Logistics of Domestic Hydrogen Conversion

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Executive Summary

This report presents an investigation of the logistical requirements associated with transitioning UK domestic properties from natural gas to 100% hydrogen. It has sought to answer a series of questions raised by BEIS on the following topics:

- Practical tasks required to transition homes from natural gas to hydrogen;
- How these tasks could be delivered;
- The associated risks, barriers and opportunities.

The investigation has involved three stages:

- Initial benchmarking - to understand the logistics of delivering existing natural gas to domestic appliances, the technical challenges associated with hydrogen and evidence from previous conversions.
- Stakeholder engagement – 1-2-1 interviews and a discussion workshop with domestic gas installation and servicing organisations, gas regulatory and servicing bodies, appliance manufacturers, academics and consultancies.
- Review and appraisal of the evidence.

The Clean Growth Strategy, published in October 2017, outlined the challenges and opportunities involved in decarbonising heat in buildings and industry. It sets out that there are a range of low carbon heating technologies with the potential to support the change needed. At present, it is not clear which approach will work best at scale and offer the most cost-effective, long term answer.

Converting the gas grid to hydrogen is one potential option for decarbonising the UK's heat. However, the end to end logistical requirements that would be associated with transitioning the UK's natural gas grid to hydrogen are not currently well understood. This report aims to improve the evidence base on hydrogen as an option for decarbonising heat, focussing on domestic properties downstream of the meter.

Practical Tasks

The evidence has been used to propose an approach to undertaking a property-by-property hydrogen conversion involving:

- Initial surveys;
- Pre-conversion preparations to the property; and,
- The actual conversion itself [Section 5.1].

It is envisaged that home surveys would be needed to assess the condition of the gas pipework and undertake an inventory of the gas appliances. A gas tightness test will be required to test the integrity of the pipework and the property will need to go without gas for a short period of time (10-20 minutes). It is estimated that the surveys will take 1-2 hours per property [Section 5.2].

The pre-conversion tasks required for the domestic gas pipework are less certain. A number of different materials are currently used for domestic natural gas pipework, including copper, steel and MDPE as well as various pipe joining methods. There are also various different legacy materials that are still in existence in homes. Hydrogen presents different safety concerns to natural gas – it has a greater propensity to leak through joints but it will also tend to disperse and dilute more readily. Welded (soldered) copper is widely used and the view from the stakeholders was that this is likely to be suitable for hydrogen, although further studies will need to be undertaken to confirm this [Sections 3.4.1, 4.1.2, 9.1]. It is judged that the inaccessibility of domestic gas pipework could be a significant barrier to conversion if pipework needs to be either fully inspected or replaced as natural gas pipes are sometimes covered by concrete or ducted

through inaccessible voids [Section 3.4.1, 9.2]. The suitability of existing domestic natural gas pipework for hydrogen and understanding the general condition and accessibility of domestic gas pipework will be considered as part of the BEIS Hy4Heat programme.

The conversion itself will involve the installation or adaptation of appliances. If existing natural gas appliances are either adapted in-situ, or replaced with hydrogen appliances then it is estimated that boiler conversions will take up to 1 day and hobs, ovens and fires will take ½ day each. New Hydrogen-Ready dual fuel appliances that have been designed in advance to run on hydrogen, but temporarily back-fitted to run on natural gas could significantly reduce the workload at the point of conversion. These could be installed prior to the conversion as natural gas appliances come to the end of their operational lives. Hydrogen-Ready appliances could then be readily switched to hydrogen on the day of conversion [Section 4.3].

Delivery of Conversion

It is a legal requirement in the UK that all operatives undertaking natural gas work are listed on the Gas Safe Register. There are currently around 130,000 individual engineers, across around 74,000 employers, and of these approximately 80% hold the domestic core qualification [1]. The structure, responsibilities and rigour of the Gas Safe organisation is considered to be well placed to oversee a hydrogen conversion [Sections 3.1, 3.3 and 6.1].

The consensus from the stakeholders was that a hydrogen workforce could be developed using the existing Gas Safe workforce but with an appropriate changeover qualification developed similar to that already used to transfer between different elements of the Gas Safe scheme (e.g. domestic, commercial, metering etc.). There are currently around 100 accredited gas training centres in the UK that could facilitate hydrogen training courses [Sections 6.1 and 6.2].

As of 2017, there are approximately 27 million properties across England, Wales and Scotland of which approximately 23 million have a metered gas connection. The size of the workforce required for a hydrogen conversion will depend on the speed of roll-out and the stakeholders highlighted that there would be significant concerns with employment post conversion if the workforce is accelerated too quickly. If a designated conversion workforce of 100,000 is developed, then in theory all UK homes could be converted in around 4 years (including initial surveys, property updates and appliance conversions). If the existing base of Gas Safe engineers is used without augmenting, then it would take significantly longer at around 16 years. In practice, any conversion would clearly require a hydrogen production capacity and hydrogen transmission grid and it is highly unlikely that these could be developed in 4 years. However, these simple calculations are useful in highlighting the scale of the particular challenge of converting domestic properties.

The stakeholders suggested that conversion would most likely be carried out regionally in harmony with the transition of the transmission and distribution network. This would also allow existing Gas Safe personnel in an area to become trained as the region they work in is converted. It is likely that there would also need to be significant movement of trained staff around the country to support the local workforce [Section 6.3].

Risks, Barriers and Opportunities

A number of risks and barriers have been identified and discussed in this report:

- It will need to be demonstrated that domestic hydrogen appliances offer similar performance and safety to existing natural gas appliances. This has been considered in a related study on domestic hydrogen appliances [2] and is also a key part of the BEIS Hy4Heat programme [Section 4.3].
- Public perception - articulating the benefits of a hydrogen conversion will be important – for example, removing the risk of carbon monoxide poisoning but also (and depending on how the hydrogen is sourced) the potential to increase the security of energy supply to the country as a whole [Section 7.2].

- Alternatives to Hydrogen - the options available for home heating are diversifying and presented with a hydrogen conversion, there would be nothing to stop householders opting to move away from gas to a fully electric solution [Section 7.2].
- Access and Modifications - there must be a firm understanding of the legal framework surrounding conversion works to address any aspects that may prove contentious. These include gaining access, enforcing conversion and ensuring clarity on who pays for any remediation work required to bring the existing gas system up to the appropriate safety standards [Section 7.2].

Prior to any conversion, stakeholders proposed that there would need to be a public communication exercise to educate people and bring them on board with the proposed plans. Persuasive reasons would need to be developed that would need to be communicated nationally and locally. For example, a hydrogen conversion could be combined with fire and internal air quality improvements or smart heating systems to reduce the overall energy demand [Sections 5.1.1, 7.1 and 7.3].

Recommendations for Further Work

During the course of the investigation, some gaps in evidence have been identified and the following recommendations have been provided:

- Safety of running hydrogen through domestic gas pipework – to understand the feasibility of using existing natural gas pipework for hydrogen or if other materials and techniques will be required. Studies should consider the potential for hydrogen leakage and material degradation within domestic pipes as well as associated experiments on building safety; dispersion, ventilation and gas detection requirements [Section 9.1].
- Representative home surveys to characterise existing domestic gas systems – to highlight the number of homes that could realistically be converted and the types of homes that would be most suited. In particular, these should consider the age, condition and ease of access of existing natural gas pipework and how this varies with age and type of property and type of ownership [Section 9.2].

It is understood that both of these recommendations will be considered as part of the BEIS Hy4Heat programme.

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This report has been produced for BEIS by Frazer-Nash Consultancy in conjunction with Almaas Technologies and Nationwide Training Services (Scotland).

- Frazer-Nash Consultancy is one of the UK's largest providers of systems and engineering technology and provides independent analysis and appraisal of new technologies.
- Almaas Technologies is an independent consultancy in the field of gas appliance development, testing and certification, with a background in gas conversion and hydrogen appliances.
- Nationwide Training Services is an accredited gas training body with extensive practical experience of gas work and previous conversion programmes.

It has involved a wide ranging stakeholder engagement and the authors are grateful to the following organisations for providing input to this study:

EMEC	NGN
Imperial College	Enertek International
SGN	Ideal Boilers
Energy Systems Catapult	IGEM
Hewitt Home & Energy Solutions	Wolseley
HHIC	Kane
KIWA	Vokera
BSI	Vaillant
Energy & Utility Skills	AGA Rangemaster
Centrica	Viessmann
Embers Installations	Atmos
Bright Green Hydrogen	TPI Europe
City of Glasgow College	Baxi
Gas Safe	Worgas
Orkney Council	Worcester Bosch
Blue Flame Associates	

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1 Introduction

1.1 Objectives

This report presents an investigation of the logistical requirements, costs and timescales associated with transitioning UK domestic properties from natural gas to 100% hydrogen. It aims to address a series of questions posed by BEIS on the following topics:

- Practical tasks required to transition homes – including the costs and timescales.
- How these tasks could be delivered – the skilled workforce required to bring about the transition and how this workforce could be developed.
- Risks and barriers associated with this transition.
- Opportunities it presents to improve domestic homes at the same time.

The full list of questions is provided in Annex A.1.

The investigation has involved a structured evidence gathering process including wide industry engagement with gas safety and training organisations, commercial gas installers and maintainers, academia and regulators as well as gas appliance manufacturers. Ultimately, this report aims to improve the evidence base on hydrogen as an option for decarbonising heat and the results will be fed into the wider work BEIS is conducting in this area.

1.2 Background

The Climate Change Act places an obligation on the UK Government to reduce greenhouse gas emissions by 80% by 2050, based on 1990 levels. Heat currently accounts for around 50% of UK energy consumption [3] and produces around a third of greenhouse gas emissions [4]. Therefore, meeting these obligations is likely to require almost full decarbonisation of heat in buildings.

Decarbonisation proposals have so far focussed on electrification (for example using heat pumps), substituting traditional fuels with biomass and district heating networks combined with decentralised Combined Heat and Power (CHP). However, there is currently no consensus on the best approach.

In addition to these options, there is increasing interest in the role hydrogen could play in decarbonising heat in the UK. Replacing natural gas with hydrogen in the current gas system would provide zero carbon emissions at the point of end use and various studies, such as the H21 Hydrogen Leeds City Gate have provided a valuable contribution to the evidence base.

1.2.1 Previous Studies

There is previous experience of significant gas conversions in the UK, with the nationwide town gas to natural gas conversion in the 1960s and 70s being the largest but also more recent experience with the Isle of Man conversion from LPG/ air mixtures to natural gas in 2013.

