biogas in rural areas; 2) Prosumer - The adoption of radical carbon reduction programmes by individuals and companies; 3) A patch-work of low carbon District heating, natural gas and other low carbon technology according to local decision; 4) Conversion of the UK to an all-electric energy supply chain. The report (scheduled for publication in spring 2016) will be useful for comparing costs on a comparative basis.
Scenarios for deployment of hydrogen in contributing to meeting carbon budgets and the 2050 target (Climate Change Committee)
E4tech, UCL and Kiwa Gastec carried out a study for the Committee on Climate Change[2]. This work examines the potential role of hydrogen in two scenarios: Critical Path and Full Contribution. In the former, hydrogen makes a significant contribution to decarbonisation in 2050 but is not dominant, while in the latter, hydrogen makes a central contribution to meeting 2050 targets. Both scenarios examine hydrogen in the transport sector. The Full Contribution scenario also considers its use as a more general low-carbon replacement for natural gas across the economy.
Hydrogen Roadmap (Innovate UK / DECC / SHFCA / UKHFCA)
This project will pull together the major themes that will enable the UK to maximise economic and social benefit from hydrogen. The desired outcome of this work is to drive sustainable economic growth in the UK hydrogen and fuel cell industry in the period to 2025 and beyond[3].

[2] Committee on Climate Change – "Scenarios for deployment of hydrogen in contributing to meeting carbon budgets and the 2050 target", Final Report, October 2015

[3] Hydrogen and Fuel Cell Roadmapping Exercise, Draft Scope of Works

Repurposing parts of the gas grid to use hydrogen, instead of natural gas would require the development of a range of hydrogen-fired appliances such as boilers, cookers, hobs and fires as well as equipment used by industrial, public and commercial operations.

The overall aim of this study was to understand the technical challenges and costs of developing gas appliances to operate using 100% hydrogen, rather than natural gas, and to understand how these barriers might be addressed. Outputs from this study will be used:

- to support DECC's consideration of the long-term challenges of heat decarbonisation;
- to complement the small town desk study, currently in progress;
- to understand the costs of undertaking a large scale hydrogen trial.

Kiwa, in partnership with E4tech provided the technical knowledge and gas appliance market experience along with in-depth understanding in the developing hydrogen technology space to undertake this study. Each organisation has an extensive network of relevant established industry contacts.

Within the study, a range of appliance types were investigated which included:

- Domestic boilers / cookers;
- Commercial catering appliances;
- Commercial systems (burners);
- Fuel cell systems.

The evidence review of the potential hydrogen appliance and equipment space is provided as Appendix 10.1.

In addition to the specific requirements for particular types of appliance, more general issues such as the hydrogen composition and quality supplied (for example the impact of odourisation chemicals and impurities on appliances) and combustion characteristics (flame visibility for domestic appliances) were considered.

This report contains:

1. Estimated costs and timescales for manufacture of suitable household and commercial appliances;
2. An assessment of controllability, usability and aesthetic design (where applicable);
3. The steps required to develop safety standards and training. The current complexity of the gas industry is such that these require some consideration;
4. The barriers to development and measures to reduce or overcome these barriers.

4 Hydrogen Properties, Safety, and Combustion

4.1 Technical Perspective

Whilst considering hydrogen as a potential energy vector for the future, alongside electricity, the main focus of programmes looking at this transition is on development of transportation and fuel cell technology. However, to enable a complete change from supplying natural gas to supplying hydrogen in a locality it will be essential for direct replacement appliances and equipment of a much wider range of types to be available.

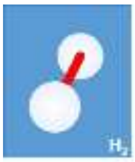
(Note: Germany has introduced hydrogen at low concentrations (up to 3%v/v or 1% by energy) into natural gas but this has been carried out to manage the production of excess windpower. This is a different driver to the direct reduction of point of use carbon emissions.)

Variations in quality of natural gas supplied appliances are already a subject of concern for gas suppliers and equipment manufacturers. British Petroleum and their partners have provided a useful guide dealing with this issue[4]. In this they note that “All gas-fired equipment is designed and built for a particular gas specification. This will include a range of gas qualities within which the appliance will function correctly. If gases outside this range are combusted, this can lead to a range of problems from poor quality combustion through to equipment damage and ultimately dangerous operation.” Therefore, it is essential to ensure that hydrogen fuelled appliances and equipment are designed to function safely and effectively and are tested and certified by independent bodies as is currently the case with natural gas appliances.

Hydrogen is already used in various industries; petroleum refining, aerospace applications, pharmaceuticals, petrochemical manufacturing, and the food and semiconductor industries. Hydrogen is also used in fertilizer production, for glass purification, in welding, and in power generators. However, the use of hydrogen as a fuel is less common.

4.1.1 Physical Properties of Hydrogen

At ambient conditions, hydrogen is a diatomic gas with a low density of 0.083kg/Nm^3 (approximately 11% of that for natural gas) compared to 1.25kg/Nm^3 for air.



It is the lightest element and in air, its buoyancy causes it to rise and disperse rapidly (at speeds of almost 20m/s). Hydrogen’s high diffusivity when compared to natural gas has two important effects:

1. Greater ability to permeate through materials and joints, although the actual rate of diffusion through pipes is very small. Calculations have shown that the yearly loss of hydrogen by leakage amounts to approximately 0.0005–0.001% of the totally transported volume[5]. Leaks from orifices will have approximately the same energy leakage rate as natural gas, but will be about three times volume;

2. Leaks will disperse more quickly.

[4] BP, & International Gas Union. (2011). Guidebook to Gas Interchangeability and Gas Quality. Retrieved from http://www.igu.org/igu-publications-2010/Guidebook to Gas Interchangeability and Gas Quality 23Aug10.pdf

[5] Division of Energy Conversion, University of Leuven (K.U. Leuven), Celestijnenlaan 300A, 3001 Leuven, Belgium

Hydrogen's low molecular weight results in it having the highest energy content per unit mass of any fuel but its low density means that its volumetric energy content is relatively low. When burned, hydrogen releases only one third as much energy per unit volume of gas as natural gas at the same pressure.

Hydrogen is not detectable by human senses as it is:

- Odourless
- Tasteless
- Colourless

It is also:

- Nontoxic
- Noncorrosive

No smoke is produced when hydrogen is burned in air, and because there is no carbon in the fuel, no CO or CO_2 are produced. Its pale blue flame is difficult to see, being barely visible in daylight. The combustion products are water vapour and some nitrogen oxides (NOx). The amount and type of NOx produced depends mainly on the flame temperatures. NOx formation and regulations are discussed in the literature review (Appendix 10.1).

Hydrogen flame temperatures are comparable to those of other common fuels, but hydrogen flames radiate less heat and are thus less likely to start secondary fires.

The properties of hydrogen and its flames present several specific issues with regards to its supply to and use in equipment or appliances:

- Detection of leaks: Odourisation of the supply for safety reasons and implications for such technologies as fuel cells;
- Detection of flames: Flame visibility issues for domestic appliances such as cooker hobs, flame detectability as used in control systems in modern gas fired boilers;
- Emissions:
    - Impacts of high levels of water vapour in flames on processes such as baking.
    - Need to control NOx emissions to meet current and impending regulations;
- Gas quality: Technological (equipment or appliances) fuel purity requirement i.e. 99.5% H_2 vs 99.9% H_2 vs 99.999% H_2.

4.1.2 The Wobbe Index

The Wobbe Index (WI) of a gas can be a convenient indicator of its interchangeability with other fuel gases.

$$WI = \frac{Volumetric\ calorific\ value\ (MJ/Nm^3)}{\sqrt{gas\ relative\ density (kg/m^3)}}$$

Currently, the acceptable WI range[6] for natural gas supplied for appliances in the UK is >47.20 and <51.41MJ/Nm^3. Relative to natural gas, hydrogen has about 1/3rd of the CV and about 1/8th of the density. These differences are largely cancelled out in the WI calculation and the WI of hydrogen is about 46MJ/Nm^3 (15/15).

This similarity in WI implies that hydrogen could be burnt in conventional natural gas appliances without modification. However, relative to natural gas, hydrogen has a much higher flame speed and its flames have much lower emissivity. So, it is likely that modifications to appliance designs would be required to enable safe and effective use with hydrogen, although there is some anecdotal evidence that boilers designed for natural gas have been successfully fired using hydrogen without modification.

The similarity in WI for natural gas and hydrogen means that the energy transportation properties of these gases are broadly similar but to store equivalent amounts of energy to that currently held in natural gas stores would require tripling of either storage volumes or pressures (or some combination of this). However, there are some

[6] Gas Safety (Management) Regulations 1996 (GSMR) units

other alternatives under development, which may to some extent contribute to overcoming this challenge, but these are not discussed in this report.

4.1.3 Energy content

The 'lower heating value' (net CV) is based on the assumption that the latent heat of vaporisation in water vapour produced during combustion is not released whereas the 'higher heating value' (gross CV) represents the total energy in the fuel. Many modern boilers burning natural gas or other hydrogen containing fuels already include the capability to recover heat from this water vapour. This capability will be of greater importance for appliances burning hydrogen alone than for those firing natural gas as the mass of water vapour produced from hydrogen is ~1.6 times that from natural gas. This implies that boilers designed for hydrogen might need to be provided with larger heat transfer surfaces than those for natural gas (possibly up to 10%). It also suggests that hydrogen fired boilers should be operated in 'condensing mode' for as long as possible to ensure that this latent heat is recovered. In practice this limits boiler return temperature to around 50°C, as this will limit the flue gas temperature and ensure that the majority of the latent heat of the steam in the flue gas is recovered by the heating system. However, tests in Germany using forced draft natural gas boilers showed no significant difference between efficiencies with natural gas and with hydrogen[7].

4.2 State of the Art

The overall purpose of this research is to develop an understanding of the technical challenges and costs of developing appliances and equipment to operate using 100% hydrogen, and to identify how these barriers might be overcome.

4.2.1 Review of Available Information

A review of published literature and information was undertaken as the first stage of the research and is summarised in this section. The full review is presented in Appendix 10.1. The objective was to examine the state of the art / market for the following types of appliance:

1. Domestic boilers;
2. Gas cookers;
3. Gas fires;
4. Commercial catering equipment;
5. Pre-mix burners;
6. Fuel cells;
7. Commercial gas burners;
8. Other relevant appliances identified by the review.

For clarity the review separates the considerations into two main parts each of which is divided into several categories:

1. The basic gas conversion technology
    - Non-aerated burners;
    - Aerated burners;
        - Partially pre-mixed
        - Fully pre-mixed
    - Flameless burners, catalytic burners.
    - Fuel cells
    - Internal combustion engines
    - Gas turbine combustor

[7] International Journal of Hydrogen Energy, "Operation of 20 kWth gas-fired heating boilers with hydrogen, natural gas and hydrogen/natural gas mixtures". First test results from phase 1 (March 1993) of the Neunburg vorm Wald solar hydrogen project, K. Hoelzner, A. Szyszka

2. The appliance within which the technology is embodied
    - Boilers
        - Domestic
        - Commercial
        - Industrial
    - Cooking appliances
        - Domestic
        - Commercial
    - Direct space heaters
        - Domestic
        - Commercial
    - Process heaters
    - mCHP

Each of the appliance/ equipment types can be based around one or more of the base technologies. The specific requirements of a particular technology may be different in different applications.

For the purposes of this review, the focus was on products in which these technologies are already or may in the future be embodied into products.

4.2.2 Example Burners and Appliances

This section includes some examples of available hydrogen combustion systems, and is intended as an introduction to offer context. There are only a few appliances / devices available to purchase, this is almost certainly because the market is immature, i.e. there has been very little incentive for manufacturers to develop appliances as the demand has been very low, whilst there is an almost total absence of distributed hydrogen.

In modern boilers the need to have accurate control over the combustion process in order to minimise energy consumption and pollutant formation has resulted in the use of burners where the air supply is positively controlled. So, the burners are in general fully pre-mixed forced/induced draft pressure jet or distributed flame types. Within the limits set by nozzle sizes the positive control approach should simplify the design of new boilers including hydrogen. Currently, boiler models designed for hydrogen firing are few, and the models that are available utilise catalytic burners rather than modified pressure jet or distributed flame technologies. As an example the Italian manufacturer Giacomini has developed a 5kW (nominal heat output) condensing hydrogen boiler that is CE marked and on the market. It employs a catalytic burner with a reaction temperature of between 250°C and 300°C. Figure 1 shows the general appearance of their catalytic burner (~ dimensions 913mm x 520mm x 327mm).

Figure 1. Giacomini hydrogen catalytic boiler (Giacomini, 2011)

Sintered metal fully pre-mixed burners have been adopted by some manufacturers in modern boilers. It is suggested that such burners are likely to present fewer issues for modification to operate with hydrogen, as they are already suitable for surface combustion. Examples of more 'conventional' appliances, such as fully pre-mixed combustion burners (fitted with burner heads or porous materials) are presented in Figure 2. Research studies indicate that designs of this type are less likely to present issues when modified to operate with hydrogen.

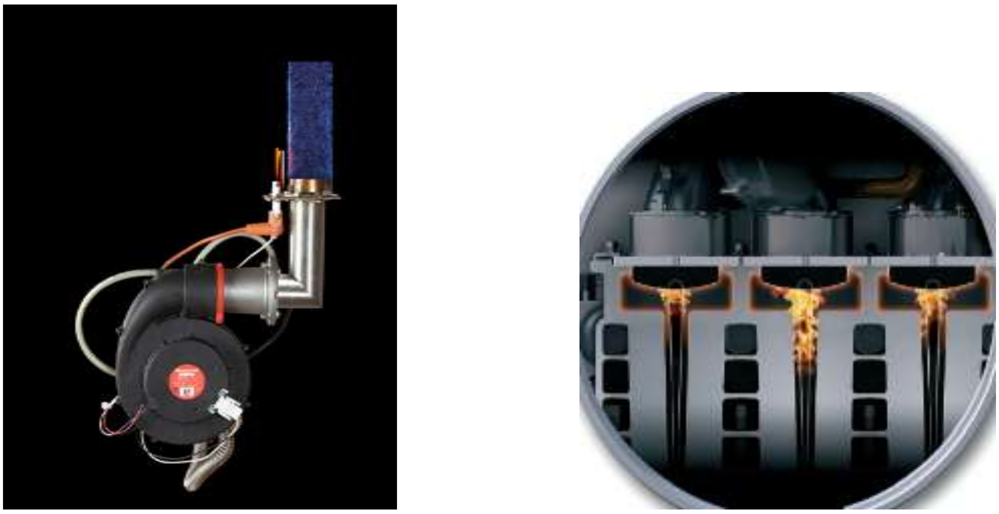


Figure 2. Examples of distributed flame gas burners from Innovative Thermal Systems[8] (left) and Alpha (right)

When looking at the domestic market, a typical radiant appliance used in households is the 'gas fire'. This is available in a variety of types:

- Conventional open fronted flued gas fired (radiant ceramic plaques);
- Fuel effect flued gas fires – glass fronted, or open-fronted;
- Flame effect glass fronted, wall mounted flueless.

In creating flame type radiant heaters for hydrogen, attention to flame visibility is required for both aesthetic and, in the case of open fronted appliances, safety reasons. Simple non-aerated bar burners for hydrogen can be found on the internet which suggests that the basic technology for a flame effect fire is possible. However, significant work may be required to develop a satisfactory visual appearance in use. Typical layouts for a domestic flueless gas fire and heater is shown in Figures 3 and 4.

[8] Innovative Thermal Systems LLC. 24200 Gibson Dr. Warren, MI 48089
T: 586-920-2900, F: 586-510-4708, M +1 519 209 5486
www.innovativethermalsystems.com

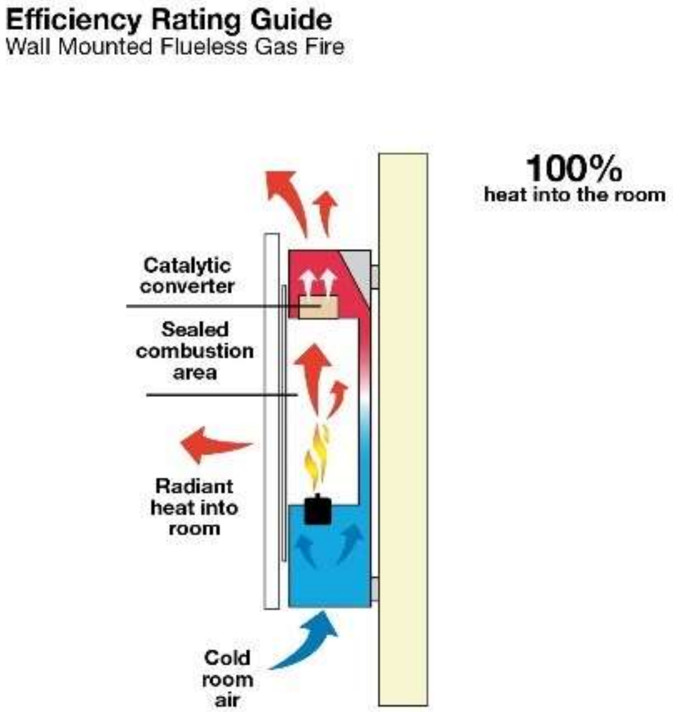


Figure 3. Example of a flueless gas fire layout

The design of simple hydrogen fired domestic heaters can be considered to be relatively simple.

Model #GFH6000 Green Flame Heater Hydrogen fuelled Input 1.3kW to 1.8kW

Figure 4. Example of Hydrogen Heater

Current designs are probably not aesthetically acceptable to many householders, however the UK is Europe's largest manufacturer of decorative gas fires, and there is no reason why a range of attractive gas fires should not be developed relatively quickly. Since many electric decorative fuel effect fires sell well and hydrogen offers the potential of a real flame, hydrogen could be regarded as less of a challenge than natural gas. It has the added benefit over its natural gas counterparts of not being able to produce carbon monoxide.

Conventional hobs are based on some form of partially premixed burner. The relatively intense colouration of the flames means that they are generally sufficiently visible to avoid accidental contact by users, however, this will require further investigation in order to maintain the required level of safety. In addition, there is also a need to ensure that heat input using hydrogen is comparable with natural gas. One example of research in this area is demonstrated by a 'hobbyist' design published in the US for a non-aerated hob burner – Figure 5.

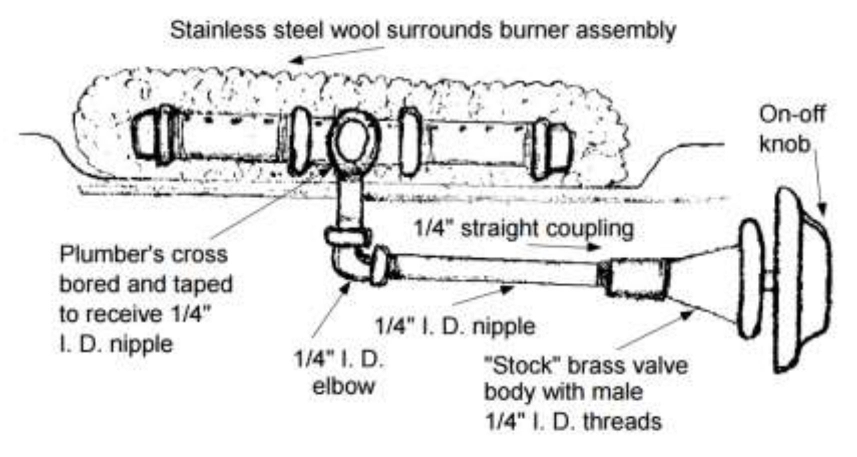


Figure 5. Pure hydrogen burner design without primary or secondary air mixing. (Booth, D. & Pyle, W., 1993)

A new type of catalytic burner based hob has been developed by the Swiss Federal Laboratory for Materials Science and Technology (EMPA). This uses a catalytic hydrogen burner based on a highly porous silicon carbide (SiC) ceramic foam with a platinum catalyst. This catalytic burner is formed from porous SiC plates coated with a platinum catalyst and air is provided so that combustion only occurs in the SiC layers. The burner has been integrated into an appliance by placing in a casing with a glass top to resemble current electrical domestic hotplates. This device also includes a heat exchanger that heats incoming combustion air to improve the product efficiency. This design overcomes any potential concerns about flame visibility. It must be stressed that the above designs of boilers and fires often incorporate catalytic combustion; they are of completely different layout and function to a fuel cell, that may contain catalysts, but in an entirely different configuration.