The town gas conversion was undertaken in the UK between 1967 and 1977 to change the gas supply from locally manufactured town gas to a natural gas, which had recently been discovered in the North Sea. During the 10 year programme, approximately 40 million appliances belonging to 14 million customers had to be substantially modified or exchanged [5]. The Isle of Man conversion involved converting 15,000 customers in the capital, Douglas in 2003, followed by the rest of the island (6,800) homes in a two-year programme starting in 2011 [6].

These previous conversions have demonstrated that nationwide gas conversion is possible and they provide useful operational experience for a large scale hydrogen conversion. However, the corollaries should not be overstated as 100% hydrogen offers new technical challenges, both on a domestic level and also in the regional or national production and distribution of hydrogen.

Some additional evidence can be drawn from related studies including the SGN Oban and Scottish Independent Undertaking (SIU) network programmes [7] [8] that involved surveying and inspecting domestic gas systems and appliances. Although these studies did not involve gas conversions they did require property surveys, inventories of gas appliances and a review of safety concerns. They have also provided useful evidence on customer engagement which would be a key aspect of a hydrogen conversion.

1.3 Layout of Report

This report is structured as follows:

- Section 2 describes the methodology used to obtain and review the evidence used in this report.
- Section 3 provides an overview of the current UK domestic gas industry, the organisations involved and the type of work undertaken. Understanding the logistics of delivering existing natural gas in homes has been an important step in identifying the logistical requirements of a potential hydrogen conversion.
- Section 4 explores the technical characteristics of hydrogen and the changes required to convert domestic gas systems from natural gas to 100% hydrogen, including those dictated by the development of hydrogen appliances.
- Section 5 outlines a potential approach for the conversion of homes from natural gas to hydrogen, including the surveys and the various stages of practical modifications.
- Section 6 discusses the skilled work force necessary to bring about the conversion, including training needs.
- Section 7 reviews the risks and benefits of converting to 100% hydrogen, as well as any associated opportunities.
- Sections 8 provides the conclusions of the work and Section 9 provides recommendations for further work based on the gaps in evidence that have been identified during the course of the investigation.

1.4 Scope of Study

This report focusses on the logistical challenges of converting UK domestic gas systems from natural gas to 100% hydrogen, from the meter and downstream. Domestic gas systems have been assumed to comprise the meter, internal pipework and pipework joints, and appliance isolators. The main gas isolator and pressure regulator at the entrance to the property are installed just upstream of the meter and have been omitted from this study.

The feasibility of developing appliances suitable for 100% hydrogen is discussed separately in the Appraisal of Domestic Hydrogen Appliances [2]. However, the logistical challenges associated with installing these appliances are discussed in this report.

2 Methodology

This investigation has required obtaining information on a broad range of topics including: practical domestic natural gas activities; gas operative training; knowledge of hydrogen as well as social aspects such as customer engagement. The majority of this information has come from the views and expertise of industry practitioners and it has been necessary to undertake a structured and robust approach to obtaining and appraising evidence. This has involved a three-stage process:

- Benchmarking;
- Stakeholder Engagement;
- Review and Appraisal of evidence.

2.1 Stage 1: Benchmarking

Initially, a benchmarking exercise was undertaken to form initial responses to the questions set by BEIS and provide background information on the existing domestic natural gas industry. Evidence was obtained on three main topics:

- Domestic natural gas industry – the tasks undertaken to install and maintain domestic gas systems and the workforce that delivers this.
- Physical characteristics of hydrogen compared with natural gas - the technical challenges this presents in the domestic context.
- Evidence from previous conversions – information on conversion processes and how these were delivered, including lessons learnt, that could be used as the basis for a hydrogen transition.

This exercise involved a review of industry and academic literature[1] as well as using in-house experience from Nationwide Training Services and Almaas Technologies. A workshop was undertaken with Nationwide Training Services to understand the existing Gas Safe industry, how it is structured and the type of work undertaken.

This benchmarking exercise provided an initial set of evidence that could be discussed, validated and tested by discussion with industry. It also highlighted gaps in existing information sources that would need to be filled using the practical expertise and knowledge of industry practitioners.

2.2 Stage 2: Stakeholder Engagement

The information produced in the benchmarking phase was then used as the basis for the stakeholder engagement. This involved a series of structured 1-2-1 interviews followed by a discussion workshop.

2.2.1 1-2-1 Interviews

A broad cross-section of stakeholders was identified within the following industry groups:

- Domestic installation and servicing organisations;
- Gas regulatory and safety bodies;
- Appliance manufacturers;

[1] Including domestic gas practices, gas safety, hydrogen characteristics and related texts on changes of gas in the distribution network. Full details are provided in the References section.

- Academics;
- Consultancies;
- Trade associations.

A formal questionnaire was developed to use in the 1-2-1 interviews based on the questions posed by BEIS and the information obtained in the benchmarking exercise. This is presented in Annex A.2.

In all, over twenty 1-2-1 interviews were undertaken, each of which lasted approximately 1 hour.

The structured questionnaire ensured that the stakeholders were given the opportunity to provide evidence on all areas of the investigation. They were all happy to follow this approach and they provided additional information in their particular area of expertise.

Overall, the interviews were useful for consolidating evidence on the current domestic natural gas industry, the type of gas work required for a hydrogen conversion and the training required. The interviews also highlighted some of the social challenges that would need to be addressed including customer perception and accessibility. The actual logistical tasks required for a given domestic conversion were harder to canvass and the stakeholders were keen to point out that their responses were limited to their knowledge of the natural gas industry, combined with their knowledge of the physical characteristics of hydrogen. However, some of the stakeholders were able to provide useful evidence of the previous transitions including the town gas and Manx Gas conversions as well as related studies such as H21 and Oban. This information was then used to construct the evidence base for this report.

2.2.2 Workshop

A workshop was held to present, test and discuss the findings of the benchmarking and 1-2-1 interviews. This was run on the 16th April 2018 at the Heating and Hotwater Industry Council (HHIC) offices in Kenilworth and had approximately 30 attendees. Many of the stakeholders who contributed to the 1-2-1 interviews attended this event and there was representation from gas servicing bodies, gas regulatory and standards bodies, appliance and component manufacturers and trade associations. The workshop provided a useful means of discussing and consolidating the evidence from the 1-2-1 interviews prior to the review and appraisal (Stage 3).

There was general agreement on the findings presented although there was significant discussion and some conflicts on the following topics:

- Typical condition of existing domestic gas systems nationally.
- Length of time typically taken to service existing natural gas systems.
- How the required transition workforce could be best developed.
- Customer perception of hydrogen conversion - including the potential challenges from consumers on safety, cost and disruption as well as how best to communicate the benefits.
- The extent to which householders would have a choice about the conversion.

Where conflicts in evidence were identified, these were compared and validated using published literature (where available), discussed with other stakeholders and reviewed internally using the in-house experience of Nationwide Training Services and Almaas Technologies.

2.2.3 Summary of Stakeholder Engagement

The combination of structured 1-2-1 interviews and a discussion workshop was found to be beneficial. Stakeholders were more likely to share their personal insights during the 1-2-1 interviews. However, the workshop was useful for discussing less technical areas, consolidating the evidence and ensuring that the resulting conclusions were sensible.

2.3 Stage 3: Review and Appraisal of Evidence

The evidence obtained from the stakeholder engagement and benchmarking study has been evaluated and consolidated to form this report.

Maintaining an impartial view on the role hydrogen could play in decarbonising heat has been a crucial aspect of the investigation. There are different views on the feasibility of hydrogen as a replacement for natural gas in homes and the use of multiple evidence sources, a broad cross-section of stakeholders and the structured methodology has been a key part in achieving this.

Throughout this report, evidence is presented to answer the questions posed by BEIS. Where evidence has been provided by stakeholders this is acknowledged but only in general terms to ensure anonymity throughout.

3 Current Domestic Natural Gas Industry

This section provides a brief introduction to the current UK domestic gas industry focusing on the organisations responsible for undertaking domestic gas work and ensuring safety. This information was obtained from the benchmarking exercise, principally by discussions with Nationwide Training Services (hereafter referred to as Nationwide) and it has been used to underpin the later sections exploring a potential hydrogen transition. Information provided by Nationwide is marked by [N].

3.1 Domestic Gas Organisations

The organisations involved in setting standards and training engineers for domestic gas work are presented in Figure 1.

It is a legal requirement in the UK that all operatives undertaking natural gas work are listed on the Gas Safe Register [9]. As an organisation, Gas Safe ensures that the list of competent and qualified engineers is accurate and up-to-date, inspects the work of Gas Safe engineers, investigates reports of mal-practice, and conducts public awareness campaigns in gas safety. The Gas Safe Register replaced Corgi in 2009 and is owned by The Health & Safety Executive (HSE). The industry body Energy & Utility Skills Register (EUSR) and the Institution of Gas Engineers and Managers (IGEM) are then responsible for developing and maintaining the standards for domestic gas work including appropriate materials and procedures. These are developed as British Standards and IGEM manage the gas standards on behalf of the British Standards Institute (BSI).

Training of Gas Safe engineers is provided by around 100 centres located around the UK and these are accredited by the United Kingdom Accreditation Service (UKAS) via various certification bodies.

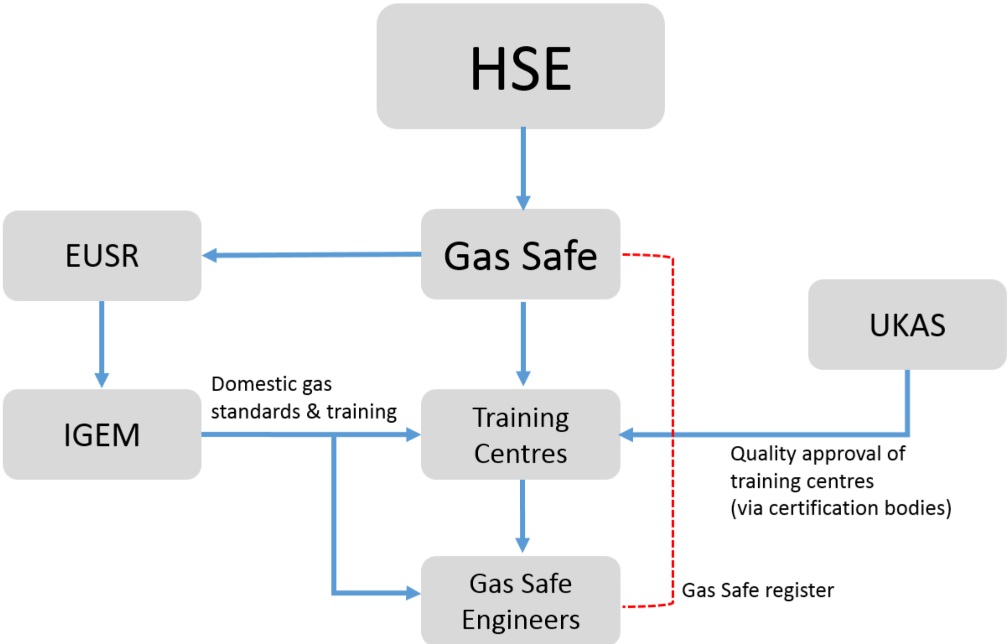

Figure 1: Organisations involved in the domestic gas industry

Domestic gas appliance standards are developed by BSI, in conjunction with appliance manufacturers and use product accreditation companies such as BSI and KIWA Gastec to test and certify their products to the appropriate standards.

The primary legislation for domestic gas work is the Gas Act 1986 and secondary legislation, such as the Gas Safety (Installation and Use) Regulations, is derived from this. The Approved Code of the Practice of Gas Safety (Installation and Use) Regulations 1998 [10] provide more practical guidance and these working documents are typically used by Gas Safe engineers.

3.2 Gas Safe Training

There are six core categories of qualification to the Gas Safe Register and registration requires qualification of at least one of the following core elements [11]:

- Commercial Natural Gas;
- Domestic Natural Gas;
- LPG;
- Metering;
- Catering; and,
- Laundry.

Registration is obtained through a mixture of theoretical and practical work and the syllabus is overseen by EUSR. Nationwide advised that for an individual with no prior gas experience around 10 weeks of classroom teaching is required and this is normally interspersed with practical work with one week of teaching per month. Furthermore, students are required to be mentored throughout their training by a qualified Gas Safe engineer. It is suggested that this could be off-putting for mature personnel entering the industry and could potentially also hinder the progress of developing a new labour force for a hydrogen conversion.

Nationwide also advised the following:

- Where an individual holds one or more of the core elements, there are reduced training periods for additional core elements.
- The domestic gas safe qualification has a number of categories which relate to different appliance types or gas work tasks. All engineers must ensure they hold the appropriate qualification, including the relevant category, for any gas work they undertake.
- The gas safe qualification requires renewal every 5 years and most practising engineers require some level of formal training to refresh their knowledge and keep up-to-date with standards and regulatory changes.

3.3 Gas Safe Workforce

The Gas Safe Register currently licences around 130,000 individual engineers, across around 74,000 employers and of these approximately 80% hold the domestic core qualification [1].

The stakeholders advised that there is currently a net increase in Gas Safe registrations of around 200 per month, with 500 new applications and 300 expiring registrations. They also highlighted that individuals holding Gas Safe qualifications also typically work as plumbers, joiners and general building service tradesmen and that not all their work is related directly to gas systems.

In this context, natural gas work is assumed to comprise all work on the gas system itself (pipework and appliances) but does not include the water-side of boilers or the central heating system.

3.4 Domestic Gas Safe Activities

Nationwide reported that at the domestic level, Gas Safe engineers undertake two main activities: initial installation and commissioning, and the ongoing maintenance and servicing of the gas system. The following information on these two activities was provided during discussions with Nationwide.

3.4.1 Initial Installation

The initial installation of a domestic natural gas system involves pipe sizing, pipe layout and connection to the various gas appliances. Boilers are generally considered to be the primary gas appliance as they provide an essential home heating function whilst hobs, ovens and fires are classified as secondary appliances. Typically, the main gas pipe entering the property is routed directly to the boiler, with branch-offs where necessary for the secondary appliances [N].

Modern pipework is typically copper, although steel and Medium-Density Polyethylene (MDPE) are also permitted under certain conditions and are becoming more common [N]:

- Copper joints are typically soldered but can also be compression fitted or pressed fit. Pressed fits are less common and rely on the crimping of a rubber washer surrounding the pipe.
- Steel is becoming more popular as it is significantly cheaper than copper although is more labour intensive to join as it requires threaded joints. Steel pipes are not typically welded in domestic applications although are in industrial applications.
- MDPE is also significantly cheaper than copper but it cannot currently be used on the interior due to fire safety. MDPE pipes must be run around the outside of buildings and also buried underground to protect them from UV damage.

Copper piping was introduced in the 1960s. Before this, lead and steel were predominantly used for domestic gas pipes. There is no legal obligation to remove old pipework unless a fault is discovered and many homes in the UK still have these legacy materials [N]. The stakeholders also reported that there are regional trends in gas pipe usage with iron predominately used in London and the South of England, and lead in the Northeast and Yorkshire.

The location of pipework is highly dependent on the space available in the property; for new builds - routing under concrete is common whilst in older properties it is typically laid under floors. There are no mandatory requirements for locating pipework other than avoiding void spaces where natural gas could build up and form an explosive cloud [N].

During the installation stage, the Gas Safe engineer ensures that the appliances have been installed according to the manufacturer's instructions, that there is adequate ventilation to the appliances and that boilers and fires are flued where necessary.

Prior to operation, various commissioning tests are undertaken:

- **Gas line tightness test.** Gas line tightness test is carried out to ensure that pipework has a leak rate below a level which could ever be considered to form a hazard. It essentially involved pressurising the internal pipework, sealing both ends and monitoring the internal pressure over time and using the drop in pressure to determine the leakage. The Maximum Permissible Leakage Rate (MPLR) is dependent on the combustible energy released and for natural gas is 0.0014 m^3/hr (1.4 litres per hour). The duration of the test depends on the internal volume of pipework but typically takes 10-20 mins to complete. The

MPLR also depends on the ability to disperse the gas and is higher for buildings of greater internal volume or greater ventilation [12].

- **Gas pressure check**. A manometer reading of gas pressure at a dedicated test point within the pipework and/or appliance [N].
- **Flue gas analysis**. Confirmation that the flue is correctly installed, it is continuous and has no leaks [13].

Aside from general tools, Gas Safe engineers use gas analysers and U-gauge manometers. The total cost of a set of tools is around £5,000 [N].

Initial installation of a domestic gas system typically takes approximately one week to complete and costs in the region of £2,000. This is essentially the first fix layout of gas pipework and associated electrical cabling and assumes easy access for pipework layout. This includes the cost of labour and the pipe, joints and ancillary components but does not include the installation or purchase of gas appliances or any remediation work required to make good any decoration. The duration and cost varies with the length of gas pipe run from the meter to the appliances and the access constraints within the property [2].

The installation of new appliances and the replacement of old natural gas appliances was discussed with stakeholders. Whilst they pointed out that this is significantly affected by access constraints, there was general agreement that a boiler takes around ½ to 1 day and secondary appliance (hobs, ovens and fires) each take around ½ day.

3.4.2 Service & Maintenance:

Gas Safe engineers also undertake both planned preventative maintenance and unplanned fault finding in the event that appliances stop working or if there are safety concerns. Annual planned service and maintenance is recommended but only mandated in rental properties [14].

4 Hydrogen Characteristics

This section compares the characteristics of hydrogen compared with natural gas and explores the impact of hydrogen on the domestic gas pipework system. It considers the potential for hydrogen to leak from the pipework and the associated implications for fire safety and the degradation of the pipework and fixings materials. It also discusses the hydrogen appliances (boilers, hobs, ovens and fires) that would need to be developed in the event of a switchover.

4.1 Gas Transportation

Natural gas (of which the principle component is methane) is less dense than air and is a colourless, odourless and tasteless gas [15] although a distinctive odorant is added to aid leak detection. Hydrogen has the smallest molecular mass of all known elements and is approximately 8 times less dense than natural gas. It is similarly non-distinct and has no discernible colour, smell or taste and similar to natural gas will require an odorant for leak detection. The physical characteristics relating the transportation of these gases are presented in Table 1. Since natural gas comprises principally methane, the properties of methane are used for comparison.

Table 1: Properties of natural gas (methane) and hydrogen.

Characteristic	Methane (principal component of natural gas)	Hydrogen
Density [16] (at 1 bar & 15°C)	0.65 kg/m^3	0.084 kg/m^3
Diffusion Coefficient [16]	0.16 x 10^{-4}m^2/s	0.61 x 10^{-4} m^2/s
Wobbe index [17]	51 MJ/m^3	45 MJ/m^3
Flame Colour	Visible / Blue	Invisible / Light Blue
Flame temperature	Lower flame temperature but higher thermal radiation heat transfer	Higher flame temperature but lower thermal radiation heat transfer
Flammability Range [16]	5-15 %	4-75 %
Flame Speed [16]	0.42 m/s	2.37 m/s
Minimum Ignition energy [16]	0.29 mJ	0.02 mJ

4.1.1 Gas Leakage

As a result of its small molecular size, hydrogen is much more prone to leakage through joints and component assemblies than natural gas [16]. Evidence from the stakeholders suggested that there is a particular concern with leakage through pressed fitted joints that rely on rubber washers and also compression fittings. Furthermore it will be necessary to determine suitable joint specifications for low pressure domestic (20 mbar) hydrogen pipework. High pressure joint specifications (typically around 350-700 bar operation) already exist and studies will need to identify the extent to which the requirements for low-pressure applications could be relaxed compared with current high-pressure hydrogen.

Hydrogen has a significantly greater flammability range than natural gas (4-75% compared to 5-15%). This presents an increased risk of unintentional combustion, particularly if gas is allowed to accumulate in high-level spaces. However, hydrogen is both highly diffusive and highly buoyant in air and will tend to disperse more rapidly than natural gas[2] [16].

The HyHouse project [17] compared the gas dispersion of hydrogen and methane from various gas leakage scenarios in a typical two story property. Controlled quantities of each gas were released and sensors were used to measure the gas distribution at various locations around the house. The project found that concentrations of hydrogen build up were not as high as anticipated and that hydrogen generally dispersed before critical concentrations were reached [17]. The HyHouse project was limited to a single property type and it is suggested that further research is required to assess the variety of building and property types representing UK building stock. In particular, the evidence from the stakeholders highlighted that there is a significant variation between types of building in both the ventilation and the porosity of the building fabric and these will need to be characterised and their impact assessed. It is proposed that the differences in dispersion characteristics between hydrogen and natural gas are explored – and the implications for ventilation understood. Appropriate type and location of gas detection will also be a key element of this.