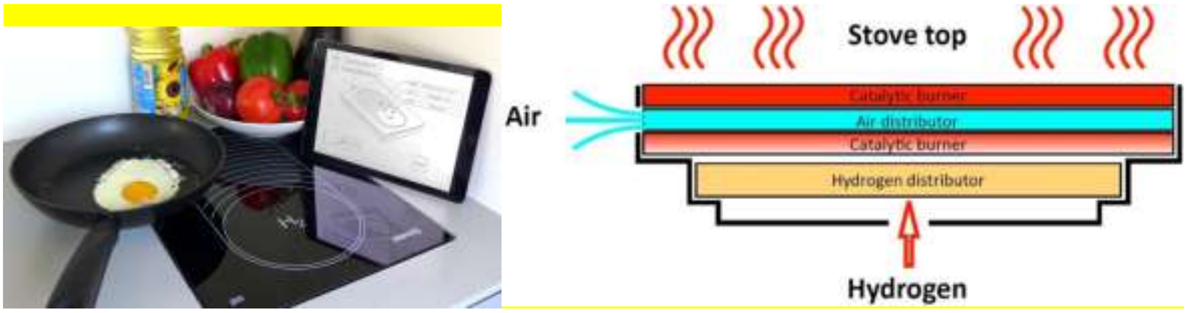


Figure 6. Integrated hydrogen catalytic burner (Ulrich, V. (EMPA), 2015)

In the fuel cell market, hydrogen use in fuel cells has received considerable attention in the wider debate on decarbonisation of heat and transport. This is due to their high efficiencies and low to zero emissions of carbon, particulate matter, and other pollutants such as NOx. Hydrogen is also the 'preferred fuel' for some types of fuel cells as it can decrease component and materials cost compared to natural gas fuel cells.

Fuel cells (Figure 7) convert a fuel and an oxidant directly into electricity (via an electrochemical reaction) without having to go through the thermal combustion and kinetic motion steps of combustion engines and generators. Fuel cells can, in principle, be applied in almost any power-generation and CHP application known, from microwatt-level to megawatt. Different fuel cells can use hydrogen, natural gas, biogas and other fuels, and air as their oxidant. Figure 8 shows an example of a fuel cell plant used for large-scale electricity generation.

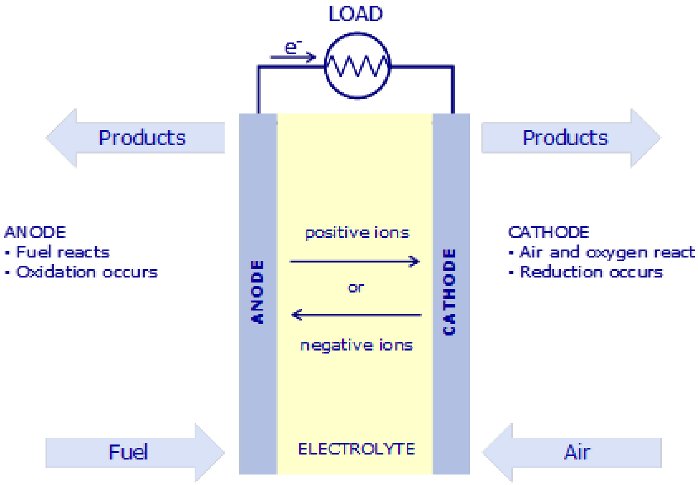


Figure 7. Schematic of Fuel Cell

Figure 8. Fuel Cells Generating Electricity at Large Scale

4.3 Safety

(Tasks 10 and 11)

The safety of a flammable gas in a particular situation and the severity of any fire and / or explosion depends upon the following:

- The concentration of the flammable gas in the air (measured as %v/v) relative to its explosive limits (the gas to air percentage mixtures at which it is explosive) and flammable limits (the gas to air percentage mix at which is it ignitable). This is in turn is a function of the gas's density and diffusivity;
- The speed of any consequential flame front. Higher flame speeds produce higher over-pressures, which are more likely to cause damage. Fires of high concentrations of hydrogen (although difficult to achieve due to its hgh diffusivity and low density) are thus likely to cause more damage than natural gas fires.
- Whether the mixture is enclosed or in free air, and the level of obstruction within the combustion zone;
- The ignition energy of the mixture.

These four principles can never be entirely separated and so out-turn risk can only be assessed quantitatively by considering all four together. These factors must be considered by appliance manufacturers in ensuring safe designs of appliance are created but they are not discussed in detail in this report.

However, it is noted that several studies of hydrogen explosivity have been undertaken. Of particular relevance is the investigation of the implications of small to modest leaks (2 to 64kW) within a domestic setting as might be caused by inadvertently puncturing a gas pipe or a loose pipe fitting. The HyHouse project[9] involved simulating a series of gas leaks within a property at three levels of air tightness to simulate different ages of construction, from aged, to new build. The simulations were carried out at various locations within the building to represent a range of appliances such as a boiler, cooker or gas fire. The leak rates were selected to be representative of those possible within a domestic setting (up to 64kW, the expected capacity for flow limiters where hydrogen is utilised as a fuel gas in dwellings). The movement and dispersion of the gases around the property were investigated, as well as the concentrations achieved at varying leak rates and air tightness rates. This project successfully demonstrated the potential of hydrogen as a safe replacement for natural gas.

Due to the higher flame speed of hydrogen (as discussed above), it has the potential to generate higher overpressures within appliances, especially if ignition is delayed. This phenomenon was well known within large baking ovens when fired with Town Gas. The metal racking upon which the bread tins sit probably enhances flame wrinkling (type of flame turbulence) which in-turn increases flame speed. It is understood that the ETI have carried out work in this area[10] and with modern control systems, solutions should be possible.

4.4 Standards

(Tasks 10 and 11)

A key aspect of the development of a supply chain for hydrogen-fired appliances is the availability of standards covering:

- Device safety and design;
- Device installation;
- Gas composition eg % purity, ppm CO, ppm sulphur, odourant etc.

Standards for gas-fired appliances are currently developed by CEN. These are generally produced in support of European directives and regulations and of relevance in this case is the Gas Appliances Directive (GAD), 2009/142/EC, soon to be replaced with the Gas Appliance Regulations ((EU) 2016/426). In principle this covers appliances burning a wide range of fuel gases, including hydrogen. Whilst very few existing EN standards currently make specific reference to hydrogen, the GAD specifically permits Notified Bodies (in the UK, BSI and Kiwa Gastec) to certify nearly all gaseous fuel appliances against the fundamental requirements of the GAD, so manufacturers can (and have already) brought hydrogen appliances to market. Several standards still contain reference to 1st family gases i.e. fuel gases containing hydrogen as specified in BS EN 437.

The GAD already defines in completely generic format the requirement to demonstrate any gas-fired appliance sold in the EU is safe. This directive already applies equally to hydrogen, town gas, biogas, natural gas, propane or butane. As indicated above it is known that hydrogen, for example, offers a greater risk from delayed ignition and standards will need to be amended to reflect this. If government policy is to encourage the development and use of hydrogen appliances, then this standards work should be started immediately. However, it is stressed that

[9] DECC, Energy Storage Component Research & Feasibility Study Scheme, HyHouse Safety Issues Surrounding Hydrogen as an Energy Storage Vector
(http://www.igem.org.uk/media/361886/final%20report_v13%20for%20publication.pdf)

[10] http://www.eti.co.uk/project/high-hydrogen/

the small number of appliances likely to be sold over the next few years can be assessed against the principles of the GAD.

Current codes of practice and installer training and certification do not deal with hydrogen appliances. This will need to be addressed to facilitate the deployment of hydrogen appliances in domestic and commercial settings. However, engineers and fitters working in the chemical process industries already have experience of dealing with hydrogen equipment and systems, and many of the pipe standards already contain reference to Town Gas, which can be up to 65%v/v hydrogen.

For the UK, gas supply standards are maintained by the individual GNO's (usually with reference to IGEM standards, whose technical rigour is accepted by the HSE and Gas-Safe).

IGEM has been identified as potentially an appropriate organisation to deal with this requirement through the extension of existing standards to cover gases comprising >99% hydrogen. However, whilst IGEM as a recognised industry body could perform this task some independence from and significant support by the UK gas industry would be required.

On the 17th December 2015 (at the instigation of Kiwa Gastec) a meeting of IGEM was held to discuss the extension of the current ranges of 1st, 2nd and 3rd family gases (i.e. those containing hydrogen, those that are predominantly natural gas and those that are predominantly liquefied petroleum gas respectively) to include 99%v/v hydrogen. The main items covered at this meeting are summarised in Appendix A2.1.

Because of a relative lack of knowledge about existing hydrogen appliances it is thought useful to offer a detailed critique as to the world and UK status of these before proceeding to detailed feedback from manufacturers.

5 Project Approach

5.1 Information Collection

The work started with a review of available literature and published information, this review is provided in Appendix 10.1.

5.1.1 Stakeholder Engagement

In support of Tasks 2 to 11, stakeholder engagement was sought through:

- Questionnaires;
- Individual and group meetings with stakeholders;
- Telephone interviews;
- Public domain information was also sourced.

Trade bodies were contacted for assistance in the identification of organisations that have an interest in the manufacture of hydrogen fired appliances. This was performed in order to establish points of contact (particularly for those we do not already know) and identify their willingness to participate in this project.

Trade bodies contacted during this study include:

- HHIC (Hot Water Industry Council);
- CEA (Combustion Engineering Association);
- UKHFCA (UK Hydrogen and Fuel Cell association);
- CESA (Catering Equipment Suppliers Association);
- SHFCA (Scottish Hydrogen and Fuel Cell association);
- BCGA (British Compressed Gas association);
- IGEM (Institute of Gas Engineers and Managers).

Kiwa is a member of all these organisations, so already has contacts in the relevant areas.

Other relevant bodies (representing combustion appliance manufacturers) who have been approached are:

- BIFCA (British Industrial Furnace Manufacturers Associations);
- ICOM Energy Association (meeting held).

Confidentiality and Data Protection

The success of this project was dependent on stakeholders contributing openly during the stakeholder meetings, telephone interviews and when completing the questionnaire. In order to minimise any issues of confidentiality and data protection which may have presented barriers to discussion, stakeholders were informed that confidentiality would be respected so that manufacturers / companies cannot be recognised through the general statements presented in this report.

During contact with manufacturers the necessary measures, described above, were conducted so that problems could not be encountered. In addition, a draft version of this report was presented to all stakeholders that contributed for their approval prior to releasing the final report to DECC.

Individual and group meetings with stakeholders

The cornerstone of this project was the collection, collation and assessment of data and information from trade bodies, manufacturers, GDNOs and academe. This included individual stakeholder interviews and focussed engagement meetings with stakeholders. Possible scenarios were presented to encourage dialogue, including limit cases with care taken during these discussions to allow the stakeholders to lead.

Structured agendas were issued posing key questions which were standardised across the appliance groups, ensuring that results from different participants were comparable. However, each meeting covered technology-specific aspects namely:

- Investigate the controls and usability of appliances;
- Identify a plan and timetable for manufacture of batches of hydrogen appliances by examining the possible routes to market;
- Estimate the costs and investment required to develop a hydrogen-fired appliance supply chain;
- Understand the barriers to developing a supply chain;
- Assess the incentives required to develop and commercialise hydrogen appliances, including training.

Meetings held:

Hot Water Industry Council (HHIC):
- Domestic Boilers
- Gas Cookers
- Gas Fires

Catering Equipment Suppliers Association (CESA):
- Domestic and Commercial Catering

Institute of Gas Engineers and Managers (IGEM)
- Covering current practice, theory and potential for IGEM Standards

Agendas and minutes with key findings from the meetings are presented in the appendices.

Kiwa also attended meetings with the Industrial and Commercial Energy Association (ICOM) and Combustion Engineering Association (CEA). However, contributions and feedback from these associations was minimal and made no significant contribution towards this project.

Individual manufacturers and companies were approached including representatives from the glass kiln industry, commercial and pre-mix gas burners and a manufacturer of hydrogen catalytic boilers - relevant information collected during these interviews is presented in this report.

Questionnaires

To assist in this data collecting exercise, a questionnaire was prepared in consultation with DECC and several manufacturers, with the objective of collecting information similar to that covered during the stakeholder meetings (reference bullet points listed under stakeholder meetings).

The questionnaire was circulated individually to manufacturers, companies and via selected trade associations. Feedback from each sector was collated and is presented in Section 6 of this report ensuring that anonymity was maintained.

Telephone interviews

For gathering input from the fuel cell community a list of 17 stakeholders were initially contacted by email inviting a face-to-face workshop in London. These included representatives from the top companies manufacturing natural gas fuel cells and with intimate knowledge of the fuel cell manufacturing process. Three of these are based in the UK, another three in North America and the remainder in Europe. The initial response from the stakeholders was very low with limited interest shown. This was attributed to the geographical location of most of the stakeholders and that they are based outside of the UK. After multiple attempts to organise a workshop, either face-to-face or via teleconference, the most viable course of action was to arrange bilateral interviews via E4tech's established network. This led to four semi-structured telephone interviews and one email correspondence with UK and European based manufacturers based on the questionnaire. One completed questionnaire was received. In total six manufacturers contributed to the fuel cell section.

Main topics covered

To complete the project tasks it was necessary to collect information under the following headings:

Product characteristics:

Task 2: Appliance controllability and usability

Production / manufacture:

Task 3: Outline plan for manufacture

Task 4: Timetable for manufacture

Costs:

Task 5: Cost of batches of appliances

Task 6: Size of overall investment

Issues/ barriers:

Task 7: Issues arising from manufacturing hydrogen appliances

Task 8: Barriers to developing a supply chain

Policy / incentives:

Task 9: Assessment of incentives required (including training)

Safety:

Task 10: Identify appropriate lab safety tests

Task 11: Assessment of safety risks in use

The information for each of these topics is presented against main technology areas in the feedback section of this report.

Task 12: Gap analysis

6 Key Findings and Stakeholder Feedback

This section summarises key information collected from stakeholders and covers a range of questions which were selected in order to assist DECC in understanding the technical challenges, associated costs and barriers. The information covers the topics listed below and were essentially collected either, by questionnaire (template shown in Appendices), interview or via stakeholder meetings:

- Technical;
- Production / manufacture;
- Costs;
- Issues / barriers;
- Policy / incentives;
- Safety.

The original technology scope was:

Technology
1. Domestic boilers (condensing regular and combi);
2. Gas cookers (attention to flame visibility/safety);
3. Gas fires (attention to flame visibility)
4. Commercial catering equipment (ability to provide suitable cooking conditions, e.g. bread, pizza);
5. Pre-mix burners;
6. Fuel cells (1kW to large scale);
7. Commercial gas burners;
8. Other relevant appliances

6.1 Domestic boilers

Boiler manufacturers welcome the study by DECC into the potential roll-out of both hydrogen appliances and an "all hydrogen" gas grid. They appreciate the overall initiative as it represents an alternative strategy to decarbonise heat, which has the potential to reduce carbon emissions cost effectively and secure a long term future for the gas network industry and the manufacturers of gas burning appliances. Manufacturers were therefore keen to contribute positively to the project.

However, they emphasise that additional costs will be incurred in the R&D, product design and initial manufacturing phases above those normally incurred for natural gas appliances, and that they would like these to be supported within a stable regulatory and political framework. This would principally consist of a clear policy direction towards a market for hydrogen-using appliances, together with a staged plan showing the number of appliances that would be likely to be required at each stage. They would like this supported by funding to create the necessary conditions for manufacturers to invest and engage in the roll-out, which could range from support for RD&D, through to support for a testing facility to allow multiple manufacturers to test appliances over long durations where a relatively large supply of hydrogen would be required. A hydrogen testing hub is likely only to have value later in the time period when reliability and endurance testing of appliances is needed. Product development testing would be conducted at manufacturers' own R&D facilities. A considerable investment in infrastructure and commitment of engineering capacity is required for product development (even for the small quantities required during the initial roll-out). Some manufacturers indicated that it is this engineering resource that creates the bottleneck, meaning that these would not be diverted to hydrogen appliances, even if funding were available, without a clear policy direction.

None of the manufacturers are currently developing hydrogen appliances although some are looking at alternative fuels such as biogas and one domestic product is currently on the market. Therefore, new products will be required, which may bring new challenges. Boiler manufacturers are confident that the cost and time uncertainties together with the other barriers identified in this report can be successfully dealt with.

One boiler manufacturer suggested that dual fuel boilers could be developed. This is a topic upon which there was, and continues to be, significant discussion. Essentially dual fuel appliances must be more complicated, physically larger and more expensive than either a natural gas or 100% hydrogen boiler, but they should simplify any conversion process. Both formal and informal replies to this data gathering exercise indicated the overwhelming majority of manufacturers thought true dual fuel (i.e. conversion using a switch or lever) was unlikely to be viable, although one manufacturer disagreed. The whole issue of dual fuelling is very complex. Ideally the change would be similar to that from natural gas to LPG, which was essentially a change of injector to accommodate change in Wobbe Index. By chance, hydrogen and natural gas have similar Wobbe Index but unfortunately the problem is more fundamental, involving flame speed and emissivity.

Dual fuel boilers would be much more complicated than single fuel burners, and involve pipework connections that would have to be ‘switched’ . This would immediately impinge upon the integrity of the system. This is unattractive in gas circuits that ideally should be kept as simple as possible. It is also likely to increase boiler physical size, which is critical in a modern condensing boiler. Increasing boiler physical size would increase cost and complexity. A ‘low cost’ gas condensing boiler can be priced as low as £400 ex works. Most of the ‘project cost’ (perhaps £2000) of installing such a boiler is the man-hours associated with the plumbing of the gas, water, flue and electrics. Whilst no hard data is available, the majority of boiler makers seem to think that simplifying and standardising the cost of the back-plate (see below) to reduce and/or almost eliminate this cost is a more cost effective way forward. It was felt that mandating designs of common backplate or requiring a manufacturer to publish and remain with a standard design of their choice would achieve most of the advantages at effectively zero cost. It would save installing dual fuel boilers in areas that may never be converted in the lifetime of the boiler.

A high percentage of wall mounted boilers are now sold with a back plate which both serves to fasten the boiler on the wall but also acts as a manifold for gas and water connections. This has valves which vastly simplifies the process of replacing the boiler. It is frequently the time taken to securely fasten this backplate to the wall and make the appropriate connections which takes the majority of the time for a new boiler installation. The idea of making new hydrogen boilers share a common back plate with existing natural gas is attractive to many manufacturers and this has the potential to reduce conversion times from (for example) a day to less than 2 hours. Such a design, whilst not technically ‘dual fuel’, considerably simplifies and speeds any conversion process.

Further weaknesses in the arguments for dual fuel boilers are as follows:

- Assuming an average boiler life of 12 years, boiler change over is quite slow. Unless plans for future areas of conversion from natural gas to hydrogen were agreed a long time in advance (10 to 15 years, which is unlikely to happen) householders would know whether to purchase a dual fuel unit or not, and many would be half way (or more) through their life before conversion.
- The dual fuelling of gas cooking apparatus and gas fires looks technically even more challenging than boilers. For example, when converting from town gas to natural gas, the configuration of the flame retention ports must be changed (due to different flame characteristics) - a flame retention port prevents the flame from lifting off the burner. The whole value of dual fuelling is that gas operatives would not have to bring with them replacement parts for the conversion process i.e. they would attend site and then using a standard fitter’s tool box adjust the burner from natural gas to hydrogen. However, this is not a trivial change for a burner (normally easily dismantled) which has been covered in extensive food spillage. It is possible to envisage an enthusiastic DIY homeowner running into difficulties when changing a burner which is covered in burnt fat.

Dual burners are possibly designable, but whether they can be offered at a realistic price and offer an appropriate level of robustness is a much more complex issue. Catering establishments are known to make un-authorised adjustments to their appliances, this and similar complexities with gas fires (where DIY shops still sell replacement coals) contribute towards making dual firing look much more complex than at first sight.

- Because some people will still have very old back-boiler back units for the forseable future, and the gas industry must achieve 100% entry prior to conversion, the actual increased simplicity of the change over using dual fuel boilers, rather than the common back-plate boilers looks modest. Contact will still have to be made with all residents, visits made, the cooker and gas fire replaced, the gas pipework checked etc.The time saved with the boiler might be one hour, over a backplate boiler. Economically asking householders to invest potentially several hundred more pounds in a boiler to simplify a gas quality change in, perhaps, 8 years time looks questionable.

Controllability and usability (Task 2)

Most manufacturers agreed that hydrogen as a fuel does not in itself present any problems that prevent the development of safe and efficient appliances. However, it was suggested the efficiency of products produced at low volumes in the initial roll-out phase may be lower than later higher volume appliances due to the challenging time scales for product development of the initial roll-out appliances. Manufacturers also raised concerns about the lifetime durability of the appliance as the flame will burn at a higher temperature which may lead to decreased lifetime. Some manufacturers suggested possible solutions to this, including modified servicing, inspection, and maintenance routines in more detail to monitor long-term product reliability. The effect of gas purity on the appliance (i.e. the percentage concentration of impurities in the gas) is considered a possible issue by most manufacturers but will depend on the types of impurities involved. The general composition of a hydrogen gas stream (e.g. very low concentrations of CO) is flagged as less of an issue than the presence of contaminants such as sulphur, currently added to natural gas for odourisation. Similar issues apply to colourants (for flame visibility) and cleaner colourants with fewer contaminants may improve the cost performance of appliances. Manufacturers note that flame visibility is not strictly necessary for heating and hot water appliances due to the sealed combustion chamber and presence of remote flame indication on most boilers, but largely support the requirement for it.

Manufacturing (Tasks 3, 4, 5 and 6)

All manufacturers agreed that the technology for safe and reliable combustion of hydrogen already exists.

One Italian boiler from Giacomoni already exists and can be purchased today (see Appendix 10.1)

The boiler is known to made in extremely small numbers.