Aside from the fire risks, both gases pose a risk of asphyxiation; however the dispersive nature of hydrogen makes it less likely to gather in high concentrations.

While there is a strong preference to continue with the same odorant for public familiarity reasons, a new odorant may need to be developed for hydrogen that is suitable for its highly dispersive and buoyant properties. Hydrogen will rise and dilute rapidly with ambient air and the odorant will therefore need to be detectable in low concentrations. It would also be beneficial if it is detectable at the location of the leak even after the hydrogen has risen away. Odorants suitable for hydrogen are being considered as part of the BEIS Hy4Heat programme, informed by SGN's H100 programme.

4.1.2 Material Compatibility and Degradation

There are many materials that are suitable for both natural gas and hydrogen [18]. However, hydrogen is known to reduce the service life of metals through a number of damage mechanisms including embrittlement, blistering, hydrogen attack and cracking. Hydrogen embrittlement is a process caused by hydrogen atoms diffusing into materials, generating a high pressure and ultimately cracking the structure [19]. The degree of hydrogen embrittlement depends on the pressure of hydrogen (hydrogen concentration) for many metallic materials [20] and so far research has generally focused on embrittlement at significantly higher pressures (700-1000 bar) than domestic gas pipework (20 mbar) (see for example [21]). Consequently, there is some uncertainty about the threshold pressure below which pipes can safely be used with hydrogen [22]. However, a report by the HSE [23] related to blended hydrogen with natural gas, highlighted that there is little evidence to suggest materials used for the low pressure distribution system will undergo degradation due to injection. It is suggested that testing will need to be undertaken on domestic pipework and fittings to

[2] The one exception is for cryogenic releases of hydrogen where the very cold vapour cloud initially formed can be denser than the surrounding air [16].

ensure adequate reliability and lifetime for low pressure applications using 100% hydrogen. Overall [23]:

- Stainless steel (grade 316) is listed as the industry standard for components in hydrogen;
- Aluminium is known to be highly resistant; and,
- Copper is appropriate for low pressure applications.

Based on this evidence and the views of the stakeholders, it is therefore likely that copper will be a suitable material for hydrogen in low pressure domestic gas systems. Plastic pipes are used away from homes in the gas distribution network but are not currently permitted for use in domestic gas applications due to fire safety [N]. It is proposed that if a body of work is undertaken to test materials for hydrogen in domestic gas systems then there could be an opportunity to assess plastic options at this stage.

Gas meters tend to use rubber or neoprene diaphragms and the compatibility of these materials will need to be checked. However, hydrogen is suitable for many elastomers [18] so this is unlikely to cause significant concern.

4.2 Gas Combustion

The interchangeability of gases, in terms of their combustion in an appliance, is characterised by the Wobbe Index. This index provides a measure of the energy flux through a burner for a given driving pressure in the pipework. Hydrogen has a significantly greater energy density than natural gas but this is offset by its lower material density, and the Wobbe index of the two gases is actually fairly similar. In principle, this means that hydrogen could provide a similar heat output to natural gas [25]. However, the different gas characteristics will mean that a number of changes are required to the appliances to ensure appropriate performance and safety. Hydrogen has a significantly higher flame speed and is likely to burn hotter than natural gas [2].

A possible impact on the domestic gas system of switching to hydrogen appliances is the system pressure. One of the main changes during the town gas conversion in the 1970s was to increase the domestic pressure from 4 mbar to 20 mbar. Natural gas combustion requires more than twice as much air for combustion than town gas and switching the gases without any conversion would have resulted in large, sooty flames that were neither efficient nor desirable for cooking and heating. Increasing the pressure, along with some modifications to the appliances (size of gas injector and burner ports) enabled more air to be drawn into the appliances which significantly improved the performance [5].

The main constituent of town gas is hydrogen [5], but it is understood that there are no plans within the Hy4heat programme to reduce the supply pressure back to that used for town gas. Modern boilers use fans to draw in, and mix air prior to combustion (pre-mixed combustion). For these appliances, adjustments in airflow could be mechanically provided by fans, whilst in the 1970s the appliances relied on the driving pressure of the gas to develop a jet that entrains and draws in adequate air supply (atmospheric burners) [5]. Modern hobs, ovens and fires still use atmospheric burners but it is likely that these could be adapted at the injector by closing primary air inlet ports.

Any change to the domestic hydrogen supply pressure would be a major decision, and would need to be informed by detailed cost modelling and a range of experimental results from the Hy4Heat project, H21 and other work. Changes to combustion and heat transfer characteristics will dictate the actual gas flow required to deliver heat at the appliances and in turn, this will determine the pressure drops within the gas appliance pipework and its components, and consequently the supply pressure.

However, even if the pressure is changed, it may not have any implications on the materials used for the gas system. Evidence from the town gas conversion suggests that the domestic pipework itself did not need to be changed for the rise in pressure unless unrelated gas safety issues were identified [5].

There are various other combustion differences between natural gas and hydrogen that will have implications to the logistical changes to the domestic gas system:

- **Nitrogen oxide (NO_x) formation:** NO_x is formed in high-temperature combustion as nitrogen in the air is oxidised. It is a known air pollutant and studies have shown that it can have an adverse impact on health for both short and long-term exposure [26] [27]. NO_x production is a legitimate concern for hydrogen appliances as hydrogen is likely to burn hotter than natural gas but until testing has been undertaken it is difficult to predict the precise implications. Ultimately sufficient ventilation will be required to eject NO_x and there may also be implications for gas detection [2].
- **Water vapour:** Hydrogen produces approximately 60% more water vapour than natural gas for the same amount of energy produced [25]. It is suggested that this is most likely to impact the design of hydrogen appliances, but may also require increased ventilation of un-flued systems.
- **Flame colour:** Natural gas burns with a characteristic visible blue flame whilst hydrogen burns with a pale blue flame that is almost invisible to the naked eye. This presents a safety risk for appliances – particularly fires and cookers with uncovered burners where appliance designs do not incorporate radiant surfaces within the combustion zone. Colourant could either be added to the unburnt gas prior to combustion or added to the combustion zone itself and this will need to be clean and non-toxic [2].

4.3 Hydrogen Appliance Variations

The appraisal of 100% hydrogen appliances [2] considered the feasibility of the following development options:

- Adaptation of Natural Gas Appliances - existing natural gas appliances would remain in place and key components would be replaced in-situ by a Gas Safe engineer to allow them to run on 100% hydrogen.
- New Hydrogen Appliances – newly developed hydrogen appliances designed specifically to run on hydrogen.
- Dual Fuel Appliances – newly developed Hydrogen Ready appliances that are designed to run on hydrogen but have been back-fitted in the factory to run on natural gas. These would require key components to be replaced by a Gas Safe engineer at the point of switchover but the appliances will be developed to facilitate this process.

Dual-fuel typically refers to appliances that are interchangeable between two gas types without the need to replace components. Whilst this option would minimise the skilled labour resource required at the point of changeover, pure dual-fuel appliances are likely to be significantly larger and more expensive than current natural gas appliances which will not be accepted by occupants. However, in the context of a single gas changeover from natural gas to hydrogen, such interchangeability is not so relevant and appliances that are designed with a hydrogen switchover in mind, but which require some components to be replaced at that point are potentially more appropriate

(Hydrogen-Ready appliances). For this reason, dual-fuel appliances have been taken to mean Hydrogen-Ready dual-fuel appliances.

In the event of a regional or nationwide conversion to 100% hydrogen, each property would require an initial survey and this is discussed further in Section 5. The adaptation of existing natural gas appliances and installation of new hydrogen appliances would require minimal pre-conversion work but then considerable work at the point of conversion. On the other hand, Hydrogen-Ready dual-fuel appliances would require pre-conversion work but then only a minimal amount of time at the point of conversion [2]. This pre-conversion work could be minimised by installing Hydrogen-Ready appliances as the existing natural gas appliances reach the end of their operation lives. Any remaining functional natural gas appliances that had not been replaced in advance would then need to be replaced prior to the transition.

Specific hydrogen training would be required for all appliance types and this is discussed in more detail in Section 5. Based on discussions with stakeholders, it is determined that the adaptation of existing appliances would require most training, with Hydrogen-Ready slightly less and the installation of new hydrogen appliances potentially the easiest to install:

- The adaption of appliances in homes would require skilled modifications to be performed and this could be made more challenging by access constraints.
- Hydrogen-Ready dual-fuel appliances that have been designed to facilitate conversion should be much easier, but they will still require some specific knowledge.
- New hydrogen appliances will require installation, similar to current practice with natural gas.

The logistical impact associated with the three appliance options is compared in Table 2. The level of domestic disruption at each stage is highlighted by a traffic light system with green and red representing the lowest and highest disruption respectively.

The stakeholders were asked about the timescales for installing new hydrogen appliances and adapting existing natural gas appliances to hydrogen. It was generally agreed that there is currently insufficient evidence on hydrogen appliances to differentiate between ‘adapting’ and ‘removing and replacing’ and the following approximate timescales were agreed to cover both of these activities:

- Boiler: 0.5 – 1 day;
- Hobs, ovens and fires – 0.5 day per appliance.

As more is understood about hydrogen appliances, it will be possible to differentiate between ‘adapting’ and ‘removing and replacing’.

The time required to convert a Hydrogen-Ready appliance is estimated to be around 1 hour and this has been determined using the evidence from the Appraisal of Hydrogen Appliances [2].

Stakeholders warned that the adaptation of appliances is likely to invalidate warranty agreements with manufacturers or retailers. Consequently, it is proposed that either the conversion body will need to guarantee the warranty post conversion, or the techniques and materials used to adapt the appliances will need to be agreed with the individual manufacturers and undertaken by accredited engineers. Furthermore service contracts for the domestic gas system could equally be invalidated by third party changes. However, gas systems are not proprietary and as long as modifications are made by accredited parties this is less likely to be a concern. The development of the first generation of hydrogen appliances is a key aspect of the BEIS Hy4Heat programme.