The issue manufacturers raised rather related to how this technology can be incorporated into current manufacturing and product lines as product designs do not exist and supply chains might need to be adapted for specialised components. Technical challenges for manufacturing new components and use of new materials may also exist for example in:

- Control strategy and flame detection (this is considered the main issue particularly in the initial low volume sales);
- Burner technology;
- High temperature seals and gaskets;
- Sizing of various components;
- Pressure regulators.

Discussion on scaling up manufacturing focused on different manufacturing ‘steps’ i.e. 1000, 10,000 and 100,000 units. Facilities to scale production up to 100,000 units in the UK exist as hydrogen appliances could be incorporated into existing production facilities, which have capacity in line with the current UK heating appliance demand. However, one manufacturer raised concerns regarding the effect of increased product diversity on production efficiency and the potentially substantial investment needed in additional testing facilities and the on-site supply of hydrogen. Not all manufacturers agreed with these complications, however, one stated that once the product had been designed, it could easily be incorporated into existing facilities - this may be attributable to differences in existing manufacturing capabilities and practices. It may be noted some manufacturers produce both large numbers of domestic boilers (for example 18kW) and small numbers of commercial boilers (for example 100kW) using the same assembly line.

Manufacturers also agreed that although facilities exist to scale up hydrogen appliance production there may be bottlenecks in the supply of components as all developers within the UK would have to, for example, work with the same gas valve, seal, control and burner manufacturers. High demand and competition for R&D capacity and skills (both internally within a company and externally) was also regarded as an area of potential concern in scaling up production.

The timeline for developing hydrogen appliances depends on the number of units manufactured. Incorporating a product line of 100,000 units is expected to take up to 5 years with the first 1,000 units ready within 2-3 years from project start. Product designs would be complete in the lead up to the production of the first batches i.e. comprising the first 2-3 years of the project. Concept development, supplier commitment, number of different burner types, and assistance with costs were flagged as key factors influencing the lead time for expanding manufacturing capacity. Unsurprisingly, the more specialist parts needed, the longer it will likely take to change the manufacturing processes. This is currently an uncertainty in timeline estimations.

There is some uncertainty about estimated costs of hydrogen appliances. This is partly due to the new components and materials and the fact that some design features are not yet known. For the cost of manufacture of the appliance, one manufacturer estimated the first 1,000 units could cost roughly four times that of a natural gas boiler with the 100,000th unit costing 1.5 times that of a natural gas boiler. Another manufacturer estimated a far higher cost for the initial units (ten times that of a natural gas boiler) but reducing to more acceptable costs on par with natural gas towards the 100,000th unit. Manufacturers place the total value of investment at around £ 5 million to reach the 100,000th unit. Involving larger companies in the process is a prerequisite as smaller companies may not be able to afford R&D investment without financial support. Larger companies will still require significant capital investment supported by (government) funding to bring consumer prices down to acceptable market prices. The exact share of investment to come from external versus internal budgets should be analysed in more detail.

Barriers (Task 7 and Task 8)

The discussion on barriers to market entry and development focused on the existence of sales and distribution channels, standards and codes and consumer awareness.

Market entry barriers

All manufacturers agreed that the necessary standards and codes are currently lacking for hydrogen boilers and that these would need to be developed, although as indicated above in the short term this is soluble through the flexibility of Notified Bodies. Hydrogen installation standards were considered to be more urgent than hydrogen product standards. It was further pointed out that it could take as much as 2 years to develop standards. New sales and distribution channels are unlikely to be needed as current boiler manufacturers could use existing channels. Smaller companies or new entrants, however, will need to establish these or cooperate with larger companies with established sales relationships.

Manufacturers also requested a hydrogen quality standard. This is clearly important, but it is also noted there is often an inverse relationship between cost of gas and acceptable quality; thus (within reason) manufacturers may be able to pre-filter / treat the gas if this enables pipeline quality hydrogen to be produced. Flame combustion of hydrogen will be always far more tolerant than catalytic combustion.

None of the manufacturers seemed concerned about the overall risk that might arise from distributed hydrogen. Three manufacturers had made domestic scale hydrogen appliances, although all in very small numbers; they seemed to regard hydrogen as merely another fuel gas.

Market development barriers

Lack of demand for hydrogen appliances (clearly because of an absence of distributed hydrogen) was given as the single and most significant barrier to deployment from all manufacturers, and this would need to be created through policy. Such a policy would need to overcome lack of consumer awareness of the benefits of hydrogen such as decarbonisation and lack of confidence in the safe operation of hydrogen appliances, although the level at which these are 'real' problems is unknown. This national message could be followed up on the regional level with exhibitions, local pilot projects and local installers that champion hydrogen using appliances. In any case, the standard of stakeholder engagement must be high to inspire confidence from consumers. Likewise, a sufficient number of appliance manufacturers offering hydrogen appliances is needed for the market to gain confidence and to offer consumer choice.

Support required (Task 9)

The manufacturing industry views supportive policy as absolutely critical to the development of hydrogen burning appliances and the hydrogen gas market as a whole, in order to drive the switch to hydrogen in the gas network. Policy must create certainty that appliance volumes will continue to grow to occupy a large share of the market in a reasonable timeframe and that significant parts of the grid will convert to hydrogen over a period of time. One manufacturer highlighted the importance of publishing a strategy document listing the names of early projects with respective hydrogen appliance supply requirements in order to engage the supply chain and manufacturers.

Manufacturers suggested that national legislation would be needed to mandate the use of hydrogen instead of methane. Design and implementation of policy should be cross-party to inspire confidence from investors and remove the possibility of political changes to policy in the future.

Furthermore, it was stressed that commitment to funding and legislative framework changes should be made before industry invests in R&D and new production lines and that installation standards (discussed above) are developed early on in the R&D process. Funding and external investment would be needed to bring consumer prices down to acceptable market levels.

NOx legislation and energy labelling were also mentioned as areas that need to be developed. NOx legislation in particular will likely affect the type of boiler being developed whether catalytic (which may add costs but can decrease or even eliminate NOx emissions) or standard hydrogen combustion boilers. Trade bodies were identified as the key organisations to provide input on the development of standards.

Generally, standards and codes need to be established. These include:

- Qualification schemes for training technicians
- Updates to installation standards
- Route for product approval under the Gas Appliance Directive

Early products may only be available in a limited range of outputs and appliance types. One manufacturer highlighted that installing the early hydrogen appliances may require measures to accommodate a larger appliance in the house which may cause inconvenience and increase the overall cost of installation. Consumers will likely need to be supported for this in the early trials where the initial hydrogen appliances may be slighter larger than those being replaced, although every effort would be made to use the current natural gas back-plate.

6.2 Domestic and commercial catering equipment

One UK manufacturer is already developing hydrogen cookers and other designs have been produced. Relatively little feedback was received on hydrogen use in catering equipment (cookers, ovens), but that which was received was very useful in identifying areas of difference between catering equipment and boilers. Many of the comments made concerning boilers apply equally appliacable to catering equipment; however, this section highlights the key differences.

Controllability and usability (Task 2)

Appliances are expected to function correctly, although there are burner flame stability/primary air mix changes which needs to be resolved through re-design. Gas purity is not expected to be an issue. One additional issue for odourisation is that any compound added, must be considered food safe for cooker applications, although current Natural Gas odorants already pass this test. In light of this, one manufacturer suggested adding a similar compound to that currently used for natural gas as it has built up a long safety track record. Flame visibility is often raised as an issue for cookers, given that the flame is exposed, but from the experience of one interviewee the hydrogen burner flame is 'relatively colourless', rather than invisible. Colourants would be one option to change this, but again, would need to be food safe. Note that as the flame is hotter than the natural gas equivalent, this may affect appliance design and/or component specification (discussed further in the 'State of the Art and Market Review', Appendix 10.1), but the end user is unlikely to notice these differences.

Manufacturing (Task 3, 4, 5 and 6)

Technologies to incorporate hydrogen into catering equipment are not currently readily available, but many appliance system components are likely to be identical to natural gas equivalents and as such are readily available, with an existing supply chain including UK and European players. The normal appliance development process in this area involves burner manufacturers and appliance manufacturers working together collaboratively, and agreeing on IP, exclusivity and manufacture under licence. Burner manufacturers usually specialise in products aimed at a particular appliance sub-sector e.g. domestic (hob burner, wok equivalent, oven burner and grill burner) or commercial (hob, oven, grill, chargrill and deep fat fryer). Each burner type will require 6-12 months development on average supported by performance assessment against an appropriate appliance standard. Several manufacturers may independently work in parallel on burner development for a single appliance manufacturer, which shortens development time. Once initial appliance development and burner development is completed, 6-12 months is needed for assessment and certification of the appliance itself. 6-12 months field trial is then needed before 6 months pre-production and a transition to regular production. Overall, the whole process totals 2-3 years per appliance.

Initial low quantities to support the first hydrogen projects can be assembled and end-of-line tested on current R&D premises based on outsourced fabrication of appliance panels. Once orders increase, facilities similar to that of other gas appliance manufacturers could be established within light industrial premises. Quantities of 1,000-10,000 units per year could be achieved for commercial equipment within a 10-year timescale if a large enough market existed. Domestic appliance manufacture with much higher volumes is likely to be outsourced/manufactured under licence to an existing manufacturer in the field. No detailed cost information is available, but development costs are estimated at around £100,000 per appliance type with some reduction of cost potentially possible if activities can be combined.

In the UK, Almaas Technologies has established a hydrogen laboratory facility and has started prototype burner work, in dialogue with burner manufacturers, with a view to incorporate these into their own range of cooking appliances.

Barriers (Task 7 and Task 8)

As for boilers, but with the added rider that the commercial catering market is much smaller than the domestic boiler or cooker market. There may therefore be lower interest from component manufacturers.

6.3 Commercial boilers

Many of the technical issues mentioned for domestic heating and hot water appliances also apply in the commercial sector. Appliances are largely expected to function correctly while the major issues concerning the purity of the gas are related to impurities rather than specific concentrations of hydrogen. The technologies to be incorporated into existing product lines already exist although, as with domestic appliances, significant steps may be required to apply them to commercial appliances.

- The commercial challenges will be stronger in the commercial sector (as opposed to domestic) heating and hot water appliances as these are developed outside of the UK (in Europe). The UK market for hydrogen appliances would have to be balanced against other European market requirements when determining priorities for development resources. One European manufacturer stated that they have production facilities to currently produce 1,000 units
- Commercial appliances may require relatively higher external financial support than domestic due to lower volumes. This is because:
  - the lower volumes / quantities associated with light commercial applications could increase the relative impact of technical challenges;
  - the demand for commercial appliances is so low that even a mandatory change may not generate a viable market at the volumes described (1st, 2nd and 3rd Generation –see section 4 and 7.4). One manufacturer estimates the first generation of hydrogen appliances to cost around 10 times that of a natural gas appliance and 3rd generation to cost 1.5 times that of a natural gas appliance. This assumes that larger commercial appliances using pressure jet burners would require a change of burner with associated matching work. It also assumes that all appliances with premixed burners will require complete replacement of the appliance during the hydrogen changeover. Appliance conversion is not considered a viable option by the manufacturers contacted for this study. The initial investment for 1st generation appliances at low volumes (<1000) is estimated at £ 2.5 – 3 million.

6.4 Fuel cells

Controllability and usability (Task 2)

Manufacturers interviewed agreed that fuel cells are able to function safely on hydrogen, and that there is nothing inherently unsafe in using hydrogen when compared with natural gas. Current fuel cells broadly fall into two categories (although there are exceptions): high temperature designs mostly solid oxide fuel cells (SOFC), which consume natural gas directly and proton exchange membrane fuel cells (PEMFC) which consume hydrogen. PEM installations that use natural gas include steam methane reformers to convert the natural gas to hydrogen prior to its supply to the fuel cell. As this step adds both complexity and cost, supply of bulk hydrogen via pipelines would reduce the costs of the PEM option.

Low temperature hydrogen PEM fuel cells inherently have faster response times than natural gas high temperature SOFC fuel cells. Such faster response is always useful for heat demand led CHP, and is essential for electricity demand led CHP. As with hydrogen boilers, hydrogen fuel cells are mostly susceptible to impurities in the hydrogen stream rather than to a highly specific concentration of hydrogen versus CO, CO2 etc. One manufacturer pointed out that they could develop a fuel cell to run on a variety of gas mixes although CO and hydrogen sensor equipment could benefit from additional innovation to decrease cost. As steam methane reformation is the likely source of hydrogen, at least in the early years of deployment, contaminants may feed through pipelines and sulphur and siloxanes can cause damage in the fuel cell. Most products are therefore likely to require a cleaning or filtering system. These systems can, however, be installed at a fairly low cost. If higher purity hydrogen was available, it should in any case lower the cost of the fuel cell although one manufacturer mentioned that using pure hydrogen in their SOFC products could decrease the electrical efficiency.

The addition of odourants to hydrogen fed through a distribution system could also cause problems for fuel cells. The traditional mercaptan based odourants added to natural gas have been shown to poison PEM membranes and SOFCs, so it is likely that alternatives will need to be sought. A number of possible odourants have been suggested, and, whilst further research is necessary, this is not expected to be an insuperable barrier. The Japanese have been carrying out tests with cyclohexene, but unfortunately this has a rather pleasant smell, rather than sulphurous odour[11].

Manufacturing (Task 3, 4, 5 and 6)

The technology for using hydrogen in fuel cell appliances is already available with a supply chain generally present for the necessary product components, according to manufacturers interviewed. Most of the components are off-the-shelf and all components outside of the stack already exist at scale. Some safety architecture and compliance modifications will still be required for the product design – one manufacturer estimates this would take approximately 1-2 years. For scaling stack production, however, additional facilities will likely need to be built. Some manufacturers already have capacity to produce 1,000 stacks but 10,000 stacks would require further investment in capacity of £3-4 million and roughly 2-year lead time. Going above 10,000 will require strong market signals for manufacturers to take the risk of scaling up. The first 1000th units are expected to cost around £ 11,000/unit. Another manufacturer, however, which is still in its start-up phase, provided a timeline of ten years before they could manufacture >1,000 products per year. Overall we consider this a longer time period but no less realistic than other manufacturers' estimates.

The existing process is considered highly scalable and manufacturers are likely to change operations of current production equipment rather than change the process itself. Overall, the commercial risk of low order volumes, rather than the technical risk, is considered more of a serious threat to scaling up. One manufacturer also pointed to the existence of a well-developed international fuel cell supply chain, particularly in Japan, that could be tapped into if required.

Barriers (Task 7 and Task 8)

Hydrogen fuel cells (probably PEM) clearly have long term potential to produce both heat and electricity in the home and commerce. These have inherent advantages over either natural gas fuel cells, which must be more complex due to their chemistry, or natural gas CHP engines. This complexity is such, that (generally) natural gas CHP units are not seen as an obvious forrunner to the hydrogen fuel cell.

Manufacturers spoken with to date, do not see any fundamental technical barriers to development although increasing stack lifetime should be an R&D priority going forward. However, a barrier to large-scale deployment is importantly cost which in turn relates to technology development, field trials, scale of production and data collection. It was also recognised that until the technology is fit for purpose many of these issues cannot easily be resolved. One manufacturer pointed out the key barrier as the OEMs' low appetite for taking on risk with new product lines and especially so in an environment of market uncertainty and low economic growth. OEMs are further needed for consumer facing roles and their sales and distribution channels as consumers are more likely to buy fuel cell appliances from well-known brand names. Market barriers were not perceived as a major issue, based on the view that when fuel cell developers have developed a real product fulfilling a customer need the market will grow organically. Finally, lack of specific training for installers was flagged as a potential barrier but one that could readily be overcome with the right training and programmes.

Support required (Task 9)

Manufacturers suggested that government or another suitable actor should try to find a reasonable way of sharing the risk and reward of fuel cell development between government, developers and other actors in the system.

[11] International Gas Union Research Conference, Paris 2008, "A Study on Detection of Hydrogen Leak in Soils", Shuji Namatame and Yasushiro Gomi, Japan Gas Association.

Developers are expected to take on significant commercial risk by developing the technology and scaling up, which they will not do unless there is a clear support system in place. One manufacturer stated, however, that although a support programme in the beginning is welcome, once each player in the industry is at ~50 MW production the industry should be self-supporting.

Development of a coherent and stable energy policy that recognises the value of fuel cells (such as carbon benefits, increased efficiency, energy security, reduced investment in grid upgrades) and fairly distributes it among system stakeholders is needed. More specifically, manufacturers pointed out upfront customer capital grants as an effective policy mechanism as customers are unwilling to spend on large capital items even if the life time returns can be attractive. It was also highlighted that the most valuable support for a pre-profit company is that which helps preserve raised capital and reduce the cost of further capital expenditure. Grants or subsidies to go towards operational expenditure (such as personnel costs) would be helpful for the majority of manufacturers in the UK. Manufacturers also mentioned that the UK should plan pragmatic and strategic steps for 2020, 2025 and 2030 and keep running analysis as data from demonstration projects becomes available.

6.5 Summary of estimated manufacturing timescales and appliance costs

Table 1. Estimated Timescales for Manufacturing Domestic and Light Commercial Boilers

Production Volume		Years*
Domestic	**Light Commercial**	
1000	10	2 to 4
10,000	100	1 to 1.5
100,000	1000	1 to 1.5
Totals		4 to 7

Table 1 Notes: *i) * Estimated timescales include product development, design, approval and manufacturing capabilities*

Table 2. Estimated Cost of Manufacturing Domestic and Light Commercial Boilers

Production Volume Domestic	Cost# *(cf NG)*	Production Volume Light Commercial	Cost# *(cf NG)*
1000	NG x 4	10	NG x 4
10,000	NG x 2.5	100	NG x 2.5
100,000	NG x 1.5	1000	NG x 1.5

Table 2 Notes: *i) Estimated typical costs for boilers: domestic ~£800 (25kW), light commercial (150kw) - £5,000*

ii) # Cost of Natural gas boiler X multiplier

Table 3. Estimated Timescales for Manufacturing Domestic Cooking / Commercial Catering Equipment

Stage of Production	Years
Burner development	0.5 to 1
Product design /assessment / approvals etc.	0.5 to 1
Full manufacturing capability	0.5 to 1
Transition from pre-production to regular production	0.5
Totals	2 to 3.5

Table 3 Notes: *i) Domestic cooker manufacturers likely to be mainly concerned with development of burner units for hobs, ovens, grills etc.*

ii) Catering equipment manufacturers will encompass the development of hobs, ovens, grills, deep fat fryers *iii) Volume manufacture -100,000 units only relevant to domestic cooking appliances*

- 1,000 to 10,000 is normal range for popular models of catering equipment

iv) No costings provided for domestic cooking / commercial catering

Table 4 Estimated Timescales and costs for Manufacturing Fuel Cells

Production Volume	Comments	Years
Product design	R&D, safety, compliance etc.	1 to 2
1000	Several manufacturers already have required capacity, production facilities. Manufacturers who need to establish capacity, production lines Estimated cost for 1st 1000 - £11,000	0 Up to 10
10,000	Further investments- required (est. £3 to 4 million)	Up to 2
100,000	This will require strong market signals before further scaling up is undertaken	unknown

7 Training and Assessment

Through statutory legislation, the Gas Safety (Installation and Use) Regulations 1998 (GSIUR) requires that any person involved in working with gas is competent so that safe gas work is achieved. Under the regulations any person involved with gas conversion work will need to be adequately trained to prove competence. Appropriate and effective further training and assessment material development as part of the current core assessment module and further possible hydrogen dedicated appliance modules will need developing to implement effective training and upskilling.

In 1967, North Sea gas was being brought ashore at Easington terminal. At this time, the ten-year national conversion programme began, which involved the physical conversion of every gas appliance in the country from town gas to natural gas[12]. The Gas Council, a nationalised industry at the time, implemented a comprehensive training programme for all its gas fitting employees therefore, retraining and filling any knowledge gaps in their workforce.

The current UK gas engineering workforce stands at around 150,000 (123,000 domestic / commercial and 27,000 factory operatives[13]). As hydrogen appliance roll-out develops, there will be a need for suitably trained engineers. Initially, the numbers will be small and the need will likely be focussed in fairly limited geographic areas. If roll-out follows an organic spread from the hydrogen sources as the infrastructure is developed, then this should be beneficial in avoiding the need to be continually training engineers in new areas.

A rigorous knowledge and skills gap analysis will be required to inform training needs. Developing new training and assessment programmes to address the potential shortfall in knowledge is demanding on resource so full consideration into the extent of managing such a project should be addressed early on in the project plan.

In addressing the knowledge gap which will exist a new recognised set of skills will be required at all levels from gas utilisation, product design, installation and commissioning in determining the effect and utilisation of hydrogen and its functionality, performance safety of the gas appliance, consumer safety and awareness appliance controls, burners, efficiency, user intervention, safety controls etc.

Converting gas appliances fuelled with methane to hydrogen gas will essentially require standardisation and a review of the current qualifications, gap analysis and formation of new occupational standards. These will need a set of structured training and assessment qualifications recognised by the skills sector council and industry. A recognised training programme to ensure engineers working on hydrogen conversion, adapted gas appliances including those manufactured to burn hydrogen will need to appreciate the effects caused by change in gas character.

A structured training and assessment specification or programme in accordance with the Standards Setting Body[14] will be required. The specification will need to outline the criteria to which the training developer or provider should develop their training programme. The specification should be aligned to National Occupational Standards or equivalent competency criteria and should provide a clear scope required to provide the learners with the required practical skills, knowledge, on-site experience and understanding to carry out safe gas work.

The Standards Setting Body is required to recognise all training for developers and providers wishing to provide training for new entrants working under the GSIUR and for training providers wishing to become recognised to offer training for those working outside the scope of GSIUR.

[12] 1967 The Gas council announced the move from town (manufactured) to natural gas. The project to refit 40 million appliances cost over £500 million and took 10 years to complete

[13] EU Skills is the SCC for the gas, power, waste management and water industries -1967

[14] Kiwa – Gastec research for the CEA

In order to effect training that is recognised and fit for purpose, consultation with stakeholders involved with gas conversion will be needed to develop the implementation and to make recommendations to the Standards Setting Body. Industry stakeholders involved with manufacturing gas appliances, gas utility and the steering committees involved in setting standards should all be considered in the development of the learning outcomes.

Developing purposeful training and assessment programmes requires considerable resources. Current '*off the shelf'* gas training and assessment products offered by approved training providers (whether it be for candidates undertaking initial or reassessment) is considered very unlikely to fill knowledge gaps to meet competency requirements for people converting appliances from methane to hydrogen.

Gas-Safe installers already have a sound understanding of the hazards of gaseous fuels and the principles of gas combustion e.g. gas/air ratio, pressure drop down pipework, and soundness testing. Hydrogen is expected to be another gas in the same fashion that propane is different to natural gas. Gas fitters will need to be comprehensively trained upon the different aspects of hydrogen, but this is expected to require days rather than weeks of training. Whilst no syllabus has been written at this stage, it is suggested that about 5 days of training and assessment should be sufficient to upskill a proficient Natural Gas and LPG operative to hydrogen. It should be noted that existing Gas-Safe engineers are required to attend a refresher course every 5 years, typically lasting 2 to 3 days.

As indicated above there are currently believed to be about 123,00 Gas-Safe gas fitters and 27,000 factory operatives working on gas. The latter, who quite legally fall outside the Gas-Safe register, work (for example) on kiln burners or in paint spray shops. It is likely that during a conversion process the number of operatives with hydrogen skills will only need to increase in direct proportion to the number of hydrogen appliances. In the very early days, a disproportionately number may be need to trained within (for example) gas network distribution companies to provide flexible 24-hour cover, but as a generalisation due to the localised nature of hydrogen roll-out, any burden is expected to be modest.

The conversion of any town or city to hydrogen will need to be organised and co-ordinated by the local Gas Distribution Network (GDN) company. It is likely that they would purchase the appliances and burners, and arrange for the zone by zone conversion. This would require substantial logistics identical to the conversion from Town to Natural Gas carried out in the 1970's. Nationwide the number of appliances would be similar, as there were far more local space heaters in those days. The gas company would need to arrange the training of appropriate staff. It is possible to envisage the GDN offering a 'basic' appliance free of charge, and householders being the opportunity to upgrade to more sophisticated designs for an appropriate fee. It should be noted that societal changes since the town gas to natural gas conversion may mean that strict parallels cannot be drawn with a natural gas to hydrogen conversion programme. It has been argued that lack of trust in the large energy suppliers may lead to less consumer cooperation compared with the 1970's conversion programme. However, evidence from the Scotia Gas Networks programme to change the properties of the distributed natural gas in Oban shows that there was very good cooperation from householders towards the technicians on the ground[15]. (Refusal to cooperate was less than 3% of the householders.)

[15] Opening up the gas market SGN 2016

8 Summary of key barriers (Tasks 7, 8 and 12)

Much of the feedback was very similar. This section summarises the key barriers identified along with potential mitigating measures and comments.

8.1 Technical barriers

Technical Barriers	Mitigating Measures / Comments
Specific product designs for hydrogen fired appliances are very limited in number and products are not commercially available.	Creation of an embryonic market through small scale trials in defined locations will encourage manufacturers to adapt or develop products. Adaptation of installed appliances is not considered a viable option by the manufacturers due to the complex logistical problems of ensuring the correct parts are delivered to the correct address during the conversion process. Further problems such as warranty issues would suggest that it would be much more straightforward to change the whole appliance. One manufacturer considers dual fuelled appliances as a possibility. This would be a valuable aid to facilitating a transition the hydrogen. It would allow all end of life replacements in an area identified for switching at some point in the future to be hydrogen capable and thus reduce the effort and cost at the time of the switch. However, the majority of manufacturers engaged by this study believe that a new family of hydrogen appliances will be necessary.
Hydrogen appliances are included within the GAD/GAR and new appliances can be certified. However, specific standards for the design of hydrogen appliances do not exist.	Scope of existing gas appliance standards need to be extended to include hydrogen explicitly including the provision of any additional clauses. This needs to be initiated as soon as possible as it could take >2years to develop these and make them available to manufacturers early in appliance the development process. Trade bodies were identified as the key organisations to provide input on the development of standards.
Burner technologies for natural gas may not ensure flame stability firing hydrogen.	Gas burner design principles are well established. Burner designs would need to be reviewed and revised taking account of the properties of hydrogen.
Control strategies suitable for natural gas combustion may not be effective for hydrogen burners.	

Technical Barriers	Mitigating Measures / Comments
Avoiding the risks associated with hydrogen/air mixes, importantly backlighting into burners.	
The low radiance of hydrogen flames presents a barrier to flame detection. This is a key capability in natural gas fired boilers being used for both safety and control. It is also an issue for open flame appliances in general and domestic cooking hobs in particular.	Work may be required to ensure that hydrogen flames are reliably detected. The addition of trace amounts of 'colourants' (compounds which when burned provide a strong tint to a flame) may provide a solution but further work is required to ensure that any additive is acceptable in terms of user safety and that it has no negative impact on any type of appliance.
Some components and materials used in natural gas fuelled appliances may not be suitable for hydrogen appliances, e.g.: • High temperature seals and gaskets; • Sizing of various components; • Pressure regulators.	Hydrogen is used in industrial contexts (about 50million tonnes per year worldwide) so solutions to specific issues probably already exist at that scale. Work may be required to adapt such solutions to domestic and commercial scale appliances.
Where technical solutions exist there is currently no market pull to create supply chains.	Work will be required to create a supply of materials and components suitable for use in domestic and commercial scale. The emergence of a potential product market is likely to be the ultimate driver for this.
The properties of hydrogen (particularly its lower volumetric energy content than natural gas) may lead to larger sized appliances than are possible with natural gas. This would be a significant barrier to gaining popular support for switching.	Manufacturers engaged with hoped that new appliances could be designed to fit within the constraint of the space envelopes of existing natural gas appliances.
The effects of hydrogen purity:	
• Suitable odorants, acceptable to the HSE, enabling reliable detection of hydrogen and without adverse impacts (particularly for fuel cells, or food safety) have yet to be identified.	A number of possible odorants have been suggested and some test work has been carried out on them. However, in order to satisfy safety regulators of the acceptability of a specific compound a coherent set of supporting data is likely to be required. This is not expected to be an insuperable barrier but collecting of the required data may be a relatively expensive piece of work.

Technical Barriers	Mitigating Measures / Comments
• CO / CO_2 / N_2 from H_2 manufacturing process • sulphur and siloxanes can cause damage in fuel cells	These could be an issue for some fuel cells but are less likely to cause problems for combustion devices. If fuel cells are to be widely adopted then, they are likely to require dedicated cleaning or filtering systems to be embedded in products or supplied with them.
It has been suggested that appliances initially available for roll-out may have relatively shorter lifespans than current natural gas appliances or than more developed hydrogen appliances which are expected to become available subsequently.	Accelerated lifetime testing of products would help to inform the position and guide as to the extent to which enhanced servicing, inspection, and maintenance routines may need to be applied.
The effect of increased product diversity on production efficiency and the substantial investment needed in additional testing facilities and the on-site supply of hydrogen.	Not all manufacturers agreed that these barriers would exist. One stated that once the product had been designed, it could easily be incorporated into existing production facilities.
There may be bottlenecks in the supply of components as all appliance developers within the UK would have to, for example, work with the same gas valve, seal, control and burner manufacturers.	There may be a requirement for upskilling of component manufacturers and the development of new designs.
Installation of hydrogen appliances could not be widely undertaken as there are currently no standards for installation of domestic hydrogen.	The processes of development of standards and codes of practice for installation and maintenance of hydrogen appliances needs to be undertaken. Extension of existing documents may suffice, however it needs to be undertaken as a matter of urgency to ensure that they are in place and that training systems have been adapted to accommodate them in time to provide staff for any significant programme of appliance roll-out. As indicated above it is vital the GDN's a fully engaged in all such work.
Specific training of personnel in both installation and maintenance for hydrogen appliances cannot be undertaken as there are no specific standards or codes of practice to which to train.	Should easily be overcome with the right training and programmes.

8.2 Market barriers

Market Barriers	Mitigating Measures / Comments
A considerable investment in infrastructure and commitment of engineering capacity is required for product development (even for the small quantities required during the initial roll-out). Some manufacturers indicated that it is this engineering resource that creates the bottleneck, meaning that these would not be diverted to hydrogen appliances, even if funding were available, without a clear policy direction. Additional costs will be incurred in • R&D, • product design and; • initial manufacturing phases above those normally incurred for natural gas appliances	Need to be supported within a stable regulatory and political framework. This would principally consist of: • a clear policy direction towards a market for hydrogen-using appliances, • a staged plan showing the number of appliances that would be likely to be required at each stage. This should be supported by funding so manufacturers can invest, and could include: • support for RD&D via a range of instruments to support the product lifecycle from concept through to functioning market; • support for a hydrogen testing hub facility to allow multiple manufacturers to test appliances over long durations where a relatively large supply of hydrogen would be available.
The appliance industry need further information about the market requirements for the products to enable them to develop appliances that meet consumer and policymaker needs. These requirements include typical appliance outputs, thermal efficiency requirements, NOx requirements, and gas quality. NOx legislation in particular will likely affect the type of appliance being developed whether catalytic (which may add costs but decrease NOx emissions) or standard hydrogen combustion.	Industry and government dialogue on market requirements is needed, so that these can be set out alongside the roll-out plan, giving a framework for manufacturers' activities.
Financing mechanisms for appliances during the conversion need to be established, resolving questions of how contracts for appliance provision in the conversion are manged, how new appliances are financed and by whom	Government and industry dialogue is needed. Lessons should be learnt from the original Town Gas to Natural Gas conversion process of the 1970's. Any roll-out of hydrogen must be mutually agreed between the Gas Distribution Network Operators, Regulators, and government.
Lack of consumer awareness of the benefits of hydrogen	Any hydrogen conversion would need to be accompanied by information provision to the public, including demonstration of hydrogen appliances

Market Barriers	Mitigating Measures / Comments
Lack of confidence in the safe operation of hydrogen appliances.	Coordination between industry players and policymakers needed to provide a source of reliable information to the public Need to demonstrate good engineering solutions to ensure gas tightness and failsafe modes if gas tightness is breached.
The commercial boiler and catering market is much smaller than the domestic boiler or cooker market. There may therefore be lower interest from component manufacturers. The commercial challenges will be stronger in the larger heating and hot water appliance sector as these are developed outside of the UK (in Europe).	A staged roll-out programme would need to identify requirements for every type of appliance, and additional support may be needed for low volume appliances

9 Conclusions

The following conclusions can be drawn from this work:

- Whilst selling in modest numbers, EU certified hydrogen fired appliances and industrial burners can be purchased in the UK today; they are only sold to eco-enthusiasts or industry that has by-product hydrogen which it wishes to employ as a source of heat.
- All of the manufacturers were confident that hydrogen burning versions of current UK gas products (e.g. combi boilers) could be designed and manufactured for prices at volume (10,000 to 100,000 units per year) not very different to those of today. Perhaps ~1.5 times the current ex-works cost e.g. £700 to £1100, rather than £450 to £750. Some suggested a smaller differential, although this will be dependent upon the level of NO_x emission permitted; this compares to the manufacturers current prices of around £3500 for a heat pump[16].
- Very low levels of NO_x (even zero) may require catalytic combustion rather than flame combustion. This is thought likely to increase cost;

Domestic boilermakers provided the most targeted suggestions on how the policy framework should be developed, but manufacturers and suppliers of other types of equipment also mentioned many of the same issues independently.

The comments and information collected demonstrate that industry has taken a positive approach when considering the development and production of hydrogen-fuelled appliances / systems and most are keen to be actively engaged. There was a general consensus that a planned and stage-wise approach would be needed to provide time for all the necessary R&D, and to confirm long term performance before any mass roll-out.

UK government support (primarily a clear policy plan and, to a lesser extent, funding) is considered essential by manufacturers if they are to gain confidence / reassurance. This should also encompass suppliers, merchant outlets to market and installers.

During these meetings (and subsequent feedback from industry), a number of policy related concerns were raised as potential barriers in moving towards localised (citywide) conversion to 100% hydrogen.

These are:

STRATEGIC POLICY FOR HEAT

- A number of manufacturers expressed the view that the free market would not make this change to hydrogen of its own choosing given that bulk natural gas was always likely to be lower cost. Strong policy direction from Government was therefore considered necessary when considering hydrogen as an important part of the future energy mix. Its widespread use should be positively encouraged, particularly in light of the overall cost and practicality of a low carbon society.

POLICY TO SUPPORT APPLIANCE DEVELOPMENT

- Government and industry need to consider product specifications, cost models, covering early R&D etc. This includes a market strategy – e.g. what will be the typical appliance output (kW) from appliances, and what NOx levels are required - this has a significant impact on design / production costs. Concerns were raised over amortisation, market competiveness / aggressiveness;
- Where RD&D is required to enable rapid development of technologies, the facilitation of support for this work may be required to overcome potential barriers. It is KIWA's view that existing tax breaks for R&D may be sufficient but if general technical barriers are found, funding programmes may need to have their scopes adjusted to enable the necessary research to be supported;

[16] Vaillant Geotherm 65/1 A air to water heat pump 230v 6kW Plumb Centre Web site, Product Code: 117758

- Lessons should be learnt from the original Town Gas to Natural Gas conversion process of the 1960s/70's. Any roll-out of hydrogen must be mutually agreed between the Gas Distribution Network Operators, Regulators, and Government. Some appliance manufacturers suggested that contracts should be managed to allow a range of suppliers to enter the market in order to develop a competitive and sustainable supply chain;
- A considerable investment in infrastructure and commitment of engineering capacity is required for product development (disproportionally high for small quantities of product as required for prototype testing). Industry needs an environment in which it can feel confident to make these investments, and would like to see models of government financial support to suit both research and early market development for small and large manufacturers alike;
- Where appropriate,
    - Funding and legislative support should look at a range of instruments to support the product lifecycle from concept through to functioning market;
    - Manufacturers currently consider that this is a high risk venture and therefore significant UK government support (at a suggested level of around 50%) is essential, unless conversion process is particularly innovatively arranged. This will assist manufacturers with internal R&D and demonstration costs; typical of the energy sector, the front-end support required by manufacturers (£10m to £50m) is a small percentage of the capital cost of any substantive hydrogen conversion scheme;
- Competent installers will be needed (hydrogen certified, retraining required) – budgets to cover costs associated with these activities will need to be found;
- Manufacturers need to consider additional costs associated with skill levels / retaining of apprentices and existing engineers;
- National installer groups (e.g. British Gas, Carillion, Homecare etc.) should be involved at an early stage;

Informally, many UK boilermakers (particularly overseas owned) expressed a strong interest in hydrogen from the perspective of driving ahead a new product that would retain their UK based R&D facilities, links with universities etc. Such groups give UK manufacturing sites good potential to export hydrogen technology. It is well known companies find it much easier to export product based upon afirm home market.

10 Appendices

10.1 State of the Art and Market Review

30686 DECC Hydrogen Fired Appliances

10.1 State of the Art and Market Review

Introduction

Whilst hydrogen is considered to be a possible future energy vector alongside electricity, the main focus of programmes looking at this transition is on development of fuel cell technology and transportation. However, to enable a complete change from supplying natural gas to supplying hydrogen in a locality, it will be essential to develop a wide range of appliances and equipment that can directly replace existing appliances.

Variations in quality of natural gas supplied are already a subject of concern for gas suppliers and equipment manufacturers. BP and their partners have provided a useful guide dealing with this issue. In this they note that[i] "All gas-fired equipment is designed and built for a particular gas specification. This will include a range of gas qualities within which the appliance will function correctly. If gases outside this range are combusted, this can lead to a range of problems, from poor quality combustion through to equipment damage and ultimately dangerous operation." So it is essential to ensure that hydrogen fuelled appliances and equipment are designed to function safely and effectively.

Hydrogen is already used in various industries; petroleum refining, aerospace applications, pharmaceuticals, petrochemical manufacturing, and the food and semiconductor industries. It is also used in fertilizer production, for glass purification, in welding, and in power generators. However, the use of hydrogen as a fuel is much less common.

The overall purpose of the research is to develop an understanding of the technical challenges and costs of developing appliances and equipment to operate using 100% hydrogen, and to identify how these barriers might be overcome.

Scope

In this review the objective was to examine, based on publicly available information, the state of the art / market for the following types of appliance:

1. Domestic boilers;
2. Gas cookers;
3. Gas fires;
4. Commercial catering equipment;
5. Pre-mix burners;
6. Fuel cells;
7. Commercial gas burners;
8. Other relevant appliances identified by the review.

For clarity the review separates the considerations into two main parts each of which is divided into several categories:

1. The basic gas conversion technology;
    - Non-aerated burners
    - Aerated burners
        - Partially pre-mixed
        - Fully pre-mixed
    - Flameless burners, catalytic burners;
    - Fuel cells;
    - Internal combustion engines;
    - Gas turbine combustor.

2. The appliance within which the technology is embodied

- Boilers;
  - Domestic
  - Commercial
  - Industrial
- Cooking appliances;
  - Domestic
  - Commercial
- Direct space heaters;
  - Domestic
  - Commercial
- Process heaters.
- mCHP

Each of the appliance/ equipment types can be based around one or more of the base technologies. The specific requirements of a particular technology may be different in different applications.

For the purposes of this review the focus is on products in which these technologies are already or may in the future be embodied into products.

Hydrogen

The properties and characteristic behaviours of hydrogen need to be taken into account in product design.

Hydrogen's volumetric energy content is relatively low. Compared to natural gas, hydrogen when burned releases only one third as much energy per unit volume of gas. However, its low molecular weight results in it having the highest energy content per unit mass of any fuel.

At ambient conditions hydrogen is not detectable by human senses as it is:

- Odourless;
- Tasteless;
- Colourless.

It is also:

- Nontoxic;
- Noncorrosive.

Hydrogen is the lightest element and in air. Its buoyancy causes it to rise and disperse rapidly (at speeds of almost 20m/s).

When hydrogen burns in air, no smoke is produced. Its pale blue flame is difficult to see, being barely visible in daylight. The combustion products are water vapour and some NOx. The amount of NOx produced depends mainly on the flame temperatures. NOx formation is discussed in the next section.

Hydrogen flame temperatures are comparable to those of other common fuels, but hydrogen flames radiate less heat and are therefore less likely to start secondary fires but may perform less effectively in some types of appliance.

The properties of hydrogen and its flames present several specific issues with regards to its supply to and use in equipment or appliances:

- Detection of leaks: Odourisation of the supply for safety reasons and implications for such technologies as fuel cells;
- Detection of flames: Flame visibility issues for domestic appliances such as cooker hobs, conventional gas fires. Flame detectability is also used in combustion control systems in some modern gas fired boilers;
- Emissions: Impacts of high levels of water vapour in flames on processes such as baking. Need to control NOx emissions to meet current[ii, iii,iv, v] and impending[vi] regulations.

- Gas quality: Technological (equipment or appliances) fuel purity requirement i.e. 99.5% vs 99.9% H_2 vs 99.999% H_2; NOTE: Techno-economic factors affecting H_2 production purity decisions are not considered. These decisions may affect the deployment of particular technologies.

NOx

NOx is the key pollutant that may be formed by hydrogen combustion in air. Its emission from stationary sources is already regulated for some types of appliance and equipment. Further controls are expected. The context and background are summarised here separately from the considerations of safe and efficient combustion. These latter are discussed only in the context of particular types of technology.

Limits on emission of NOx from a range of gas fired appliances and equipment both in the EU and elsewhere are in place or are expected to be introduced. Table 1 to These thresholds are those that apply specifically to plant firing "gaseous fuels other than natural gas" and hence to plant firing hydrogen.

Table 3 summarise limits set in EU directives, regulations or standards that are or will be applicable to gas (including hydrogen) fired equipment.