Logistical Impact	Adaption of appliances	New hydrogen appliances	Hydrogen-Ready dual-fuel appliances
Initial survey [S]	Initial survey likely to be required for all appliance variations. Survey time – 1-2 hours (see Section 5).		
Pre-conversion work [S]	Minimal hands-on pre-work	Minimal hands-on pre-work	Installation of appliances as natural gas appliances fail. Remaining appliances pro-actively replaced. ½ -1 day for primary appliance (boiler) ½ day for secondary appliances
At the point of conversion [S]	Full appliance conversion and testing: 0.5-1 days* for primary appliance (boiler) ½ day* for secondary appliances *Disruption highly dependent on accessibility of appliances, availability of internal spaces and number of components to change.	Full appliance conversion and testing. 0.5-1 day for primary appliance (boiler) ½ day for secondary appliances	Appliances converted from natural gas to hydrogen. Appliance designed to facilitate process. 1 hour for each appliance.
Ongoing servicing/maintenance post conversion [2]	Single annual service but requiring more components to be replaced on each visit. Reduced product life compared to natural gas appliances	Single annual service with time and cost similar to current natural gas appliances. Product lifetime similar to current natural gas appliances (10-15 years for boilers, hobs and ovens, 15-25 years for fires)	
Training requirements [S]	Specific skills related to appliance conversion – may focus on a particular appliance or type of appliance.	Only requires installation of new appliance – no internal works required.	Specific skills related to conversion of appliances. Could benefit from a standardised conversion kit across industry.
Other Issues [2]	Uncertain if conversion kit can be developed that is sufficiently universal to fit different product variations. Increase in noise expected and limited ability to add acoustic damping.	Would require replacing a natural gas appliance with a hydrogen appliance that is potentially still functional.	Appliances may require some doubling up of components but it is envisaged that these appliances could fit into the same envelope as current natural gas appliances.

Table 2: Domestic logistical variations for the appliance variations. [S] indicates information that was provided by stakeholders

5 Domestic Conversion Process

This section explores the practical delivery of a potential conversion, assuming that a region has been identified as being suitable. It describes the sequence of practical tasks that would need to be undertaken to bring about the switchover and highlights the potential logistical challenges.

5.1 Practical Tasks & Sequencing

The following approach is proposed for the switchover of an area. This is based on the approach taken for the town gas conversion [5], combined with the findings from the stakeholder engagement:

- Initial engagement with the customer;
- House surveys;
- Servicing existing gas system and addressing any faults;
- Installation of new appliances/ conversion of appliance; and,
- Commission for hydrogen and handover to customer.

These are discussed in the following sub-sections. A schematic illustrating the stages in the town gas conversion is provided in Annex A.3.

5.1.1 Initial Customer Engagement

Customer engagement and buy-in was highlighted at the workshop as a crucial aspect of a potential conversion. Prior to any conversion there would need to be a public communication exercise to educate people and bring them on board with the proposed plans. Stakeholders emphasised that householders should feel like they are able to make an informed decision about converting their home to hydrogen based on the facts and other options available to them. It was proposed by stakeholders at the workshop that this engagement should address the following:

- Why a conversion to hydrogen from natural gas is being proposed - what are the benefits – at a national and also domestic level?
- Whether hydrogen is safe?
- How it is likely to impact them, both physically and financially?
- When it is likely to affect them? and,
- What alternative choices they have to heat their home and how do these weigh up against hydrogen?

In the build up to the town gas conversion in the 1970s, various letters were sent to the households, initially letting them know that natural gas conversion was coming to their area but also to forewarn them that some preliminary visits would be required. Reminder letters were sent to ensure that the customers would be in during the actual day of conversion, and if this was not possible, that they should make arrangements for entry into their premises [5]. Clearly methods of communication have changed significantly since the 1970s and any public feeling – positive or negative has the potential to be spread widely and rapidly on social media.

A switchover will require multiple visits to collect information and undoubtedly result in some physical disruption to the property. Stakeholders suggested that it may be necessary to offer incentives to customers to compensate them for the disruption. The Oban project, which only required around 30 minutes of surveys per property offered the free installation of carbon monoxide (CO) detectors to all properties tested and free repairs or replacements where a working appliance was found to be faulty could not be repaired economically. This project also used a variety of media to ensure good public knowledge and engagement including leaflets, local press and radio, presence at local community events and social media [8].

5.1.2 Home Surveys

Home surveys would be needed to assess the extent of work required to convert individual homes. In discussions with stakeholders it was agreed that by this time, the general requirements for changes to pipework, fixings, ventilation and gas detection needed for hydrogen will have been determined and this survey will be used to assess the elements of individual properties that will need to be changed. Furthermore, a key part of the survey would be an assessment of the accessibility of the gas pipework and inventory of gas appliances.

Some form of gas tightness tests will need to be undertaken to test the integrity of the pipework and this will require the property to be without gas for a short amount of time – typically 10-20 minutes (see Section 3.4.1).

There was considerable discussion by the stakeholders on the required duration of a home survey for a hydrogen transition. The main reasons cited were the variations in durations of current natural gas servicing appointments due to accessibility constraints and also the potential desire to identify complementary home improvements that could differ between households (discussed separately in Section 7.1). Surveys undertaken as part of the Oban project took around 30 minutes [8] but it was generally agreed that for a hydrogen conversion these would need to be longer at around 1-2 hours allowing for a gas tightness test. Accessibility for the surveys is clearly a concern, but it was found not to be a significant issue in the recent Oban study which involved surveying approximately 7,700 properties. The access rate achieved in this voluntary participation scheme was 86.9% [8].

5.1.3 Updating Domestic Gas Systems

The town gas conversion included a service of the gas system service prior to the actual conversion work. Whilst all appliances required adapting or replacing for natural gas, the domestic pipework itself did not need to be changed for any fundamental differences between town gas and natural gas, apart from where the pipework or gas fittings were not considered safe for the existing town gas. In the most part, the town gas conversion involved changing regulators and filters at the entrance to the home for the new higher pressure but did not require any other changes to the internal pipework [5]. At this stage it is not known if any pipework would need to be changed for a hydrogen conversion. However, whilst it is likely that copper pipework will be suitable for hydrogen (discussed in Section 4.1.2), it is proposed that the integrity of any joints is more questionable, and some joints may require upgrading. This is discussed further in Section 9.

The new hydrogen pipework will also need to be suitable for natural gas as prior to the switchover, the property will continue to operate on natural gas. A potential issue at this stage is the discovery of safety concerns with the gas system. During the town gas conversion, if inadequacies in the gas system were found during the initial survey, customers were told that they had to make these good prior to conversion. It was sometimes difficult to persuade customers that they had to upgrade their system if the upgrades were based on general safety concerns, rather than specific issues related to the gas conversion itself. Where old appliances were identified that could not feasibly be converted, attractive trade-in terms were offered for newer appliances as these reduced the cost of conversion [5].

Customers are currently responsible for maintaining a safe gas system in their home and to rectify unsafe situations when they occur. The discovery of gas safety concerns during the course of a hydrogen transition was discussed with stakeholders.

There was general agreement that householders may associate the sudden need for repairs to the existing gas system with the hydrogen transition and therefore may be hesitant to rectify the problems themselves.

In the event of a hydrogen transition, if the conversion team discover that the current gas system is unsafe then they would be obliged to make it safe – either by isolation or, if feasible to rectify the fault. It is proposed that it is less clear who pays for any remediation and this will need to be clearly defined from the outset and applied universally to avoid confrontation and dissatisfied customers.

5.1.4 Conversion and Commissioning

On the day of conversion, it is assumed the focus will be on the appliances as it is proposed that the gas systems, ventilation and building structure and materials will have been updated and tested previously as part of the pre-conversion.

A suggested plan of activities required for the conversion, showing the interaction with the gas distribution system is presented in Figure 2.

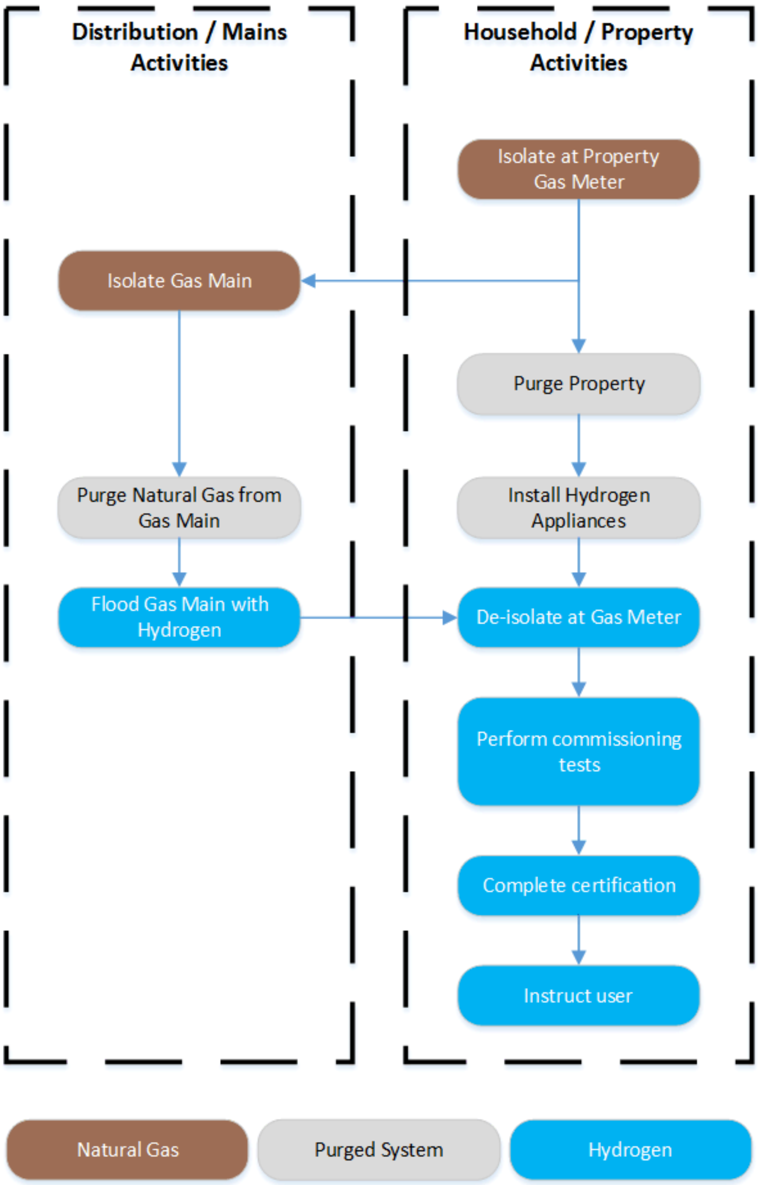

Figure 2: Proposed steps in a domestic hydrogen conversion

5.1.5 Post Conversion Issues

A number of post conversion problems were encountered in the town gas switchover and there was a 20% call-back rate [5]:

- Dissatisfied customers with new/converted appliances.
- Work not fully completed during conversion or post-survey issues not closed out (such as interior decoration not subsequently made good).