Table 1. Energy Related Products Directive 2009/125/EC - Implementing Regulations

Scope	Regulation	Standard - as identified in communications from the EC (full standards replacing those originally referenced)	Technology	Implementation date	NOx, mg/kWh gross input
local space heaters	2015/1188	Not yet announced	open fronted local space heaters using gaseous or liquid fuel	01/01/2018	130
local space heaters	2015/1188	Not yet announced	closed fronted local space heaters using gaseous or liquid fuel	01/01/2018	130
local space heaters	2015/1188	Not yet announced	luminous local space heaters	01/01/2018	200
local space heaters	2015/1188	Not yet announced	tube local space heaters	01/01/2018	200
space heaters and combination heaters	813/2013	BS EN 15502-1:2012 Gas-fired heating boilers Part 1: General requirements and tests	fuel boiler space heaters and fuel boiler combination heaters using gaseous fuels	26/09/2018	56
space heaters and combination heaters	813/2013	FprEN 50465:2013 (BS EN 50465:2015 European product standard for combined heating power systems using gas fuel)	cogeneration space heaters equipped with external combustion using gaseous fuels	26/09/2018	70
space heaters and combination heaters	813/2013	FprEN 50465:2013 (BS EN 50465:2015 European product standard for combined heating power systems using gas fuel)	cogeneration space heaters equipped with an internal combustion engine using gaseous fuels	26/09/2018	240
space heaters and combination heaters	813/2013	New European Standard under development within the CEN/TC299 WG3 experts group	heat pump space heaters and heat pump combination heaters equipped with external combustion using gaseous fuels	26/09/2018	70
space heaters and combination heaters	813/2013	prEN 12309-2:2013 (BS EN 12309-2:2015 Gas-fired sorption appliances for heating and/or cooling with a net heat input not exceeding 70 kW)	heat pump space heaters and heat pump combination heaters equipped with an internal combustion engine using gaseous fuels	26/09/2018	240

Scope	Regulation	Standard - as identified in communications from the EC (full standards replacing those originally referenced)	Technology	Implementation date	NOx, mg/kWh gross input
water heaters and hot water storage tanks	814/2013	prEN 89:2012 (BS EN 89:2015 Gas-fired storage water heaters for the production of domestic hot water) prEN 26 (BS EN 26:2015 Gas-fired instantaneous water heaters for the production of domestic hot water)	conventional water heaters using gaseous fuels	26/09/2018	56
water heaters and hot water storage tanks	814/2013	prEN 89:2012 (BS EN 89:2015 Gas-fired storage water heaters for the production of domestic hot water) prEN 26 (BS EN 26:2015 Gas-fired instantaneous water heaters for the production of domestic hot water)	heat pump water heaters equipped with external combustion using gaseous fuels and solar water heaters using gaseous fuels	26/09/2018	70
water heaters and hot water storage tanks	814/2013	prEN 89:2012 (BS EN 89:2015 Gas-fired storage water heaters for the production of domestic hot water) prEN 26 (BS EN 26:2015 Gas-fired instantaneous water heaters for the production of domestic hot water)	heat pump water heaters equipped with an internal combustion engine using gaseous fuels	26/09/2018	240

Table 2. Medium Combustion Plant Directive (EU) 2015/2193 (MCPD)

Technology	Implementation date	NOx, mg/Nm^3
new medium combustion plants other than engines and gas turbines	20/12/2018	200
new engines	20/12/2018	190
new gas turbines	20/12/2018	75
existing medium combustion plants with a rated thermal input equal to or greater than 1 MW and less than or equal to 5 MW, other than engines and gas turbines	01/01/2025	250
existing medium combustion plants with a rated thermal input greater than 5 MW, other than engines and gas turbines	01/01/2030	250

These thresholds are those that apply specifically to plant firing “gaseous fuels other than natural gas” and hence to plant firing hydrogen.

Table 3. Other Standards

Standard	Technology	NOx class	NOx, mg/kWh gross input
EN676 Automatic forced draught burners for gaseous fuels (Referenced in EU Directives: • 2006/42/EC Machinery Directive • 2009/142/EC Gas Appliance Directive • 97/23/EC Pressure Equipment Directive	Automatic forced draught burners for gaseous fuels: tested at the supply voltage declared by the manufacturer with reference gas G 20	1	≤170
		2	≤120
		3	≤80

NOTE: EN 676 sets NOx performance classes only for operation on 2nd and 3rd family gases.

The above tables provide a brief overview only and the actual regulation or related standard must be consulted for precise details.

The formation of NOx in combustion systems is complex. The presence of nitrogen bonded within fuel molecules is the source of ‘fuel NOx’. Almost all such nitrogen is converted to NOx under normal combustion conditions. This is not a relevant mechanism for NOx formation from the combustion of pure hydrogen.

At high temperatures, nitrogen from the air can combine directly with oxygen to form ‘thermal NOx’. The rate of formation is a function of temperature and residence time in the flame. Significant levels of NOx generally result under oxidising conditions, above 1,204°C[vii].

Bartok et al studied NOx formation for a range of fuel gases including hydrogen under well-defined conditions using a small, laboratory jet stirred burner which provided a close approximation to a perfectly stirred flow systems[viii]. Amongst their findings was that “With hydrogen as the fuel, the NOx emissions are reduced to much lower levels at all mixture ratios compared with methane at the same temperatures.” They also noted that the presence of methane or carbon monoxide in the hydrogen led to production of higher levels of NOx. At the time they ascribed this to ‘kinetic coupling’ and now this would be attributed to the ‘Prompt NOx’ formation mechanism which is generally believed to involve fuel fragments (mainly -CH) in a series of reactions.

For pure hydrogen/air flames, only the ‘thermal NOx’ formation route is available. So, control of NOx formation could be achieved in two main ways:

- Limiting flame temperatures to below 1,200°C;
- Limiting nitrogen availability, i.e. use of oxygen or oxygen enriched air rather than air.

Flame temerperatures are affected by the type of combustion system. Haruta and Sano[ix] noted that "conventional flame-type combustion of hydrogen produces large amounts of nitrogen oxides in a diffusion flame" whilst on the other hand saying that "in a premixed flame … NOx emission level is very low". At the same time they note the risks of lightback in a premixed hydrogen burner. They state a temperature range of 2,100 down to 1,200°C for flame type combustion.

Limiting flame temperatures is achieved by combustion system design methods which are already applied for firing hydrocarbon gases. One approach to this is limiting oxygen availability through staging of combustion. Allouis et. al.[x] investigated staging combustion of methane/hydrogen (up to 80%vol.) mixtures using catalytic partial oxidation in a hybrid catalytic/open flame burner. They reported significant NOx reductions. There are numerous possible configurations for catalytic hydrogen fuelled devices and although some of the catalysts that have been investigated are precious or rare metals other lower cost materials have also been considered e.g.:

Haruta and Sano[ix] noted that "oxides of inexpensive transition metals such as Co, Ni, Mn, and Cu were active at intermediate temperatures although they required a little preheating for the initiation of hydrogen combustion." whereas "Pd and Pt metals supported on a carrier could initiate hydrogen combustion even at a temperature below 0°C."

Haruta et. al.[xi] found that all the following systems 'worked' for hydrogen combustion:

- a ceramic honeycomb impregnated with Pt
- two Ni metal foams of different pore sizes coated with Pd powder
- a ceramic foam coated with Co-Mn-Ag oxide powder

However, there are other considerations apart from the materials used which impact on the performance of the catalytic combustion device.

Poisoning of catalysts can occur but it is often related to the presence of specific elements and compounds so the choices of specific catalytic systems by manufacturers will depend on what impurities or additives are present in the hydrogen supply.

Dilution of the fuel air mixture by addition of inert gas is another approach to controlling flame temperature. Flue gas recirculation is one approach to this and for hydrogen this would be tantamount to using steam as the inert gas.

If the hydrogen supply contains carbonaceous impurities (e.g. CO or CH_4) then the situation would be more complex as the Prompt NOx mechanism may contribute to NOx formation and other approaches to NOx control may be required.

Gas Conversion Technologies

Key issues to be considered are safe and efficient combustion and control of emissions. The formation and control of NOx is discussed above. In this section conversion of hydrogen to release heat through a variety of oxidative mechanisms is considered.

Jones[xii] provides a comprehensive overview of the factors affecting the design of burners for domestic appliances. The principles described are also applicable for the design of other scales and types of burner.

Non-aerated burners

Non-aerated burners create diffusion flames. All of the combustion air mixes with the fuel gas by diffusion. This can only occur once the fuel gas has reached the burner nozzle.

Non-aerated burners were widely used in domestic and other gas fired appliances prior to the conversion of the UK to use natural gas. According to Jones[xii] "from 1945 the majority of British domestic gas appliances (except cookers) were fitted with non-aerated burners" but then adds that "The advent of natural gas necessitated a reversion to the aerated burner, because of the inherent problems of flame instability and sooting with non-aerated hydrocarbon burners." He notes that since the move to natural gas the use of non-aerated burners has been confined to pilot lights (which subsequently have largely disappeared) and production of 'decorative' flames in solid fuel effect gas fires.

There is no risk of sooting from hydrogen combustion but some burners of this generic type have demonstrated an intolerance with regards to fuels with high hydrogen contents. So, non-aerated burners may be an option for hydrogen fuelled appliances but care will be required with burner design.

H2-NRG [xiii] offer some simple small-scale non-aerated hydrogen burners. These are:

- 'Candlestick' micro burner for providing a pilot flame;
- 'Burner BAR' which provides a larger burner possibly suitable for cooking applications.

Currently these burners are not embodied in any products although an objective is deliver a "customisation for a "Off the Shelf" domestic water boiler system" although it is not explained how this will be achieved. No details of design are available but the BAR is shown as a rectangular metal shell with a number of holes. Presumably these are sized to achieve diffusion flames. It is noted that the burners all incorporate 'flashback arrestors'.

Considering larger scale equipment, with regards to cement kilns burners, Hoenig et.al.[xiv] comment that "Burning hydrogen in non-mixed open jet flames is not a state-of-the-art technology". So, creation of non-aerated burners for some applications may require significant development effort with consideration given to the equipment within which they will be required to operate and in particular the space within it into which the burner fires.

Aerated burners

Aerated burners all involve some degree of pre-mixing of fuel with combustion air before the burner nozzle and for the reasons noted above this is the default burner type used for gaseous hydrocarbon fuels. The design of the section between the injectors where fuel gas and air enter the burner assembly and the burner head where the mixture enters the combustion zone must control the amount of air entering and ensure mixing and distribution of the mixture to the burner apertures or nozzles.

Pure hydrogen is stable but when air is introduced there is a risk of ignition once the upper flammability limit is reached i.e. a concentration of hydrogen in air of about 75% vol. So, the level of pre-mixing is an important factor in determining how the burner must be designed to achieve safe operation. This will include the method of pre-mixing. At low levels of hydrogen (up to ~9%) in air the combustion is limited in direction and is by 'deflagration' only. Above this level spherical flames are possible and above about 20% the combustion regime may transition to detonation. This suggests that mixing hydrogen into air may present less risk than mixing air into hydrogen.

Partially aerated burners

Examples of partially aerated burners/applications include:

- drilled bar burners - cooker ovens and grills;
- box burners – boilers and space heaters;
- circular cooker hotplate burners;
- jetted burners consisting of an array of small individual aerated burner jets screwed into a manifold.

The four main components of aerated burners are:

- the injector;
- primary air entry for entrainment;
- mixing tube;

- burner port.

Partially aerated burners are typically configured as follows:

- an injector nozzle consisting of one or more small holes through which gas is delivered to the inlet of a mixing tube;
- the gas entrains primary air as it enters the mixing tube;
- the mixing tube, which may be shaped in the form of a tapered venturi or may have parallel sides, is designed to ensure thorough mixing of gas and air, such that a constant air/gas ratio is maintained throughout the burner head;
- the mixture is distributed uniformly to the burner ports.

The basic design principles / methodologies are established and applicable to both partially and fully aerated burners. Of particular importance when considering modifying or developing burner designs to operate with hydrogen is its high burning velocity compared with hydrocarbons and the associated increased risk of 'light-back'.

Fully pre-mix burners

In fully premixed burners all the combustion air is mixed with the fuel prior to it reaching the burner nozzle (or equivalent). Burners of this type are most likely to be found in boilers/water heaters and for process heating.

In fully premixed burners the fuel air mixture is always flammable and so presents risks of 'light-back' which must be dealt with in the design of such burners. In principle this is not different to the situation for hydrocarbon fuels. However, it does need to be addressed specifically for designs of hydrogen burner, taking into account that compared to hydrocarbon gases, hydrogen:

- requires a higher volume flow rate to provide similar energy inputs;
- produces higher flame velocities increasing the risks of light-back.

Flame lift results when fuel velocity leaving the burner nozzle exceeds the flame speed. The flame speeds of hydrogen are relatively high compared to those for natural gas. However, the nozzle velocities may also be higher as a result of the relatively low volumetric energy content of hydrogen.

Fully pre-mixed distributed combustion burners

Burners of this general type use burner heads or porous material rather than with a defined set of holes. The flames are not localized at individual holes but are distributed over the material surface.

A variety of possible porous materials include sintered metals, metal or ceramic meshes and ceramic foams.

Sintered metal fully pre-mixed burners have adopted by some manufacturers in modern boilers.

Figure 1. Examples of distributed flame gas burners from Innovative Thermal Systems[xv] (left) and Alpha (right)

Such burners are likely to present fewer issues for modification to operate with hydrogen. Ceramic foam burners designed for pre-mixed natural gas and air have been shown to be suitable hydrogen methane mixtures up to 70% hydrogen.[xvi]

Flameless catalytic burners

Catalytic combustion burners function differently to burners with defined flames although there are similarities to burners with distributed flames as described in the above section "Fully pre-mixed distributed combustion burners".

Jones[xii] provides a general description for catalytic gas burners key points of which are:

- Can be diffusion or pre-mixed;
- Pad of ceramic fibres with catalytic particles distributed evenly through it;
- Need ignition source – electric pre-heater/pilot light;
- Flameless, resistant to drafts and changes in gas composition;
- High radiant efficiencies (>50%) are achievable;
- Low NOx;
- Fuel gas slip is a potential issue for hydrocarbon fuels with methane being the most difficult to burn out;
- Catalyst poisoning from carbon particle deposition can occur.

They have for many years been used to provide heating in leisure settings such as caravans and boats as their relatively low operating temperatures reduce the risk them starting fires. Products are available for providing heating in industrial and commercial spaces such as warehouses and factories. One feature of burners of this type is that they can be designed to have all sorts of surface profile. So, in addition highly specialised process heating applications can be satisfied.

Generally, switching from hydrocarbon to hydrogen retains the advantages (low NOx) and reduces or removes some disadvantages (no possibility of carbon deposition, hydrogen is much easier to burn out than hydrocarbons so lower risk of fuel-slip).

The range of potential substrates available is wider than suggested by Jones and includes sintered metals and metallic or ceramic foams. Haruta et. al.[xi] investigated catalysts on metallic and ceramic foam substrates for catalytic space heaters. Looking at pore size they found that there was a balance to be struck between:

- Larger pores increasing combustion efficiency;
- Larger pore sizes reducing uniformity of flame distribution.

They also noted that combustion efficiency increased with hydrogen premixing with air (at 40% 'stoichiometric' amount and up to fully premixed).

Fuel cells

Hydrogen use in fuel cells has received considerable attention in the wider debate on decarbonisation of heat and transport. This is due to their high efficiencies and low to zero emissions of carbon, particulate matter and other pollutants such as NOx. Hydrogen is also the 'preferred fuel' for some types of fuel cells as it can decrease component and materials cost compared to natural gas fuel cells.

Fuel cells convert a fuel and an oxidant directly into electricity (via an electrochemical reaction) without having to go through the thermal combustion and kinetic motion steps of combustion engines and generators. Fuel cells can in principle be applied in almost any power-generation and CHP application known, from microwatt-level to megawatt. Different fuel cells can use hydrogen, natural gas, biogas and other fuels, and air as their oxidant.

All fuel cells are similar in structure. As shown in Figure 2, the simplest fuel cell takes a fuel (for example hydrogen) and passes it over (and partially through) a porous catalysed surface (the anode). Electrons are liberated and pass around an external circuit, recombining with the ions that pass through the electrolyte (also known as the ion-exchange membrane). On the other side of the electrolyte is the oxidant, usually air but occasionally pure oxygen. This is also passed over a catalytic surface (the cathode) to help the oxygen to combine with the ions and electrons on the other side and complete the fuel oxidation reaction. For the simplest fuel and oxidant combination of hydrogen and oxygen, only water and heat are produced as by-products and the oxidation reaction can be up to 70% efficient - from fuel input to electricity output.

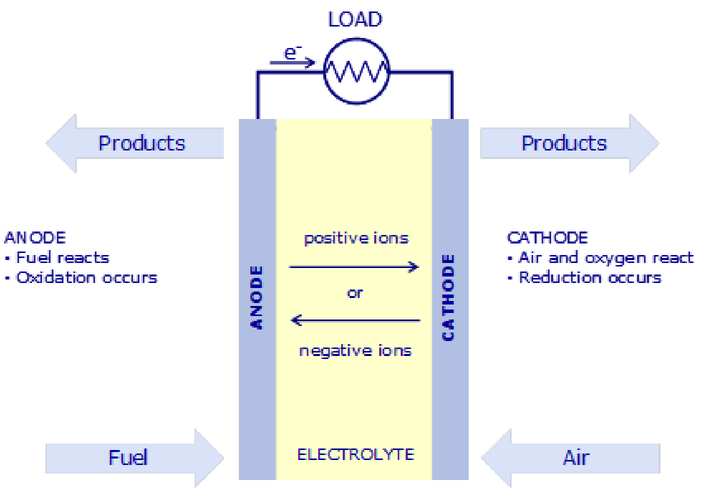


Figure 2. Schematic of Fuel Cell *(Source: E4tech)*

While all fuel cells are similar in structure they can differ significantly with regard to the materials used, their technical characteristics and by extension their applications. Two main types of fuel cells are proton exchange membrane fuel cells (PEMFC or PEM) and solid oxide fuel cells (SOFC). PEMs are more suited for mobile (e.g. cars) and portable applications (e.g. mobile telephones, tablet computers, etc.) due to their quick start-up times while SOFC is more common in stationary applications, such as micro-CHP (0.7–5 kWe), because of their higher efficiencies, relatively long start up and cool-down times, and generally higher temperature heat output. The fundamental difference between the different fuel cells is the electrolyte itself, which allows different ions to be transported in the different cases.

Internal combustion engines (ICEs)

ICEs are widely used for provision of emergency power generation. They are also the basis of some CHP systems. ICEs designed for hydrogen or gas mixtures containing high levels of hydrogen were developed as long ago as the 19th century. The possibility of operating modern transport ICEs on hydrogen (HICEs) has been investigated and HICEs have been trialled successfully. Generally, the studies have been in relation to transport applications e.g. the US DoE's Advanced Vehicle Testing Activity[xvii] and others mentioned in below.

Blarigan & Keller considered the effects of fuel mixing, fuel composition (99.9% hydrogen, 30% hydrogen/70% natural gas and 100% natural gas) and demonstrated the possibility of meeting the then Californian emission limits for NOx for HICE powered motor vehicles[xviii]. It is not possible to make a direct comparison with these requirements as they are framed in terms of g/mile and the authors undertook a range of conversion steps to make their analysis but the significance of the work is in the demonstration that control of mixing and combustion conditions in the engine enabled NOx emissions to be controlled.

The Hyfleet project website[xix] comments that "Hydrogen internal combustion engines are typically based on ICEs designed for the combustion of natural gas (CNG). However, substantial research and fundamental adjustments are necessary to make them powerful components in powerful vehicles. But as most components are identical with those used in conventional diesel engines, the costs at present remain much lower than those for fuel cell propulsion systems."

There are several specific considerations in creating and operating a HICE as described in the College of the Desert training course for engine technicians[xx]:

- Fuel Mixture: HICEs can run on lean mixtures which generally gives greater fuel economy and more complete combustion. It results in lower temperatures resulting in lesser formation of NOx;
- Ignition energy: Hydrogen's low ignition energy enables prompt ignition of lean mixtures. However, it can also lead to hot spots on engine cylinders causing 'pinking' and flashback;
- Quenching distance: This is smaller for hydrogen than for petrol which can increase the tendency to 'backfire';
- Auto-ignition temperature: Hydrogen has a relatively high auto-igntion temperature. This has important implications when a hydrogen-air mixture is compressed being an important factor in determining the compression ration an engine can use;
- Flame speed: At stoichiometric fuel mixtures the flame speed for hydrogen is nearly an order of magnitude greater than that of petrol and under these conditions can more closely approach the thermodynamically ideal engine cycle. However, at leaner mixtures the flame velocity decreases significantly;
- Diffusivity: Hydrogen's high diffusivity facilitates the formation of a uniform fuel air mixture;
- Density: Hydrogen's low density leads to a low energy density of the hydrogen-air mixture and hence relatively lower power outputs.

In principle HICEs are available technology but they are not currently being manufactured for use in mCHPs.

Gas Turbines

The requirements of LNG plants have already prompted gas turbine (GT) manufacturers to carry out work to extend the ability of their products to operate across wider ranges of gas specification[xxi].

Hydrogen or high hydrogen content fuel gases are available from some industrial processes. The use of hydrogen as a fuel for large industrial GTs has been considered.