It is suggested that these problems could be mitigated using a post installation service check and early on in the whole conversion programme this would also be an opportunity to gain feedback and improve the process.

5.2 Cost and Timescales of Conversion Work

The predicted timescales and associated costs of the various stages of a conversion are presented in Table 3. In Section 4.3, the timescales associated with the different appliance options were discussed – noting that Hydrogen-Ready appliances would be installed in advance of the conversion, whilst the adaption of existing natural gas appliances and the installation of new hydrogen appliances would be undertaken at the point of conversion. There is no significant difference in the total amount of time required within each property between these appliance options and so for simplicity in this section a single timescale is assumed to apply to all three options.

The costs have been determined based on the average salary of a Gas Safe engineer (£35,000, Section 3), assuming 250 working days per year and a contingency multiple of 2 to allow for transportation time and costs (corresponding to approximately £300 per day). These times and costs are based on a single Gas Safe engineer per property.

Table 3: Duration and cost of conversion works

Stage	Duration	Indicative labour Cost
Initial survey	1-2 hours Based on evidence from town gas conversion and Oban project but also discussed actively with stakeholders.	£100 Although an initial survey should only take 1-2 hours, the cost will depend on the number of properties visited in a day. This is conservatively assumed to be 3.
Pre-conversion updates to domestic gas system (non-appliance time)	½ -1 day to update pipework assumed It is not currently known what changes to the pipework are required and therefore it is difficult to predict the pre-conversion work. This estimate was provided by, and discussed with stakeholders but is for initial indication only. If significant upgrades are required or if pipework is not accessible then this will be significantly longer.	£150 - £300 + parts* *It is currently difficult to predict the cost of parts until the requirements for materials have been determined.
Appliance conversion/installation (appliance time)	½ -1 day for boiler Up to ½ day for other appliances. Based on typical current natural gas activities and discussed actively with stakeholders.	£500 - £600 (2 days assumed) + appliance costs.

5.3 New-Build Homes

This section has so far assumed that conversion would involve the adaptation or replacement of appliances in a similar manner to the previous town gas and Manx Gas conversions.

At the workshop, it was identified that new-build homes present a possible opportunity for easy transition without the disruption required in existing properties. These properties could be fitted with a gas system that is suitable for hydrogen, combined with Hydrogen-Ready dual fuel appliances that have been temporarily been back-fitted to run on natural gas. These houses could then be run with natural gas until the point of changeover but then readily switched over to hydrogen. A basic survey prior to the formal conversion would be required but the system and appliance information would have been fully documented from the outset so the survey should be limited to a brief safety check. This approach is particularly attractive for new build properties where there are a significant number of houses in close proximity that could all be converted together.

6 Hydrogen Workforce Requirements

6.1 Qualification & Competency

At present, all domestic natural gas work must be completed by a registered Gas Safe engineer and it is proposed that the structure and rigour of the Gas Safe qualification is an appropriate starting point for developing a strategy for a hydrogen conversion.

The consensus from the stakeholders was that a hydrogen workforce could be developed using the existing Gas Safe workforce but with a changeover qualification similar to that already used to transfer between the Gas Safe core elements (Section 3.2). Hydrogen has fundamentally different properties to natural gas and this will require new techniques to be developed and learnt. Nevertheless, the broad technical knowledge of Gas Safe engineers will be beneficial for working on hydrogen.

An alternative approach proposed, and then discussed with the stakeholders is to develop a newly skilled conversion team from scratch. This approach has been used in the SMART meter roll-out and has the advantage that it could allow personnel to be trained up significantly faster with only the specific skills required for conversion. Overall after some discussion, the consensus of opinion was that hydrogen conversion would require a broad practical gas related skill-set as well as specific knowledge on the safety implications of hydrogen and therefore should use Gas Safe as the starting point.

Based on the review of the current natural gas industry and the input from the stakeholder engagement, three levels of training are suggested to develop a hydrogen conversion workforce and these are summarised in Figure 3. The extent of training recommended is based on the relevant experience and competency level of the potential workforce and is generally in line with the current Gas Safe training.

Hydrogen Changeover Qualification	Moderate Training & Assessment	Extensive Training & Assessment
Appropriate for practicing Gas Safe engineers Depends on current competency level and prior competency should not be assumed. Similar procedure to the existing changeover qualification.	Appropriate for those who previously held Gas Safe qualifications or those working in other relevant trades. Extent of training largely depends on relevant competency and previous experience and time out of industry.	Appropriate for those with no prior relevant experience. Must develop full competency and incorporate the whole gas system.

Figure 3: Three levels of training for hydrogen conversion depending on prior experience

6.2 Training

During the town gas conversion, most of the work was carried out by independent contracting firms who trained up new staff without prior gas experience for the programme. These firms were responsible for recruiting and training their employees as well as carrying out the conversions in their particular areas. The training programmes lasted 4-6 weeks and were undertaken by 13 schools spread around the country. The training syllabus was agreed nationally by the Gas Council and the Training Boards of the Gas and Construction Industries. Evidence suggests that there were retention issues, but financial incentives were used to encourage staff to stay available until no longer required [5].

Further refresher courses were provided at various stages and these also allowed converters to progress through various grades. The training of the survey and conversion teams were maintained almost until the end of the programme to replace those leaving the programme. There was an increase in numbers of qualified engineers leaving the programme as work in an area started drawing to a close. To avoid this becoming a significant logistical issue, financial incentives were offered to the engineers to remain in the programme until its completion [5].

Stakeholders reported that there are currently around 100 accredited gas training centres in the UK. Training is commercial and competitive in the UK and the consensus was that training bodies would develop their facilities to cover hydrogen if a demand for hydrogen training courses develops. Stakeholders advised that typical training courses retail at around £600 per day.

In addition to the development of the personnel required to perform the actual hydrogen conversion, stakeholders pointed out that there would be a requirement to either upskill or attract new engineers to the wider gas industry to enable a hydrogen conversion. An example was provided regarding the technicians and engineers required to develop and manufacture new appliances or engineers performing upgrades to the upstream gas network.

6.3 Workforce Size

The size of workforce needed for the conversion is highly dependent on the required speed of the conversion. The stakeholders highlighted that drastically increasing the size of the workforce for a short period of time should be avoided, as this would lead to employment concerns following the conversion.

The industry stakeholders suggested that conversion would be carried out regionally as the gas distribution networks are converted. This would also allow existing Gas Safe personnel in an area to become trained as the region they work in is converted. However, they also pointed out that the existing 130,000 pool of Gas Safe engineers is geographically fragmented and therefore trained staff may need to move around the country to support the local workforce.

Despite these complications, some simple calculations at a nationwide level can be used to obtain a sense of the scale of workforce required. Section 4.3 discussed the logistics of installing different hydrogen appliance options (adapted, new hydrogen appliances and Hydrogen-Ready) – drawing out whether these appliances would be installed in the pre-conversion phase or at the point of conversion. As there is no significant predicted difference in the total time required to install each of these options, in this current workforce calculation no distinction is made between the appliance options and the conversion is split simplistically into three aspects (initial survey, property updates – comprising mainly updates to pipework) and appliance conversion/installation.

The following timescales associated with converting individual properties are assumed (extracted from Table 3).

- Initial survey: 3 homes surveyed per day.
- Property updates (pipework): ½ day (but depends on changes required).
- Appliance conversion/installation: Boiler conversion takes 1 day. Hobs, ovens and fires each take 0.5 days.

As of 2017, there are approximately 27 million properties across England, Wales and Scotland [28] [29], of which approximately 23 million have a metered gas connection [30]. The total associated number of installed gas boilers, hobs, ovens and fires is presented in Table 4.

This corresponds to a total of 52 million man-days of effort:

- Initial survey: 8 million man-days (23 million homes x ⅓ man-day per home)
- Property updates: 12 million man-days (23 million homes x ½ man-day per home)
- Appliance conversion/installation: 32.75 million man-days (21.2 million man-days for boilers, 5.2 million man-days for fires and 6.35 million man-days for hobs and ovens).

Table 4: Estimated installed and purchased appliances and typical lifetimes

Gas Appliance Type	Estimated installed appliance base [31]
Boilers	21.2 million
Fires	10.4 million
Hobs and ovens	12.7 million

Two workforce scenarios are considered as follows:

- **Scenario 1:** If a conversion workforce of 100,000 was developed and each person spent 50% of their working year on conversion (50% x 250 days = 125 days) then the whole exiting stock of UK homes could be transitioned in approximately 4 years. If no pre-conversion work is required (i.e. homes are surveyed but no updates to pipework are required) then this timescale would reduce to approximately 3 years.
- **Scenario 2:** If the conversion was only undertaken by the existing Gas Safe workforce of 130,000 then it is probably only reasonable to assume that 10% of their time is spent on conversion[3]. Based on this, the existing appliance base would take approximately 16 years to complete. If no pre-conversion work is required then this timescale reduces to approximately 12 years.

In comparison, the town gas conversion required converting 40 million appliances over 10 years [5]. The total number of appliances currently in existence is only slightly greater than this at 44.3 million (Table 4) which shows that the predicted timescales for a hydrogen conversion are largely comparable with the town gas conversion.

Any hydrogen transition would need the hydrogen production capacity and hydrogen transmission and distribution grid to be in place prior to domestic conversion and in practice it is not feasible that these could be developed on these timescales. However, these scaling calculations indicate the scale of the challenge of converting domestic properties.

Regardless of whether the conversion labour force comes from the existing pool of Gas Safe engineers or newly qualified personnel, the industry stakeholders pointed out that this would have an impact on availability of associated trades. A related concern is the impact to the appliance manufacturers of a fast conversion programme. Manufacturing would need to be accelerated, only to suffer a slump in demand afterwards [2].

[3] Stakeholders pointed out that Gas Safe engineers typically only spend a small proportion of their time on gas work with the remainder on general plumbing and building services.

6.4 Enabling Organisations

During the town gas conversion, Watson House in London provided technical support to the conversion programme [5]:

- Conversion procedures, particularly where manufacturers were no longer in business.
- Development and testing of conversion kits for appliances which presented particular difficulties.
- Offering technical support to the conversion teams.
- Bringing some 6,000 of customers' appliances into laboratory for off-site conversion on occasions when they could not easily be dealt with at the customer's premises.

This support was instrumental to the success of the conversion and it is proposed that a similar organisation could be considered for a potential hydrogen switchover. The Hy4Heat programme is intending to explore the requirements for an appliance and equipment testing facility.