The requirements of LNG plants have already prompted GT manufacturers to carry out work to extend the ability of their products to operate across wider ranges of gas specification[xxii]. They were able to demonstrate low emission capabilities at a range of loads (between 30% and 90%) for fuel gases including hydrogen. They concluded that a turbine combustor designed for IGCC application "can be readily used to meet the low emissions requirement and wide engine operating range on high hydrogen content syngas fuel operation in advanced 50 Hz and 60 Hz gas turbines in IGCC applications."

Chiesa et al[xxiii] discussed the issues and in particular noted the limitations on the options for NOx control imposed by the high flammability limits of hydrogen. They performed simulations to assess the impacts. Their findings were that it is possible to run gas turbines designed for natural gas on hydrogen, however the stoichiometric flame temperature must be limited to around 2300 K to comply with NOx emission limits without flue gas NOx abatement. Even with limiting the temperature of the flame, only minor losses of efficiency were observed. The flame temperature was limited by introducing a diluent gas into the hydrogen stream, the diluent gases investigated were steam and nitrogen. The use of nitrogen as a diluent led to minor decreases in efficiency.

B&B-AGEMA, Kawasaki and FH Aachen have together developed hydrogen combustion technology for gas turbines. At the STAR Global Conference in 2015 they showed that very low NOx levels could be achieved[xxiv].

Appliances and Equipment

According to Jones[xii] "Engineers involved with domestic gas appliances can normally restrict their area of interest to gaseous fuels burning in air at approximately atmospheric pressure. The prime objectives of the burner designer are to ensure that (a) the correct mixture of gas and air is supplied, (b) ignition is controlled and reliable, (c) the resultant flame is of the required shape and structure and is stable, and (d) the appliance is inherently safe."

These prime objectives are generally applicable for gas combustion appliances.

In addition to these functional objectives, it is also necessary to achieve environmental objectives and in the case of hydrogen combustion this means achieving NOx emission limits.

In designing hydrogen fired products, various aspects need to be considered, including:

- Burner selection: Burners need to be matched to their application such that such characteristics as flame shape/ size and heat release rate/ pattern are suited to the surface/ space that they are required to heat;
- Burner positioning: Burner positioning is also a consequence of the characteristics mentioned above;
- Opportunities for innovative product designs: In creating products for a different fuel, there may be opportunities to create new product types or at least to create products that meet demands in different ways;
- Flue arrangements: Flueless arrangements offer some attractions and there may be more opportunities for these for appliances firing hydrogen.

Boilers and Water heaters for Domestic and Small Commercial Applications

In modern boilers, the need to have accurate control over the combustion process in order to minimise energy consumption and pollutant formation has resulted in the use of burners where the air supply is positively controlled. So, the burners are in general fully pre-mixed forced/induced draft pressure jet or distributed flame types.

Driven by the efficiency requirements in current regulations, gas fired boilers rated up to 400kW are now condensing. That is that they are designed to recover heat from the water vapour in the flue gas produced by combustion of any hydrogen in the fuel. The amount of heat associated with water vapour in the flue gas from hydrogen will be proportionately higher than that from firing natural gas (to release the same amount of heat ~1.7 times as much water vapour is produced from hydrogen as from natural gas) and so recovering this heat using condensing technology will be of greater significance. However, it is noted that this opportunity is very limited when the boiler water return temperatures exceed around 50°C. So, the benefits for boilers used to provide hot water for processes operating at higher temperatures are limited.

The functionality of water heaters is essentially the same as that required for the water heating capability of a combination boiler and the technologies used are essentially the same. In fact, some boilers that are presented as regular boilers are effectively combination boilers with the water heating capability not enabled. The reverse approach is not seen for water heaters, however they could be viewed as boilers that only have the water heating capability installed. This is the same as for storage water heaters which operate similarly to storage combination boilers.

Studies of performance of boilers fired with hydrogen and mixtures of hydrogen and natural gas have been undertaken. Hoelzner & Szyszka[xxv] investigated the operation of two Buderus 20 kWth Logana-Ecomatic-plus condensing boilers firing hydrogen, natural gas and hydrogen/natural gas mixtures. These are cast iron boilers introduced in the early 1980's and not typical of most modern domestic boilers. For this work prototype burners from Kromschroeder were used. They found little dependence of performance on fuel gas. An increase in NOx production was found as hydrogen content of the gas mixture increased. This was attributed to increases in flame temperature but the researchers admit that no burner optimisation had been undertaken at this initial stage of the studies. Nonetheless, the work illustrated that creation of hydrogen fired boilers might initially be achieved by re-burnering of existing boiler designs.

In modern boilers the need to have accurate control over the combustion process in order to minimise energy consumption and pollutant formation has resulted in the use of burners where the air supply is positively controlled. So, the burners are in general fully pre-mixed forced/induced draft pressure jet or distributed flame types. Within the limits set by nozzle sizes the positive control approach should simplify conversion of burners to fire different gases, even hydrogen.

Currently, boiler models designed for hydrogen firing are few and models that are available utilise catalytic burners rather than modified pressure jet or distributed flame technologies.

Italian manufacturer Giacomini has developed a 5kW (nominal heat output) condensing hydrogen boiler that is CE marked and on the market. It employs a catalytic burner with a reaction temperature of between 250°C and 300°C. Due to these low combustion temperatures thermal NOx does not occur. Technical data of this hydrogen boiler is provided in Table 4 and the unit is shown in Figure .

Table 4. Technical detail of the Giacomini hydrogen boiler[xxvi]

Technical detail	Unit	Value
Nominal heat output	kW	5.01
Nominal heat power	kW	5.36
Useful efficiency (maximum)	%	106.7
Inlet gas pressure	bar	5
Purity of hydrogen	%	99.5
Hydrogen consumption at nominal power	Nm^3/h	1.67
Maximum temperature on catalysts	°C	400
Average exhaust temperature	°C	40
Maximum condensing water in exhaust	l/h	1.34
NOX concentration	ppm	0
Water set temperature	°C	30-60
Net weight	kg	40
Length	mm	888
Width	mm	520
Height	mm	314

Figure 3. Giacomini hydrogen catalytic boiler (Giacomini, 2011)

Studies have been undertaken with combustion taking place inside 'catalytic heat exchangers'[xxvii] but the technology does not appear to have progressed to being embedded into products.

Direct Space Heaters

Appliances that are not externally flued will introduce higher levels of moisture into a space compared with a natural gas fired unit. There are in any case minimum room size and ventilation requirements for natural gas fired appliances used without external flues[xxviii]. These requirements would need to be examined to determine whether they are sufficient to avoid build ups of moisture in spaces and the consequent condensation and such issues as mould growth. There may be implications for appliance design such that emission of water vapour would need to be controlled. Possible approaches include; enhanced ventilation requirements for spaces and regulation of the permitted rates of water vapour emission which may requireme incorporation into appliances of condensing capabilities.

Gas fired radiant heaters

Radiant gas fired heaters are used in a variety of settings. In domestic and some small commercial uses, radiant gas fires may be used and these typically also provide some heat by convection. Current natural gas / LPG designs generally seem to use partially pre-mixed burners although there are some designs based on catalytic burners.

For domestic use the typical appliance is the 'gas fire'. This is available in a variety of types:

- Conventional open fronted flued gas fired (radiant ceramic plaques);
- Fuel effect flued gas fires – glass fronted, or open-fronted;
- Flame effect glass fronted, wall mounted flueless.

In creating flame type radiant heater for hydrogen, attention to flame visibility is required for both aesthetic and, in the case of open fronted appliances, safety reasons. Simple non-aerated bar burners for hydrogen can be found on the internet e.g. those offered by H2-NRG[xxix], which suggests that the basic technology for a flame effect fire is possible. However, significant work may be required to develop a satisfactory visual appearance in use.

Enclosed flame effect fires that use natural gas incorporate additional protection to ensure that CO or unburned fuel is not emitted. (Note the conversion catalyst at the outlet to the combustion space in Figure 4.) This would not be an issue for units fired on 100% hydrogen.

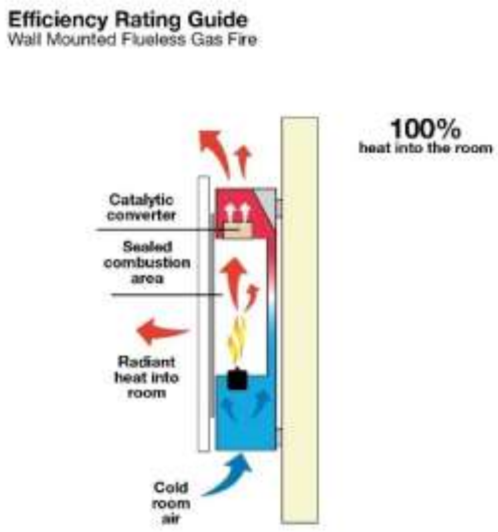


Figure 4. Example of a flueless gas fire layout

Radiant heaters are widely used to provide space heating for warehouses, retail sheds, sports centres, factories, and other buildings containing similarly large spaces. Radiant heaters contain a burner that is used to heat a tube, cone or plaque that emits infrared radiation when hot. This infrared radiation is focussed and directed downwards by reflectors within the product.

Tube heaters involve firing a fully pre-mixed burner into a tube, effectively a long, hot flue which radiates heat into the space. Conversion to fire hydrogen is likely to involve similar considerations to those generally applicable for designing and operating pre-mix burners.

Jones[xii] discusses two main types of radiant burners:

- Radiant plaques - discrete holes through the ceramic form the burner ports;
- Porous medium burners - consisting of layers of ceramic fibres, or foam through which the gas/air mixture may pass.

These are fully aerated burners with significant levels of excess air. The flame types and issues, particularly light-back are similar in plaque burners to other burners where discrete burner nozzles are used. However, for porous medium burners it is noted that there are three combustion regimes have been identified:

1. ‘Free flame’, where flames burn above the surface of the burner without significant emission of radiant heat;
2. ‘Surface combustion’, where combustion occurs at or just under the burner surface, raising the latter to incandescence;
3. ‘Unstable interstitial combustion’, where the burning velocity is greater than the flow velocity and the flame propagates, often very slowly, upstream through the porous medium, resulting ultimately in light-back behind the burner block. This propensity for light-back appears to be a function of the pore size in the burner.

In the case of hydrogen, the high flame velocity makes light-back much more likely than for hydrocarbon gases. Particular attention would need to be given to this in creating fully aerated porous medium burners.

Catalytic flameless heaters

The ‘combustion’ temperature is much lower for catalytic combustion than for conventional combustion.

Pyle et. al described the conversion of catalytic radiant heater from natural gas to hydrogen operation[xxx]. These are typically designed for use with propane in mobile/leisure applications such as heating boats or caravans and have outputs of up to a few kW. The investigations involved minor modifications to the fuel supply arrangement. The combustor was a Pt impregnated silica quartz fibre pad and ignition was achievable with no external ignition source such as a spark or flame. The combustion was not aerated.

This demonstrated the principle of creating a hydrogen fired catalytic heater. However, from the descriptions provided it was clear that additional work would be required to produce a safe and reliable product.

Gas fired convector heaters

Gas fired convector heaters for domestic and small commercial uses are typically compact units. Flued and flueless designs are available. These units do not require flames to have aesthetic appeal and the main issue in creating hydrogen products would be the design of suitable burner units.

Cooking Appliances

In general, the technologies used in domestic and commercial cooking appliances are of similar types. The most obvious difference is in the output of burners for these two applications, with higher ratings being required for commercial cooking appliances.

Some hydrogen fired cooking equipment is available on the internet mostly from US suppliers. Their existence indicates interest in the use of hydrogen for cooking and that efforts, albeit generally at small scale, are being made to enter this currently niche market. However, evidence of demonstration of compliance with existing US gas appliance standards / regulations was not found and the information available for some of them give a low level of confidence in their safety.

Often the opportunities for hydrogen firing highlighted in the US are associated with use of surplus renewable power to drive electrolysers attached directly to combustion systems which are designed to operate with the resultant HHO fuel. So, knowledge may not be directly transferrable to the use of distributed hydrogen.

Gas Hobs

Conventional hobs are based on some form of partially premixed burner. The relatively intense blue colouration of the natural gas flames means that they are generally sufficiently visible to avoid accidental contact by users.

As already mentioned, hydrogen flames are hard to see in direct light. However, they are expected to be reasonably visible in practice in kitchens. Nonetheless, creating analogous products to burn hydrogen will, for safety reasons, require some attention to ensure adequate levels of flame visibility.

As already mentioned, light-back is a particular risk for hydrogen air mixtures. One example of a hobbyist design published in the US is for a non-aerated hob burner[xxxi] (Figure 5). The incorporation of the steel mesh around the burner is reported to provide a visual indication of the presence of the flame as the hot metal glows red during operation.

A US supplier was identified that had been selling old style stand-alone gas hobs with 1, 2 or 3 burners for ‘hydrogen or propane’[xxxii] but these are no longer available.

The lower volumetric energy density of hydrogen compared to natural gas means that achieving sufficient levels of heat input to match those from natural gas use may be an issue. This is highlighted in the hydrogen homestead investigation[xxxiii]. However, further study is required to this potential barrier can be overcome either through design modification or a technology change and it is possible that a move to hydrogen will open opportunities for other technological approaches to enter the market place.

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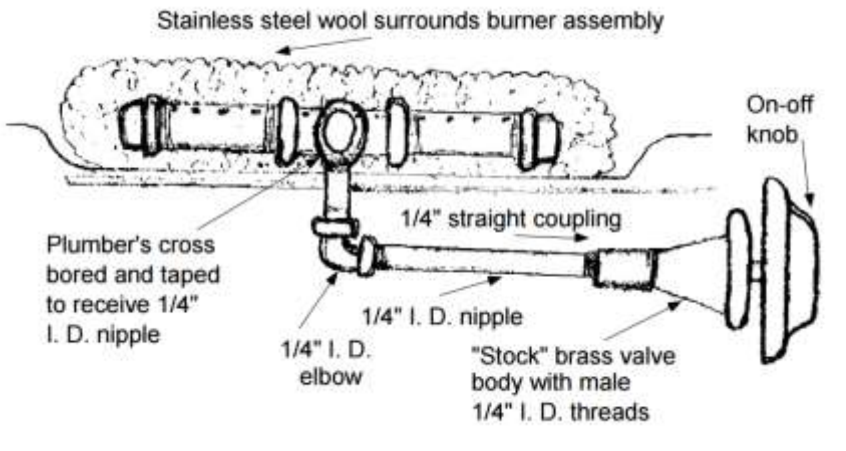

Figure 5. Pure hydrogen burner design without primary or secondary air mixing. (Booth, D. & Pyle, W., 1993)

A new type of catalytic burner based hob has been developed by the Swiss Federal Laboratory for Materials Science and Technology (EMPA)[xxxiv]. This uses a catalytic hydrogen burner based on a highly porous silicon carbide (SiC) ceramic foam with a platinum catalyst. This catalytic burner is formed from porous SiC plates coated with a platinum catalyst and air is provided so that combustion only occurs in the SiC layers. The burner has been integrated into an appliance by placing in a casing with a glass top to resemble current electrical domestic hotplates (Figure 6). This device also includes a heat exchanger that heats incoming combustion air to improve the product efficiency. This design overcomes any potential concerns about flame visibility.

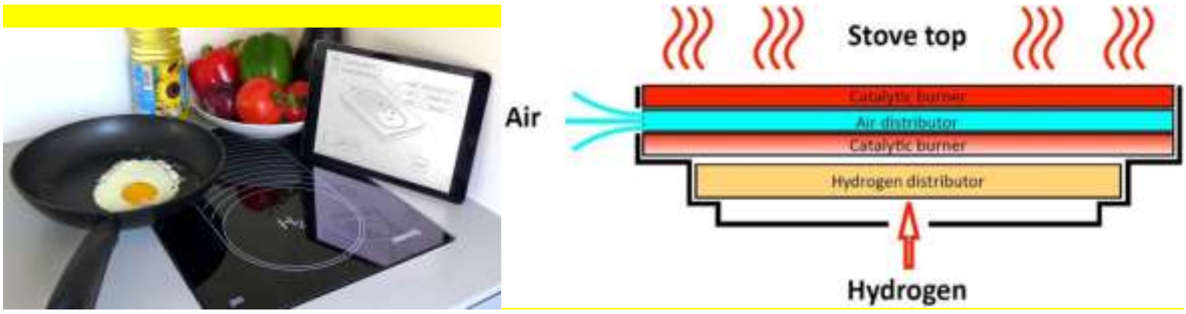

Figure 6. Integrated hydrogen catalytic burner (Ulrich, V. (EMPA), 2015)

Gas fired ovens

Gas fired ovens have a particular need to achieve suitable cooking conditions within a confined space. The relatively higher levels of moisture generated from hydrogen combustion compared to hydrocarbon fuels is a factor that will need consideration in the design process.

Some types of oven cooking may benefit from higher moisture levels (e.g. meat roasting and bread making, the latter which often employs additional moisture injection or, at commercial bakery, steam) whilst in other cases (e.g. pastry baking, the baking time may be extended or it may be difficult to achieve the desired bake). However, it does not appear that this would be a fundamental barrier to creating effective hydrogen fired ovens as there are possible avenues that could be investigated to provide the required cooking environment. These could include:

- appliances of the solid fuel range style (combustion is not inside the oven) although this will not suit all users
- adding the ability to condense some of the moisture (about 40% removal would reduce it to the levels present in natural gas fired ovens) perhaps also providing combustion air preheating,

Burners

Industrial burners are available for a wide range of fuel gases due to fuel availability from hydrocarbon processing. Manufacturers offer either burners specifically designed for fuels or customised versions of standard process burners. For example, Saake offer burners to utilise a variety of gases including refinery gases with significant hydrogen contents[xxxv]. They note that all special gases “require a heat value measurement in the gas valve train to record the actual, current heat value and transfer it to the burner control unit. In this way the burner will then receive the correct amount of air or additional natural gas as well to combust the special gas cleanly and with priority.”

Fuel cells and Micro-CHP

Hydrogen is an ideal fuel for fuel cells as there are no risks of carbon deposition or poisoning of the catalyst by e.g. the odorant present in natural gas, although it is likely that hydrogen supplied through gas distribution networks will require such additives to facilitate leak detection and this will subsequently need removal. Using hydrogen in fuel cells instead of natural gas will also decrease material and component costs as there would be no need for the steam reformer. The barriers to creating suitable hydrogen fuel cell appliances should therefore not be higher than for creating them for natural gas. PEMFC and SOFC are TRL 9 for some applications, but still require subsidies for many applications as they are not yet fully commercially mass-produced. Development activities currently focus on cost reduction and stack lifetime improvement. Current lifetimes for stationary applications vary, with Japanese companies warrantying residential PEM CHP units up to 60-80,000 hours with the ENE-FARM fuel cell warranting up to 10 years[xxxvi]. Other types of fuel cell achieve around 30,000 hours with developers aiming to double this by system optimisation and development of more robust materials.

In general, a decentralised micro-CHP fuel cell system can be more efficient than the typical current combination of the grid plus a boiler, as there is less inefficiency associated with energy conversion and transmission losses. But a central issue in designing fuel cell CHP is that electricity and heat demand in homes are independently variable, both diurnally and annually, which makes sizing a small generator for a home very hard. At one extreme, the generator can provide even the highest peak demand of the home, in which case it will be very expensive and not used at full capacity for the vast majority of the time. Sizing it to only provide the baseload power, so it will run permanently at high efficiency, means that the by-product heat it produces must also be used and something else must supply the remainder of the power for peak demand.

As for market development, sales of fuel cells in all applications Europe are low, including for stationary power. Nevertheless, for fuel cell mCHP Europe probably ranks second to Japan in terms of its near-term potential, with a number of current and past support schemes creating sufficient interest for large manufacturers to become engaged. However, these support schemes are much smaller than those in Japan and expected to remain so. In addition, Europe has more manufacturers and more different system designs so cost reduction through manufacturing volume and supply of similar parts will be limited for some time. The different system designs are in part due to the different underlying technologies; in part to the different heating, electricity and hot water requirements in countries with both different climates and different buildings standards.

Germany is the most appealing market at present, as shown both by the variety of available support and the number of locally-based manufacturers. Customers potentially have both greater ability and willingness to pay for the perceived advantages of fuel cells. The Netherlands and the UK also have some appeal. Table 4 shows the number of stationary fuel manufacturers in different countries.

Table 4. Number of stationary fuel cell manufacturers in different countries

Country	Number of manufacturers
Canada	2
China	7
Denmark	2
Germany	11
Japan	4
Mexico	1
Republic of Korea	5
Singapore	1
South Africa	1
Spain	1
Sweden	1
Taiwan	4
UK	4
USA	7

Source: E4tech internal. Data from Fuel Cell Industry Review (2015)

While a large German support programme for fuel cells is anticipated in the near future, it is not confirmed and no clear indication of its possible size has been announced.

The competitive landscape in Europe is complex – not only do both PEM and SOFC systems exist, but sizing is different, and developers span the range from extremely large corporations to pure-play fuel cell start-ups, both public and private. Each of the roughly ten active players has systems with advantages and disadvantages.

Overall, it is unclear whether the market will develop sufficient volume to 2020 to allow costs to be reduced enough for fuel cell mCHP to become mainstream. While the total accessible market in just Italy, Germany and the UK is estimated at around 300,000 units per year, only a fraction of this would be captured by fuel cells in the near future. Examples of current available products on the market include:

- Buderus Logapower FC10 energy centre: this is based around a ceramic solid oxide fuel cell (SOFC) which operates at 700 °C and provides electrical and thermal outputs of 700W each. It is claimed to achieve an electrical efficiency of up to 45%. The system also houses a Buderus Logamax plus GBH172 hybrid gas condensing boiler with a nominal output of 14 kW, a 75-litre hot water storage tank and a 150-litre buffer tank;
- BDR Thermea Gamma 1.0: this is a Proton Exchange Membrane (PEM) type fuel cell appliance which delivers 1.0kWe and 1.7kWt. It is yet to reach market but is undergoing field trials;
- Dantherm: offers the ElectraGen –system for modular backup power solutions using hydrogen. System available in 1.7 kW and 5kW. Dantherm also offers products running on reformed methanol fuel;
- Viessmann Panasonic: Vitovalor 388-P[xxxvii]. Low temperature PEM fuel cell providing 0.75kWe and 1kWt;
- Hexis Viessman: Galileo 1000 N[xxxviii] SOFC micro-CHP running on natural gas or bio-methane providing 1kWe and 1.8kWt running at an electrical efficiency of 35% (AC, net; based on lower caloric value) and an overall efficiency of 95% (based on lower caloric value);
- SolidPOWER BlueGen: SOFC micro-CHP running on natural gas or bio-methane running at an electrical efficiency of 60% and an overall efficiency of 85%.

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Table 5. Techno-economic parameters for common micro-CHP fuel cell systems

Companies	Price	Performance
Hexis, ElCore, Buderus, Junkers, Senertec, SolidPower, SolidPower BlueGen, Vaillant, Viessmann, Ceres Power, Bosch, RBZ, Dantherm Power and IRD	€8,000-€12,000 for a 1kWe fully integrated system (SOFC - including auxiliary condensing boiler for winter heating loads, and water tank) is required to bring fuel cells into the mass market	Efficiencies range from 32-60% (LHV) net electrical and lifetimes of around 30,000 hours (or around 3.5 years assuming 100% load factor).

Source: E4tech internal

Other Relevant Appliances / Applications

Process heating burners

Coates et.al described investigations for firing of a rotary kiln with hydrogen[xxxix]. The burner used for the test work was a standard commercial Wide Range burner (from Maxon[xl]) for firing natural gas, hydrogen with a maximum firing rate of 150,000 BTU/hr (~44kW). The conditions tested are summarised in Table 6.

Table 6 Kiln burner test conditions

	Natural gas	Hydrogen
Firing Rate, kW	26.7	26.7, 43.1, 46.0
% Excess Air Range	-55 to +41	-86 to +910
Probe temperature range, °C	765 - 924	816 - 982
Flame	Transparent	Orange

Images of the flames at various firing rates and excess air levels show a more complex picture. At the lowest firing rate of about 27kW and excess air level of +13% the natural gas flame was transparent but blue in colour. Firing hydrogen at the same rate there was an opaque orange luminous flame. This gradually became transparent and less coloured as excess air level was increased from -52%, through -23%, -2%, +50% until at +97% the flame was colourless and transparent. They also showed that the brightness and colour of the flame became more intense with increased firing rate.

The study showed that stable hydrogen/air flames could be produced for a wide range of fuel air ratios. Ignition with natural gas for a limited period was found to increase reliability and safety.

Hoenig et. al.[xiv] in their review of options for carbon reduction in the cement industry note that due to its "explosive properties" hydrogen could not be used as the main kiln fuel in existing cement kilns unless diluted with other gaseous fuels or inert gases such as nitrogen or steam. Hydrogen's combustion characteristics and flame radiance are such that "the clinker burning process would have to be significantly modified".

Gas-fired heat pumps

Gas-fired heat pumps can, in principle, be used to increase the efficiency of domestic/commercial heating by extracting and upgrading heat from the surroundings are of three main types; gas engine, absorption and adsorption. An overview of opportunities from Delta-EE in 2012[xli] found no products suitable for domestic retrofit applications. The most commonly available type is gas engine based although these tend to be larger than is suitable for most domestic applications. However, other types are available in the market.

- Since 2013 Viessman were marketing a gas fired adsorption heat pump (Vitosorp 200-F) and a gas absorption heat pump (Vitocaldens 222-F Compact Gas-Hybrid).
- Since 2012 Vaillant have marketed (though not in the UK) a gas fired absorption heat pump (zeoTHERM) and a gas fired adsorption heat pump (zeoLITH).

The market in the UK for domestic gas fired heat pumps appears quite immature with few products available. However, development of hydrogen fired versions of such products would appear only to offer similar challenges to those for creation of suitable hydrogen burners for domestic boilers or for creation of hydrogen fired gas engines for other applications such as mCHP.

Generators and Micro CHP

A range of technologies are currently used for small and micro- CHPs and standby generators.

Internal Combustion Engines (ICEs)

Possibly the most common mCHPs are based around ICEs. Some products are available

- BDR Thermea: Dachs Pro 20
  This is based around Volkswagon EcoBlue 2.0 engine, producing 5.5kWe and 12.5kWt.

There do not appear to be any reasons why a gas, diesel or petrol ICE in a generating set or CHP could not in principle be replaced with a hydrogen ICE.

Fuel cells

A few natural gas fuel cell based products are already available or expected to enter the market. These include:

- Buderus Logapower FC10 energy centre - This is based around a ceramic solid oxide fuel cell (SOFC) which operates at 700 °C and provides electrical and thermal outputs of 700W each. It is claimed to achieve an electrical efficiency of up to 45%. The system also houses a Buderus Logamax plus GBH172 hybrid gas condensing boiler with a nominal output of 14 kW, a 75-litre hot water storage tank and a 150-litre buffer tank;
- BDR Thermea: Gamma 1.0;
  This is a Proton Exchange Membrane (PEM) type fuel cell appliance which delivers 1.0kWe and 1.7kWt is yet to reach market but is undergoing field trials;
- Dantherm.
- Viessman Panasonic: Vitovalor 388-P[xlii]
  Low temperature PEM fuel cell providing 0.75kWe and 1kWt;

Hydrogen is an ideal fuel for fuel cells as there are no risks of carbon deposition or poisoning by e.g. the odourant present in natural gas, although it is likely that hydrogen supplied through gas distribution networks will require such additives to facilitate leak detection. So the barriers to creating suitable fuel cell appliances should not be lower than for creating those for natural gas.

Stirling engine

There are a few examples of Stirling Engine based mCHP directly fired by a gas burner:

- Baxi: Ecogen[xliii] / Remeha: Evita[xliv]
  Both produce up to 1kWe;
- Micro Engine Corporation[xlv].

All these products are based around ‘Free Piston Sterling Engine’ technology and are marketed as combi or system boiler replacements.

The main requirement to enable hydrogen firing is likely to be adjustment to the burner head design and possibly to the gas train.

Micro-gas turbines

Currently microGT based mCHP are not apparent in the market so they must be considered as still to be in a development stage.

There is some evidence of work on the application of microGTs for small scale generation. Calabria et. al.[xlvi] investigated the creation of a small scale portable power generator based on a microGT available for 'model aircraft' market in the US[xlvii].

However, whilst at 'industrial scale' gas turbines for a range of fuels including hydrogen are potentially available at the micro-scale the studies related to hydrogen firing are largely based on modelling and no evidence was found of the availability of such technology.

UK Specific

Most major manufacturers of gas fired appliances and equipment have a global reach. Their response to opportunities for hydrogen fired types in the UK market is likely to be affected by this.

Locally in the UK there are small/micro businesses that are seeking to prepare for a potential market in domestic scale appliances, principally for cooking appliances in this market. Here in the UK there are a number of very small companies in the cooking area, for example

Almaas Technologies Limited[xlviii] is a small independent clean-tech company conducting hydrogen burner feasibility work with the aim to develop fit for purpose products of high quality and performance to support the de-carbonisation of heat applications and commercialisation of low/zero carbon energy systems'. They have already demonstrated the conversion of catering appliances to hydrogen fuel.

Pure Energy Centre are a renewable energy technology company based in Shetland. They provide a range of hydrogen technology products and offer to supply hydrogen cookers[xlix] and boilers[l] (which appear to be badged version of the Giacomini product, however, no images are currently available on their website).

Conclusions

The same basic technologies for utilisation of natural gas in appliances and equipment may also be applied for hydrogen.

Some adjustments to the design of combustion devices may be required to accommodate the physico-chemical properties of hydrogen.

For burners burner nozzle/orifice dimensions and hydrogen|air mixing arrangements require particular attention. In some cases, similar types of burner are used in a variety of appliance types so development work for a boiler may also open the way for related products such as waterheaters to be offered as hydrogen fuelled versions.

For some types of device, the transition to hydrogen from natural gas firing appears relatively straightforward e.g. for fuel cell based products.

Ability of technologies to meet regulatory requirements and in particular those for NOx emission (many of which will apply from 2018) is an important consideration for product developers. Some technology options are inherently low in NOx production (e.g. catalytic burners and fuel cells) although they will not be suitable for all types of application.

Ultimately the entry into the market of products will likely be driven by the demand created by the opportunities created by firm plans for converting gas supplies from natural gas to hydrogen. Initially these are likely to demand 'like for like' replacement of equipment so hydrogen versions of appliances currently in use are likely to be drawn into the market. As the process progresses there is likely to be more opportunity to offer alternative technologies which require more work to install because e.g. central heating systems need to be modified to work effectively with them., but provding longer term benefits.

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10.2 Notes of meetings

10.2.1 Institution of Gas Engineers and Managers

Hydrogen distribution and use

Current practice, theory and potential for IGEM Standards - Asking the right questions

Meeting report from 17th December 2015

Attendees

Alastair Rennie (AMEC)
Alan Christie (DECC)
Chris Gorman (IGEM TCC Chairman)
Graham McKay (BSI and IGEM GUC Member)
Mark Crowther (KIWA)
Jon Saltmarsh (DECC)
Lewis Quinn (KIWA)
Marcus Newborough (ITM)
Mark Crowther (KIWA)
Martin J Brown (DNV GL)
Paul Robson (E4Tech)
Phil Burnett (IGEM Head of Technical Services)
Rebecca Roughton (IGEM Technical Officer, Secretary)
Richard Miles (Bosch)
Ross Anderson (ICOM and IGEM GUC Member)
Sarb Bajwa (IGEM Chief Executive Officer)
Siv Almaas (Almas Technologies)
Steve Corner (BOC)
Stuart Hawksworth (HSL).

Meeting Report

General Introduction and facilities

Phil Burnett - Head of Technical Services at IGEM was the chair for the meeting and facilities and introductions were made to the group. Notes were taken by Rebecca Roughton – Technical Officer at IGEM.

All the attendees for the day introduced themselves, their background and particular interest in Hydrogen.

Introduction about IGEM

Sarb Bajwa gave an introduction to IGEM. IGEM is a professional registration and membership body and is trusted and recognised in the gas industry both in the UK and worldwide. IGEM has developed a suite of technical Standards that have been drafted in compliance with relevant Codes of Practice, Regulations and Legislation to establish robust industry requirements for best practice, taking into consideration new technology and innovation.

These Standards are reviewed on a regular basis to factor in changes in best practice, Legislation and Regulations ensuring the Standards are always up to date and current. This process fundamentally is primarily facilitated by volunteer Panel members who are recognised within the industry for their particular area of expertise.

Jon Saltmarsh

A presentation was made by Jon Saltmarsh from DECC. This covered the importance of energy and that the UK have great potential for technology and new ideas moving forward in the forms of heat pumps, hydrogen and biogas to name a few.

Other aspects highlighted were;

- Long term plans for the UK and energy
- Costs
- Decarbonising the gas grid
- People and legal acceptance
- Further work in this area.

Mark Crowther

The next presentation was by Mark Crowther from KIWA. This was to set the scene for the day. A background to the group was given around Hydrogen as a potential fuel and what work has already been done.

Mark discussed the “converting Leeds to Hydrogen” project (H21 project) that is being undertaken by Northern Gas Networks.

IGEM has been identified as being the most obvious organisation to support any future utilisation of hydrogen through the potential development of additional IGEM Standards in relation to hydrogen. Currently there are few standards available that deal with Hydrogen as a transported fuel.

Mark also briefed the group on the HyHouse project that Kiwa have been working on.

Marcus Newborough

The day then proceeded with a presentation from Marcus Newborough from ITM. This presentation was based on the future supply and demand situation for hydrogen and who would have responsibility for this.

The production of Hydrogen was also discussed along with the demand for heat and storage. The supply and demand issue was a topic the group felt was not necessarily in the remit for the purpose of the days’ discussion.

Stuart Hawksworth

The final presentation was by Stuart Hawksworth from the Health and Safety Laboratories (HSL). Stuart went through examples of the issues found so far, in particular associated with use of hydrogen in vehicles. This is because the pressure is higher and presents a bigger challenge due to the turbulence.

Work has been done for industry and nuclear and HSL have been looking at ventilation control of the flammable atmospheres associated in particular with the buoyancy of hydrogen. The Health and Safety Executive currently have a guidance document RR715 for Hydrogen and fuel cell installation.

Stuart also referred to the High Hydrogen Project which is based on gas turbines and pure Hydrogen for energy installations, together with the explosive behaviour and the need to fully understand the conditions that cause problems.

The conclusion from this presentation was that although Hydrogen can be a difficult gas to work with, the challenges are not unsurmountable and can be overcome.

Open forum discussion

The day followed with a more open forum approach with the chance for the group to discuss their issues, comments and concerns. These comments and discussions from the day have been summarised into the following key topics;

Standards and IGEM

- How this work on potential Hydrogen Standards could be fed into the current system from a process perspective
- Whether there is a need for new Standards or to modify the relevant existing Standards to incorporate Hydrogen as well as the usual gases
- Depending on decisions relating to the above, this work could be either incorporated within the body of existing Standards, or added as a separate appendix or supplementary section
- Not all IGEM Standards would be applicable
- Timescales required for IGEM to review, update and publish any changes in the Standards would need to be taken into consideration.

Appliances and equipment

- How appliances will work when burning 100% Hydrogen and the associated safety/environmental concerns
- Certification, safety and testing of Hydrogen burning appliances and whether existing appliances can be converted
- Some manufacturers are prepared for this
- The Gas appliances directive already includes Hydrogen in its expression and CE marking is following this principle
- Would also need to take into consideration all other materials and gauges to ensure compliance
- In the past many appliances were simple, now much more complex
- Need to give reasonable time for manufacturers to create/adapt appliances if Hydrogen introduced.

Infrastructure

- Capability of polyethylene and steel pipe for conveying Hydrogen and whether the existing infrastructure needs to be adapted
- Conversion – if conversion needs to be adopted, how this will work and what are the associated risks and costs. Evidence would need to be obtained for this
- The conversion from ‘‘Town Gas’’ took a long time and presented many challenges. A local or regional conversion to Hydrogen would present many similar aspects to consider. Is it possible to mix Hydrogen and Methane which would be an alternative to a full conversion?
- Hydrogen concentrations required and carbon deposits produced, however mixing is not the way forward
- To prove and use the existing infrastructure instead of creating new pipework if this is possible
- Evidence would need to be gathered about using Hydrogen in the existing infrastructure taking into consideration all aspects of the transmission and distribution pipework; welds, fittings, valves, regulators, meters etc. plus any associated pressure losses
- Will the proximity distances for high pressure pipelines need to be readdressed and will the existing proximity distances be appropriate if the pipe is conveying Hydrogen instead of Natural Gas?
- Key stakeholders must be involved.

Incorporation

- Gas Safety (Management) Regulations discussed in terms of the current Regulation

- The level of conversion, starting on a smaller scale and how this would be introduced?
- Discussion on resources and what will be achievable by 2050
- Supply and demand and boundary conditions
- Security of supply and strategy for the future
- Storage and assets and trying to match what is needed to maintain the security of supply
- Whether it is possible to switch from Natural Gas and Hydrogen and vice versa to match supply and demand
- The levels of pressure, velocity and flow required in pipework and how this will be managed, maintained and controlled
- Production and distribution of Hydrogen
- Odourisation for public safety
- Will need input from Gas Distribution Networks for their support.

Costs

- Costs involved for a conversion, production, transmission and storage Hydrogen, consumers need to be in the forefront
- Funding for any evidentiary work to be carried out, can be part of the innovation funding if available
- This is positive step forward for Ofgem to consider.

Other aspects

- The H21 Leeds project may have a significant impact on policy decisions regarding Hydrogen moving forward
- Flame visibility is a concern and leakage limits/rates might be different
- The characteristics of Hydrogen, the ignition, lower density and flammability range
- The training of employees and safety
- The Wobbe index range between Natural Gas and Hydrogen.

Actions and next steps

- The TCC chairman agreed for an IGEM Hydrogen Working Group to be set up to discuss the various issues with Hydrogen and the potential for IGEM Standards
- IGEM to write out to attendees to seek representatives and a chair for the working group
- IGEM to contact Northern Gas Networks to discuss potential funding to support the working group
- The report from the Leeds H21 project will be an important factor in moving the work forward; this report is due to be issued in April 2016.

10.2.2 HHIC

HHIC – Development of a supply chain for hydrogen-fuelled technologies

Kiwa Gastec, Cheltenham

Thursday 7th January 2016

Notes of Meeting

Attendees:

Steve Sutton	HHIC	
Neil Macdonald	HHIC	
Stephen Stead	Toshiba Global	
Martin Butcher	Vaillant	
Edward Harris	Bosch	
Richard Miles	Bosch	
Gary Mitchell	Bosch	
Tom Collins	Bosch	
Mike Hook	Biasi UK	
Darren Smith	Alpha-Innovation	
Jeff House	Baxi	
Mark Crowther	Kiwa	
Iain Summerfield	Kiwa	Chairperson
Mark Dorrington	Kiwa	
Oliver Grasham	Kiwa	

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1. Round table introduction

2. Introduction from Iain Summerfield (Chairperson)

Summarising:

- Iain Summerfield explained that Kiwa Ltd., in partnership with E4Tech, have recently been awarded a DECC (Department of Energy and Climate Change) contract to research and understand the technical challenges and costs of developing gas combustion appliances and fuel cell technologies which will be capable of operating in a 100% hydrogen grid.

- DECC recognise gaseous hydrogen as one of several plausible routes for decarbonisation of the UK energy supply system. At present DECC are gathering evidence to see if the development of hydrogen is a viable way to low-carbon heating at mass scale.

- Mark Crowther emphasised that DECC view carbon emissions reduction as essential, and therefore Government support may be available in the longer term to people developing reduction strategies.

- This was the first meeting of a series of stakeholder meetings (HHIC, CESA, CEA and fuel cell stakeholders) held with the objective of gathering and sharing information in support of the main aim of providing a view of the costs and barriers to the development of hydrogen appliances and to understand how these barriers might be addressed. Steve Sutton recommended that Kiwa also include ICOM and engage with British Gas (**Action 1**).

- Steve Sutton asked that he be copied in on details relating to the fuel cell meeting (**Action 2**).

- It was emphasised that the success of this project is dependent on stakeholders contributing openly both during the meeting and when completing the questionnaire, however, Kiwa will prepare appropriate confidentiality agreements and data protection procedures, if requested by stakeholders.

- Brief presentations were given by Mark Crowther (MEC) covering completed and on-going projects (further details provided in PowerPoint presentation). Results to date demonstrate the potential of hydrogen as being a safe replacement for natural gas. These projects have not identified any 'significant' technical showstoppers to the roll-out of hydrogen as a replacement for natural gas. Projects discussed included:

    - HyHouse;
    - H21 Leeds City Gate Project;
    - The existence of other DECC and CCC projects were mentioned.

- Kiwa presentation and HyHouse report will be circulated to attendees (**Action 3**).

- The level of decarbonisation would be very deep. 100% at point of use and possibly about 80% from hydrogen from an SMR.

- In a brief report of the IGEM meeting (held just before Christmas 2015), Iain explained that no specific IGEM standards / regulations currently exist for hydrogen fired appliances nor distribution networks. However, IGEM are now committed to review the inclusion of hydrogen (as another flammable gas) to their existing suite of standards.

- A discussion was held covering sources of hydrogen which are currently available. These included:

    – Renewable sources (wind, PV, etc.);
    – Steam Methane Reforming of natural gas with Carbon Capture and Storage (SMR and CCS);
    – Electrolysis using electricity from nuclear power plant.

- A manufacturer asked about the latest projected retail price for such hydrogen. MEC said this was difficult but after being pressed indicated probably / possibly (and for the furtherance of the discussion) significantly less than the current price of electricity, but this was the total cost including buying the natural gas, decarbonising it in an SMR, disposing of the CO_2 and converting houses (i.e. it was 'well to sofa'). This number could not be compared with the cost of electricity out of a power station. It was recognised that the costs discussed were only indicative given that the roll-out of hydrogen as a domestic fuel is unlikely to happen before 2020. One manufacturer was very concerned that this was a very large cost increase, but MEC explained that all foreseeable routes to deep de-carbonisation did involve cost increases, and saw no reason for not having these conversations regarding options for the future.