7 Risks, Barriers and Opportunities

The UK's natural gas supply currently involves multiple interlinking systems which deliver continuous service to millions of individual customers. It is suggested that maintaining this service through a transition to hydrogen will require complete and simultaneous conversion of all of the system's elements: gas sourcing (production and importing), transportation, storage, distribution and supply, in order to be successful.

The elements of the supply infrastructure upstream of the meter and the organisations which deliver them, regularly coordinate activity to deliver a common purpose. However, the elements of the industry which provide services downstream of the meter in domestic properties do not currently have to deliver coordinated activities and therefore a strategic programme of change of this type presents a challenge.

This section outlines the particular challenges that affect the providers of services downstream of the meter. However, the integration of the upstream and downstream elements will ultimately also need to be considered.

7.1 Additional Opportunities Offered by a Hydrogen Conversion

Previous conversions have involved property surveys and this information has provided useful information that has helped progress safety and innovation. In the town gas conversion, the unprecedented surveying of the domestic gas infrastructure highlighted significant sub-standard pipework and other inadequate installation and gas fittings. This provided the catalyst to strengthen the Gas Safety Regulations [5]. Similarly, the Isle of Man upgrade was used as an opportunity to introduce gas safety regulation, upgrade ageing infrastructure and carry out safety checks [32]. It is proposed that a formalised inventory of domestic properties could similarly be used to develop new materials and techniques.

Our experience from Low-Carbon Network Fund and Network Innovation Competition projects on both the gas and electricity networks is that energy consumers are not willing to undergo disruption for purely environmental benefits. It is proposed that it may therefore be necessary to use the provision of other benefits as an incentive for homeowners to engage in the conversion process. In addition to surveying houses and converting them to hydrogen, stakeholders cited that the following could offer additional enhancements:

- Fire and air internal air quality survey, including smoke alarm testing, general fire safety and the provision of adequate ventilation.
- Home energy efficiency measures including:
  - Insulation and ancillary heat loss prevention measures;
  - Smart home controls and advanced networked thermostats;
- Part exchange of old natural gas appliances for new hydrogen ready appliances;
- Provision of any upgrades required for hydrogen enabling new pipework or valves at low or no cost;

It is suggested that a suitably qualified and experienced surveyor would be required in order to scope the potential for each of these enhancements in a domestic property. These benefits would also need to be offered on a consistent basis in order to maintain public opinion and commitment. If these enhancements were offered on a commercial basis, there is a strong requirement to ensure customers are not pressurised or miss-sold benefits.

7.2 Risks, Barriers and Mitigation Options

A UK-wide conversion to 100% hydrogen would require personnel to enter every grid-connected home in the country and undertake a safety-critical conversion. The general complexity and sensitivity of the programme presents significant practical risks to its overall success that are discussed as follows:

Property Access and Domestic Modifications

It is proposed that there must be a firm understanding of the legal framework surrounding conversion works to address aspects of the conversion which may prove contentious. These aspects may relate to:

- Gaining access;
- Enforcing conversion;
- Handling unsafe situations; and,
- Responsibility for gas system.

If the position relating to these aspects is known and communicated up front then they are likely to present less of a risk to the delivery of the conversion.

Stakeholders highlighted that gaining access to homes may be particularly challenging due to a large proportion of UK homes being unoccupied during the day and gas appliances being in use when the home is occupied.

Workforce

The skill pool of qualified and experienced technical personnel to deliver this change over is currently too small to achieve it in reasonable timescales. As discussed in Section 6, a hydrogen conversion would require a pool of expertise with both a broad gas knowledge and specific training in hydrogen. Lessons can be learnt from the SMART meter roll-out.

The study has highlighted the following options for mitigating these risks:

Surveys to characterise housing stock

By engaging with stakeholders, this investigation has highlighted that there is a lack of high quality information on the housing stock and in particular the routing, material and condition of the gas pipe and associated equipment. It is proposed that a sampling and surveying study would help to more accurately bound the costs, barriers and risks of converting the housing stock in a given area.

Training

Stakeholders highlighted that the lack of appropriately trained and experienced individuals to enact the transition is a potential issue affecting the speed, certainty and safety of the potential roll out. It is proposed that the scoping, creation and initial delivery of a training course to be the hydrogen equivalent of the Gas Safe qualification would be a ‘no regrets’ development. Even if complete rollout of hydrogen across the grid does not happen, there is likely to be enough demand for these skills across the future hydrogen economy to warrant the course’s development. Technical staff wanting to work on hydrogen vehicles, fuel cells or electrolysis for energy storage will need a similar set of basic theory, technical competencies and safety knowledge.

Quality and Costs

Safety and cost efficiency are also divergent aims for the roll-out programme. There are safety risks created by the transition and these need to be managed through verification and independent safety checks on installation. It is proposed that this could be accomplished through dual working, random spot checks of installations or by peer review and sign-off. Each of these approaches to verification has its own costs and benefits and a cost-benefit exercise would need to be undertaken to establish the most suitable verification approach.

Education and Communication

Stakeholders engaged in this study highlighted that public perception and acceptance of hydrogen as a heating fuel is currently unknown and could be a barrier to a future hydrogen roll-out. Education and communication will therefore be essential to the successful transition from natural gas to hydrogen. Stakeholders emphasised that it will be vital to communicate the benefits of a hydrogen conversion – removing the risk of carbon monoxide poisoning being a key benefit but also (and depending on how the hydrogen is sourced) the potential to increase the security of energy supply to the country as a whole.

Relevant project experience is presented in Section 5.1.1 where community communication was required. Best practices and lessons learned can be adopted for these to develop a clear communications strategy for any roll-out.

Stakeholders reported that hydrogen is not well known as a fuel and as a result, customers may be reluctant and cautious of using it as an alternative to the familiar natural gas. However, public perceptions are liable to change as the technology becomes more familiar. Hydrogen fuel cell technology is becoming better established for both vehicles and for industrial power support. There are also flagship projects such as the roll out of hydrogen fuelled busses in Aberdeen [35]. All these successful projects help build public confidence and normalise the concept of using hydrogen as a domestic fuel.

In Orkney, various hydrogen projects have been received very well by the community. By involving customers from the beginning and communicating the benefits well, the customers were positively disposed to the changes [36].

Trials

It is proposed that a small-scale trial would be beneficial in normalising hydrogen as a fuel; developing a training pipeline of suitably qualified and experienced hydrogen engineers; getting operational experience of both transition to, and operation of, a hydrogen grid and providing a proof of concept of generation, transport and consumption of hydrogen. Grid-edge communities have the following characteristics and it is suggested that these make them suitable for a small-scale trial:

- Limited number of homes,
- Surfeit of renewable electricity generation which is often export constrained and can therefore be used to electrolyse water;
- Population who are more community focussed and a history of innovative energy adoption (e.g. Eigg Electric/ Surf ‘n’ Turf on Eday, Orkney); and,
- May have issues with energy security (e.g. reliant on fuel shipped in by tanker) which might make a hydrogen roll-out more attractive than it might be on the mainland.

During the town gas conversion, two small-scale conversions were undertaken in Canvey Island, Essex and Burton-on-Trent. During these trials, many thousands of different models of gas appliance were encountered and this highlighted the need to accurately predict the types of appliances in use across the country. When the full conversion started, most area boards chose to begin operations in lightly populated, outlying areas to gain experience before tackling the most densely populated areas [5].

7.3 Caveats and Limitations

In any large programme of change involving many different organisations that need to be brought together there are various uncertainties that need to be considered. In the context of the evidence base produced in this report, the caveats and limitations in this evidence are discussed as follows:

The analysis of the evidence gathered through interviews, stakeholder discussion and literature review does not indicate that there are specific discontinuities or large inflection points in the cost/ benefit trade space for the transition. Consequently there is unlikely to be a specific number of personnel or transition timescale which would have an outsized effect on the outcomes of the programme. This has been a qualitative exercise to identify the necessary logistical steps and potential barriers in the performance of a hypothetical transition to full hydrogen. The nature of the research means that we have been able to identify and assess a number of key concerns and contingencies in performing that conversion downstream of the meter, but we are unable to quantify their impact.

All of the numbers presented in this report, therefore, have significant uncertainty associated with them. Interviewees were generally reticent to provide quantitative estimates of timescales and costs; there is also genuine difficulty and uncertainty associated with the future prediction of the costs and performance associated with step-changes in technology. Any pathway models resulting from this study should therefore take account of this through rigorous input sensitivity studies. It is suggested that the duration of a ‘normal’ house conversion and personnel retention and retraining cost are key variables in this. Section 9 provides recommendations for additional investigations to develop higher quality, more accurate data to reduce these uncertainties and these will be key to better quantifying the costs and timescales associated with a transition.

One limitation of this study, which will need to be resolved to enable accurate predictions, is the gas system up-stream of the meter. Understanding the relationships between planning and transition timescales for the transmission and distribution grids and domestic property conversion has not been considered and will be important. From speaking to stakeholders, it has become apparent that the industry is not used to co-ordinating planning and work between these two elements of the system and there seems to be poor mutual understanding of the culture and operating approach between the two. Miscommunication or unaligned planning between stakeholders in the transition process will have a disastrous effect on project costs and timescales.

In the same way, it is anticipated that the programme duration will be sensitive to the length of time of an average conversion. If a property takes three days to convert when only one is planned the resultant disruption will have a disproportionate knock-on effect to the overall costs and timescales.

Table 5 summarises a series of trade-offs that would affect a hydrogen transition. These are proposed based on the consolidated evidence obtained from the stakeholders.

Table 5: Trade-offs affecting the cost of transition

Trade-off	Discussion
Cost, Quality, Timescales	The whole transition programme will be subject to the normal large project 'trilemma' where costs, timescales and quality of work are all interdependent on one another and optimising one element is at the expense of the other two. For example, a higher quality transition (delighted customers, minimised installation defects, etc) can only achieved by increasing timescales or incurring larger costs.
Workforce Size	The more personnel that are trained, equipped and deployed on the transition programme the more quickly it will be able to be completed. To effect a very quick transition would require a large number of suitably qualified and experienced staff to achieve the large number of conversions per day. A large workforce, and requirements for a large change in workforce, will also drive the programme costs. Many stakeholders have advised against creating a 'spike' in new entrant trainees due to the potential poor consequences for staff development, experience transfer, quality of work and staff retention.
Existing Housing Stock	There are significant unknowns regarding the material, quality and suitability of the full population of domestic gas installations. No survey data appears to exist and anecdotal discussion with stakeholders indicates that quality of installation can vary significantly from property to property. Costs and timescales will be sensitive to the average length of a property conversion and therefore a representative sample of this information needs to be surveyed and recorded. One possible option for the phasing of a hydrogen transition roll-out is to focus on new build properties initially before moving on with the legacy housing installations (Section 5.3). This would require the new-build houses to be on a designated gas distribution grid.
Geographical Area	The timescales suggested for domestic conversion (0.5 to 1 day, per boiler (Section 5.2) means that a conversion team are not likely to be converting more than two properties in a single workday. This limits the effect that travel time between conversions has on the timescales of transition in a given area. The speed of transition is then primarily governed by the number of personnel who can be deployed. Socio-economic factors associated with an area are likely to have some effect on occupiers' engagement with the process and may be a factor, but these are beyond the scope of this study.