- Indicative costs were also discussed for gas conversion of a typical house. This discussion was based on findings from the Isle of Man project where properties have recently been converted from Town Gas to Natural Gas. This cost about £3,500 per property [17](By way of comparison, this was about half the price for internal solid wall insulation.) This is definitive figure has been published by the Isle of Man gas company. This figure was split into £1200 for actual appliance replacement/conversion (eg boilers, fires and cookers etc) and £2300 for other works eg service pipes, new meters, overheads etc but the precise definition of the categorisation is unclear.

[17] Private communication Manx Gas to M Crowther, supported by Ref' ieg-manx gas conversion project 21June 2012 Ross Armstrong'.

- Envisaged possible product roll-out was discussed with possible timings for a possible scenario.

Village	1,000 appliances	2018/19
Town	10,000 appliances	2021
Leeds	75-80,000 appliances	2023

It was stressed this was only a possible scenario (an 'Aunt Sally'). Most manufacturers thought this reasonable.

3. Key Topics for discussion

- Iain then opened the floor for discussion with the aim of collecting first thoughts, concerns, suggestions etc. The discussion centred around, but was not limited to the following points:
  - Plans and timetables for batch manufacture of hydrogen appliances;
  - Manufacturing costs;
  - Investments required by manufacturer;
  - Controls and usability of hydrogen appliances;
  - Issues associated with the manufacture of hydrogen appliances;
  - Barriers to developing a supply chain and incentives to overcome these barriers;
  - Review standards / regulations for testing hydrogen appliances which includes safety risks;

- A lively discussion took place with positive input from all manufacturers. The main points and feedback are summarised below with actions from the meeting listed at the end of this note. Iain explained that the information collected will be presented to DECC to enable them to understand the current position and concerns of manufacturers.

- Kiwa to circulate final report for 'DECC Desk study on the development of a hydrogen-fired appliance supply chain' to the participants. Report estimated completion date May 2016 (**Action 4**).

4. Summary of main points raised

- All manufacturers present were interested in contributing towards the aims of this project. Manufacturers' future roles were obviously dependent on their future market strategies and available budgets for R&D and product roll-out;
- None of the manufacturers are currently developing hydrogen appliances although some are looking at alternative fuels such as biogas. Only one domestic product was currently on the market;
- DECC support is essential if manufacturers are to gain confidence / reassurance – confidence also required in the future for suppliers, merchant outlets to market, installers (throughout the entire supply chain);
- Concerns over price war for contracts particularly during the initial stages of establishing a hydrogen network i.e. Leeds project onwards; contracts should not be arranged so that one company won everything;
- During the initial roll-out of products it is important that DECC engage in regulatory discussions with the distribution networks, perhaps setting target prices for all manufacturers providing a 'level playing field');
- DECC to provide delivery specifications, cost models, covering R&D etc.
- Manufacturers consider that this is a high risk venture and therefore DECC support in essential (50% support funding). This will assist manufacturers with internal R&D and demonstration costs;
- Manufacturers will need to consider IP issues;
- Manufacturers need to understand market strategy – e.g. what will be the typical appliance output (kW) from appliances - this has a significant impact on design / production costs. Manufacturers cannot design and produce family of products on small orders;
- Concerns were raised over amortisation, market competiveness / aggressiveness;
- Palatable costs to the public were discussed – fuel poverty issues depending on the geographical locations – not manufacturers' concern but needs addressing;

- Competent installers will be needed (hydrogen certified, retraining required) – costs associated with these activities;
- Different market strategies - training skills / competence will change (NG to Hydrogen);
- Manufacturers need to consider additional costs associated with skill levels / retaining of apprentices and existing engineers.

- All points raised above will be expanded upon and presented to DECC in the final report, ('DECC Desk study on the development of a hydrogen-fired appliance supply chain').

5. Concluding Remarks

- Hydrogen products were technically feasible;
- Manufacturers were positive in engaging and significant steps were made in understanding manufacturers' issues and concerns;
- They stressed the need to include the whole supply train e.g. including wholesalers & installers;
- They stressed the need for a planned and stage wise approach that would give time for all the necessary R&D, and to confirm long term performance before any mass roll-out;
- DECC support required in order to gain manufacturers' confidence;
- Manufacturers will hold their own internal reviews;
- Following distribution and completion of the questionnaire Kiwa will liaise with each manufacturer as appropriate.

6. Actions

1. Kiwa to engage with Industrial and Commercial Energy Association (ICOM) and British Gas – Service suppliers.
2. Kiwa to liaise with HHIC (Steve Sutton) regards E4Tech fuel cell stakeholder meeting;
3. Kiwa to circulate PowerPoint presentation and HyHouse report (or provide link);
4. Kiwa to circulate the final report of this study, 'DECC Desk study on the development of a hydrogen-fired appliance supply chain'.

Kiwa Ltd.

15th January 2016

HHIC – Development of a supply chain for hydrogen-fuelled technologies

Kiwa Gastec, Cheltenham (map provided)

Thursday 7th January 2016

Agenda

09:45 Coffee / refreshments

10:00 Introductions and welcome

10:10 Background:

- Why develop hydrogen fuelled appliances?
- Drivers / Government support
- 'DECC Desk study on the development of a hydrogen-fired appliance supply chain'

10:30 Insight into completed and ongoing hydrogen projects

10:40 Importance of stakeholder engagement and confidentiality

10:50 Coffee / refreshments

11:05 Key topics for discussion

- Plans and timetables for batch manufacture of hydrogen appliances
- Manufacturing costs
- Investments required by manufacturer
- Controls and usability of hydrogen appliances
- Issues associated with the manufacture of hydrogen appliances

12:30 Lunch

13:30 Key topics for discussion (continued)

- Barriers to developing a supply chain and incentives to overcome these barriers
- Review standards / regulations for testing hydrogen appliances which includes safety risks
- Others

14:30 Concluding discussion and any other comments

14:45 Going forward and how feedback from the meeting and questionnaire will be appraised and reported

15:00 Closing remarks

Site tour of Kiwa facilities at convenient juncture.

10.2.3 CESA

CESA – Development of a supply chain for hydrogen-fuelled technologies

CESA, 3 Albert Embankment, London

Tuesday 9th February 2016

Notes of Meeting

Attendees

Phil Martin	Cedabond	
Penny Dunbabin	DECC	
Douglas MacLachlan	Falcon Foodservice Equipment	
Scott Dackombe	Foster Refrigerator	
Andy Gentle	Hobart	
John White	Lincat	
Peter Sage-Passant	Mechline	
John Towersey	Mechline	
Bryan Whittaker	CESA	
Nick Oryino	CESA	
Keith Warren	CESA	Chairperson
Mark Crowther	Kiwa	
Oliver Grasham	Kiwa	

1. Round table Introduction

2. Background from Mark Crowther

Mark began by explaining the need to achieve GHG emission reductions, discussing potential household energy use options which account for roughly 40% of end-use energy:

- Biomass-fuelled district heating – however, expensive and requires large quantities of biomass;
- Biogas – interesting option but scaling up would require a lot of work to meet national energy consumption;
- Renewable electricity – wind/solar dependent on weather conditions;
- Hydrogen – essentially decarbonised natural gas.

Some of the major challenges associated with all renewable energy options were highlighted:

- Seasonal variations in energy demand which can be up to 7:1 between summer and winter;
- Infrastructural costs;
- Safety;
- Fuel cost issues.

Mark explained that hydrogen could be seen as a convenient energy vector and he highlighted some of the similarities with natural gas:

- Natural Gas (NG), Wobbe number ~ 47-52 MJ/m^{3,} hydrogen ~ 45/46 MJ/m^3.

- Similar volumes of energy through a distribution pipe when using the same pressure drop ~ 80—85%;
- Most of the UK gas networks are large enough to accept H_2 with very few modifications.

Mark briefly explained the aims and status of the H21 Leeds Citygate project and also discussed some of the H_2 production options:

- Water electrolysis (electricity could be derived from renewable options);
- NG steam reforming – which can be 75-80% thermally efficient;
- SMR with CCS – capture 90% of the carbon – Leaves a carbon-free energy vector at point of use and almost carbon free at point of production.

Storage of H_2 in caverns was highlighted as an existing practice (e.g. Teesside since 1960s). The potential plan being: build 4 new SMRs at Teesside (each size of rugby ground), pipe H_2 towards Leeds, store in salt beds near Aldborough, where there are existing natural gas caverns. H_2 can then be piped to Leeds.

Initially suggested that SMR should be a H_2 production method.

Similarities with switch-over from town gas to natural gas in the 1970s were discussed.

- Town gas contained 50-60% hydrogen – evidence it can be used safely.

It was emphasised that a partial conversion in Leeds could not occur, it would be a complete city conversion or no conversion.

Mark described the gas transportation options in the UK:

- National Transmission System ~ 85bar – used to move large quantities of natural gas around the UK;
- That gas is depressurised in above ground installations – low pressure plastic pipework then distributes to catering establishments, domestic and industry;
- There are a few large industrial users of NG that take gas straight from the high pressure pipeline (big cement works, factories) - these systems would not be converted;
- SMR would take NG from high pressure NTS and input to the low pressure transmission system.

Phil Martin asked what the main differences would be for the appliances.

- Mark explained hydrogen's flame velocity is much greater compared with towns' gas compositions and as such you could not perform a simple conversion to H_2 for existing appliances. For example, a new burner would be necessary;
- No CO_2 or CO using H_2, therefore eliminates risk of poisoning;
- The greater flame temperature makes H_2 burning more susceptible to NO_x formation;
- These are technical issues that need addressing, but not impossible as H_2 has been proven to be just 'another flammable gas'.

Phil Martin asked how CCS works in reference to North Sea burial.

- Saline aquifers are found thousands of feet underground and have sufficient hydrostatic pressure to retain the CO_2. Many research projects have been undertaken concluding that CCS is a safe and viable option.

Bryan Whittaker asked about the costs associated in converting to H_2.

- Mark informed that the cost studies have not been finished;
- 'Back of the envelope' calculations suggest the end cost will be significantly less than the current price of electricity
- It was emphasised that the cost quoted above includes capital cost repayments, decarbonisation, plant operations etc.

John White questioned the effect of increasing costs of energy for the consumer.

- Mark shared these concerns but other options are costly, e.g. household conversion to full electricity ~ £8,000;
- Other conversions can also be much more hassle;
- Comparison made with 'Green Deal' where getting people to implement options proved a major barrier;

Penny Dunbabin added that the UK has reduced GHG emissions by 35% on 1990 levels. However, further reductions become more difficult and the harder it becomes to implement changes. Penny noted that "easy options" are always carried out first e.g. double glazing, combi boilers, insulation. Now there is a move to decarbonise electricity and heat and H_2 is one option under consideration.

Scott Dackombe asked about cost comparison with current NG price and what would occur in the future.

- Mark informed the meeting that the cost of H_2 would always be relative to NG, provided H_2 production was produced from SMR;
- In the United States bulk H_2 (ex factory fence) is 1.8x the cost compared with NG.

Douglas MacLachlan asked if any other countries have incorporated H_2.

- Main feedback was 'not really';
- But town gas still used in Hong Kong, Singapore and some parts of China on a large scale;
- Phil Martin questioned the 'win-factor' for the consumer and the timescale.

Penny Dunbabin highlighted that this is a preliminary stage of a series of discussions within DECC in order to reach a decision on the future of the gas grid which needs to take place in the next 5 years. The point of this meeting is information gathering from stakeholders so DECC can make the best possible decision where a cheap easy solution does not exist for the consumer.

Phil Martin described how the industry has come on leaps and bounds with energy consumption over the previous few decades and indicated that the industry is very good at pushing through policies.

H_2 safety and Kiwi's HyHouse project was then discussed and the following key points raised:

- Even with sealed house H_2 still escaped because its small molecular size;
- 3x more H_2 needed to achieve stoichiometric combustion levels;
- Only problem found was if vehicular gas leak occurred in a garage.

Peter Sage-Passant informed the meeting that Mechline produce high quality flexible gas hoses and it was agreed that this would be an area for R&D going forward.

Peter Sage-Passant asked if any studies had been undertaken on the effect of H_2 on nitrile rubber – Mark Crowther was not aware of any.

Mark Crowther discussed conversion options in Leeds the following points were discussed:

- Leeds would be divided into zones and changeover would occur zone-by-zone over 3 years during 30 weeks per year, customers would typically be off- the grid for 1-2 days;
- Looking at converting ~240,000 domestic houses.

Mark Crowther informed the meeting that it is proposed that Leeds would be a large-scale trial that would take place following a series of smaller conversion trials. It is envisaged that the first stage will be the conversion of a small row of unoccupied houses over ~6 months to allow for public confidence building and information gathering.

Douglas MacLachlan enquired on the timescales before appliance trails would take place.

- Mark could not be more specific than ‘a few years’ and explained that feedback from stakeholders and industry was vital for development of the project;
- However, gas industries are very interested and are looking to ensure their commercial future;
- European interest is limited but not unapparent with Italian boiler company Giacomini having developed a 100% H_2 boiler.

Mark Crowther started discussions on the current status of H_2 appliances.

- H_2 produces excess moisture in ovens: good for roasts and vegetables;
- Whereas not as suitable for pastry.

ITM power were developing a range of H_2 appliances but studies were discontinued

- For future reference Marcus Newborough was in charge of the programme.

Mark discussed specific issues:

- Lack of visible flame;
- High moisture levels (baking);
- Requirement of delayed ignition in bread ovens.

Peter Sage-Passant raised concerns that increase in gas price would push people to electric appliances. Douglas MacLachlan added that this may be augmented because H_2 appliances could alter a kitchen ‘environment’ and aesthetics with gas extraction etc.

Keith Warren informed Mark of work conducted by the Carbon Trust on an industrial energy efficiency accelerated project, sponsored by CESA and funded by DECC. 4 case studies of industrial kitchens which would be useful as an information base to do comparative modelling of hydrogen use in kitchens. Keith Warren will provide Mark with a copy of report (**Action 1**).

Mark relayed feedback from boiler industry and concerns over tendering and market autonomy. Tendering must be managed to give suppliers fair chance at market.

- Keith Warren suggested this may be less of an issue with catering equipment as manufacturers production lines are more batch-based rather than mass-production;
- Therefore, the more important factor would be funding from DECC for R&D so that pay-back times could be alleviated;
- Mark suggested it would be up to industry R&D as to whether they would generate a new product, kits or upgrading equipment.
- Penny Dunbabin suggested that the development of prototypes might be eligible for anESPRC funded project to aid in reducing time-frame;
- Mark Crowther added that IGEM are planning to incorporate H_2 to existing standards.

Mark opened the floor to questions.

Keith Warren asked what changes would be needed in appliances. Response included:

- Complete change of burner assembly but remaining components (including ignition) could most-likely be re-used;
- Positivity amongst other attendees regarding upgrading options and relative ease undertaking these;
- Mark Crowther suggested that changeover times is the main concern for gas companies and therefore any options that reduce this time would be very attractive.

Peter Sage-Passant queried the role of domestic flue less appliances and potential NO_x formation.

- Mark Crowther discussed potential for catalytic combustion technology but thought flame combustion technology would be cheaper;

- DECC and DEFRA would have to set industry limits and designs would operate accordingly.

Feedback questionnaires discussed and promise of anonymity. Collection of attendee emails conducted.

Keith Warren suggested CESA could help with the framing of the questions to be as industry specific as possible and could be distributed to multiple parties. Make sure they include wider engagement issues that CESA can help with (**Action 2**).

3. Concluding Remarks

Trial stages vitally important.

Catering industry is 3rd biggest employer in the UK, important to get it right!

Keith Warren to give Mark Crowther information on market size (**Action 3).**

Positive responses on technical feasibility.

R&D funding vital.

4. Actions

1. Keith Warren to provide copy of report Carbon Trust industrial energy efficiency accelerated project, kitchen modelling case studies.

2. CESA to help frame questionnaire questions and distribution.
3. CESA to give Kiwa information on market size.

Kiwa Ltd.

15th February 2016

CESA – Development of a supply chain for hydrogen-fuelled technologies

CESA, 3 Albert Embankment, London (map provided)

Tuesday 9th February 2016

Agenda

14:00 Introductions

14:05 Background:

- Why develop hydrogen fuelled appliances?
- Drivers / Government support
- 'DECC Desk study on the development of a hydrogen-fired appliance supply chain'

14:15 Insight into completed and ongoing hydrogen projects

14:45 Importance of stakeholder engagement and confidentiality

15:50 Key topics for discussion

- Plans and timetables for batch manufacture of hydrogen appliances
- Manufacturing costs
- Investments required by manufacturer
- Controls and usability of hydrogen appliances
- Issues associated with the manufacture of hydrogen appliances
- Barriers to developing a supply chain and incentives to overcome these barriers
- Review standards / regulations for testing hydrogen appliances which includes safety risks
- Others

16:30 Concluding discussion and any other comments

16:45 Going forward and how feedback from the meeting and questionnaire will be appraised and reported

17:00 Closing remarks

10.3 Questionnaire Template

Appliance Controllability and Usability	
Depending on the design type of the appliance there is a need to consider the specific impacts of the combustion characteristics of hydrogen - manufacturers used their experience and findings from their own investigations / development	
Will the appliance function correctly (safety, efficiency)?	
Will the quality of gas (99.9% purity vs 99.999%) effect performance?	
Odourisation issues?	
Flame visibility issues?	
Other considerations?	

Manufacturing Plan	
Consider key steps for the manufacture of; 1,000, 10,000 and 100,000 CE compliant hydrogen appliances:	
Does the technology exist that can be incorporated into your product?	
Do product designs already exist and if so how long did the design, testing and certification stage of the development take?	
Is a supply chain present for product components?	
Do the necessary facilities exist to manufacture 1,000, 10,000 and 100,000 units?	
What other procedures need to be in place in order to develop and manufacture the product?	
Are there any design issues which may impact on the manufacturing plans?	
Other?	

Timetable for Manufacture	
Consider development of estimated timelines for the manufacture of the specified volumes (see 2.) of market ready appliances timescales :	
If the technology necessary does not already exist, how long will it take to develop it?	
How long will it take to produce product designs?	
How long will it take to have the manufacturing capability in place for the volume of appliance in question?	
How long will product manufacture take? – e.g. manufacture could be outsourced to enable production to start more quickly, but this may compromise quality.	
What are likely to be the rate determining steps within this process?	
What other considerations could affect the time taken to reach volume production?	

Cost of Manufacture	
Based on findings from 2 and 3, consideration was given to estimated manufacturing costs for each level of batch (e.g. 1,000, 10,000 and 100,000 units):	
Estimated cost for each production volume of products? - ex works cost including R&D, amortisation etc. - Parts and assembly	
Other?	

Size of Overall Investment	
Consider level of investment required to enable you to deliver the specified volumes of appliance:	
What is the estimated investment required to design hydrogen fuelled appliances?	
What is the estimated investment required to set up manufacturing / change components?	
What is the impact of company size, research budgets and their required payback criteria?	

Issue arising from Manufacturing Hydrogen Appliances	
There are potentially a number of areas where issues may arise in establishing the manufacture of hydrogen fuelled appliances for example	
What are the technical challenges for manufacturing new component types and use of new materials?	
What are the impacts on manufacture of current products?	
What is the competition for resources (R&D or manufacturing facilities, components, skills, materials etc.)?	
Other?	

Technology Development Barriers	
Will infrastructure and fuel supply challenge the development of hydrogen appliances?	
What technology challenges are expected to impede the development of hydrogen appliances?	
What capability and skills would the sector lack?	
Would suitable testing and demonstration be possible within today's framework?	

Supply Barriers	
Is there potential for sufficient scaling of production?	
If not, where are the main supply chain bottlenecks?	
What would be the causes of the bottlenecks?	

Market Entry Barriers	
Are the necessary standards in place for roll-out of hydrogen appliances?	
Will new standards and codes for appliances be needed?	
Who should be responsible for developing and enforcing standards?	
How could sufficient awareness of hydrogen appliances and benefits be communicated to consumers?	
Would existing sales and distribution channels be suited to hydrogen appliances?	

Market Development Barriers	
Would insufficient demand for hydrogen appliances be a barrier?	
What commercial challenges need to be addressed in order for hydrogen appliances to be sold in volume?	
What other issues could prevent the development of a market for hydrogen appliances?	
What role should policy play in supporting market development? When will this be needed and in what form?	
What else on the consumer side should be considered to ensure successful sale of hydrogen appliances?	

Market Support Barriers	
Will any specific training for engineers/installers be needed to install the appliances?	
Would there be a lack of qualified personnel to install and maintain hydrogen appliances?	

Support Required	
Actions that may be required to overcome the barriers and issues raised in questions 6 and 7:	
What policy and regulation would be required for hydrogen appliances to enter the market?	
What supporting measures would encourage sales of hydrogen appliances (hydrogen infrastructure, information, servicing etc.)	
How manufacturing challenges could be overcome?	
When will the support be required?	
Who should be responsible for implementing the support?	
What would be the cost of providing the support?	
What else should be considered to ensure successful manufacture and sale of hydrogen appliances?	
Other	
Other issues to be considered.	