8 Conclusions

This report has explored the logistical challenges of converting homes from natural gas to 100% hydrogen. Evidence has been obtained from a variety of sources including stakeholders from the current domestic natural gas industry; reports from previous conversions and scientific research on hydrogen characteristics. This has been explored and validated by comparing the different sources, detailed 1-2-1 interviews with industry, and a discussion workshop.

This evidence has been used to propose an approach to undertaking a property-by-property hydrogen conversion involving: initial surveys, pre-conversion preparations to the property and the actual conversion itself. Whilst there is significant uncertainty about the national timescales for transition, this outline approach should allow the evidence gathered to be relevant to a variety of national roll-out scenarios. Evidence from previous conversions and current natural gas servicing durations have been used to estimate the duration of each element of conversion.

- Initial surveys have been predicted to take 1-2 hours.
- Pre-conversion updates have been predicted to take between half a day and a day, assuming that the pipework is readily accessible, although this is dependent on the technical changes required to the gas pipework and the scope and variation of this are not currently well understood.
- Length of domestic conversion itself will depend on the number of appliances in a property, but it is anticipated that boilers will take up to one day's work and hobs, ovens and fires half a day each.

The size of workforce needed for the conversion is highly dependent on national ambitions for the speed of the conversion and is completely dependent on the development of the associated hydrogen production and transmission systems. However, considering domestic conversion in isolation, simple calculations suggest that a nationwide domestic conversion could reasonably be completed in 4 - 16 years, depending on the workforce deployed. Stakeholder consensus for national roll-out strategy is that conversion would most likely be carried out regionally, in harmony with the transition of the transmission and distribution network.

The skills required to bring about a hydrogen transition are consistent with those developed as part of existing Gas Safe registration for natural gas. It is therefore envisaged that Gas Safe training is a suitable starting point, with specific hydrogen elements added to the existing core competencies. Stakeholder evidence highlighted that drastically increasing the size of the Gas Safe workforce for a short period of time should be avoided, as this would lead to employment concerns following the conversion. Regionalised roll-out allows existing Gas Safe personnel in an area to become trained as the region they work in is converted. However, it is envisaged that there would need to be significant movement of trained staff around the country to support the local workforce.

The condition of pipework within properties is not well characterised and this will have a significant impact on the timescales and achievability of transition. Stakeholders provided a variety of anecdotal evidence relating to the difficulties that individual properties might pose and work is required to quantify the effects that this would have regionally and nationally. A number of different materials and various pipe joining methods are currently used for domestic natural gas pipework, including legacy materials not covered by modern standards. However, the majority of UK properties are serviced by welded (soldered) copper pipes and the view from the stakeholders was that these are likely to be suitable for hydrogen. It is envisaged that the BEIS Hy4Heat programme will seek to explore many of these questions.

9 Recommendations

Based on the evidence reviewed in this study, a number of gaps in evidence have been highlighted. To assess the feasibility of converting UK homes to 100% hydrogen, it is suggested that it will be necessary to understand the technical requirements for safely transporting hydrogen gas in homes and the domestic modifications required to meet these requirements. It is understood that these will be considered as part of the individual work packages in the Hy4Heat programme.

Two separate tasks are suggested:

- Design specification for the use of 100% hydrogen in homes.
- Home survey to characterise existing domestic gas systems.

9.1 Design Specification for Hydrogen in Homes

This will involve experiments to understand the safety of running hydrogen through domestic pipework systems and also the implications to building safety if hydrogen does escape.

Gas Pipework System

Welded copper is widely used for domestic gas pipework and this is a good starting point as it is likely to be suitable for use with hydrogen. However, other commonly used materials, such as steel and their respective joining techniques should be tested as well. This also provides an opportunity to determine if plastic pipework, which currently cannot be used for fire safety, is suitable for domestic gas applications.

It is suggested that tests will need to include the following:

- Leakage rates through pipework and fixings – initially at the domestic gas pressure of 20 mbar but exploring the effect of variations in driving pressure.
- Degradation of materials by hydrogen to understand the operational lifetime of the components.

It is proposed that the tests will need to allow for variations in operating conditions (temperature and humidity) as well as the implications of hydrogen purity and odorants that will need to be added to aid detection.

Building Safety

It is proposed that experiments and modelling will be required to understand the consequences of hydrogen leakage:

- Dispersion of hydrogen in houses and the potential to form combustible gas mixtures.
- Ventilation required to exhaust hydrogen clouds from buildings as well as NO_x and the additional water vapour that is produced from hydrogen combustion.
- Effect of building fabric porosity on the ejection of hydrogen.
- Requirements for gas detection and where this should be located.

The results of these work packages could be used to form the basis of a design specification for hydrogen.

A separate, and relatively straight forward task, would then be to compare and contrast the materials and procedures that are required for hydrogen, with the existing procedures for natural gas – essentially a gap analysis. This will highlight whether:

- Existing domestic gas systems are appropriate for hydrogen;
- The hydrogen specification can be met with only small modifications to the existing domestic pipework; or,
- Existing domestic pipework systems need to be entirely replaced.

If significant changes are required for hydrogen, it may be appropriate to develop a specification for new-build homes (Section 5.3). These domestic gas systems would be developed with hydrogen in mind but installed in the first instance using natural gas. At the point of changeover, the property could then be immediately ready for hydrogen.

9.2 Survey of Domestic Gas Systems

It is proposed that a survey is undertaken to characterise the existing installed base of domestic gas systems. This would highlight the number of homes that could realistically be converted to hydrogen and the type of homes that would be most suited. Such a survey would need to be representative of the UK as a whole and therefore need to take into consideration regional variations in materials used. It is suggested that this survey should include the following:

- Gas pipework and fixings used, size, age and condition of pipework.
- Ease of access to pipework (whether the pipework is readily accessible from underfloor voids, encased in concrete or buried underground.
- Number and type of gas appliances, age, condition and accessibility.
- Provision of ventilation to appliances and gas pipework.
- Installation and sealing of gas flues.
- Gas tightness of pipework (see tightness test in Section 3.4.1).

It is envisaged that this information will be dependent on the property type and the survey should also determine more general information to allow trends between gas system and property type to be produced. This will also highlight the types of properties that are best suited to a conversion. In particular:

- Type of property - Houses are likely to have more appliances, longer gas runs and more accessible pipework. Pipework in flats is likely to be less accessible.
- Age of property – Older properties are likely to use legacy materials (steel and lead) that may not provide compliant gas tightness.
- Type of ownership – the need for rented properties to undertake an annual gas check may mean that these properties are better maintained than owner-occupied properties.

There are likely to be correlations between the type of ownership and the age of the property. Within the private sector, 20% of owner occupied properties and 35% of privately rented properties were built pre-1919 [37]. It is proposed that upgrades and modifications have been undertaken over the lifespan of these properties, however there is likely to be significant variation in the approach to installation in terms of pipework, fittings and routings. Ultimately, it is the inter-relationship between property types and the domestic gas system that is particularly of interest. Once these have been correlated, it should be possible to identify regions around the country that are most suited to hydrogen conversion.

Overall, surveys offer a variety of benefits even if an eventual hydrogen conversion is not progressed. In the town gas conversion, the unprecedented surveying of the domestic gas infrastructure highlighted significant sub-standard pipework and other inadequate installation and gas fittings. This provided the evidence and catalyst to strengthen the Gas Safety Regulations [5]. Similarly during the Manx Gas conversion, the surveys were used to carry out extensive safety checks within customers' properties [6].

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ANNEX A -

A1 Questions set by BEIS

The formal list of questions posed by BEIS that this report has aimed to answer are listed as follows. The relevant part of the report that answers each question is highlighted in square brackets.

1. What practical tasks would need to be undertaken in order to transition UK domestic properties from natural gas to hydrogen from the meter and downstream? [4] [5.1]

2. What options exist for delivering the tasks identified? [5, 6]

3. How would these tasks be sequenced and co-ordinated? [5.1]

4. Would opportunities exist to combine this exercise with other works required to improve properties to reduce overall disruption? For example would it be practical for energy efficiency measures to be installed at the same time? [7.1]

5. How much would it cost and how long would it take to transition a home from the meter and downstream (both in terms of the individual tasks and in total)? [5.2]

6. How often and how long would access to homes be needed for and what tasks would require access to the home? [5.1]

7. What skills would be required to deliver the tasks identified and what training/qualifications would be needed to deliver this? [6.1, 6.2]

8. What workforce size would be required in order to deliver this? [6.3]

9. What issues might arise during the first few weeks/ months following the transition and what overhead and training might be required to address these? [5.1, 5.5]

10. At what stage would the household's gas need to be turned off and how long will their gas need to be off for? [5.1]

11. What are the key drivers behind the cost and timings of a transition? For example would the logistical requirements, costs and timings differ according to the following and if so, what are the differences and why? [9]
    a. Property type (e.g. flats vs houses)
    b. Age of property
    c. Type of Ownership (e.g. freehold vs leasehold)
    d. Type of Occupant (e.g. owner occupied vs rented vs social housing).

[4] Depending on where the meter is located this may include pipes both in the home and outside.

12. In practice, what information would need to be understood about the homes being transitioned and the different types of existing gas appliance in the homes before a transition could be completed and how would that information be obtained? [5.1.2, 9]

For example, would surveys of the homes and the types of gas appliance contained in each home to be converted need to be completed and what level of detail would be required? [5.2]

13. What are the different logistical implications associated with the 4 appliance variations being considered as part of hydrogen appliances project currently being undertaken by Frazer-Nash[5] for BEIS: Full replacement, Adaptable, Dual Fuel and Hydrogen Ready?: [4.3]
a. What different logistical processes would be required?
b. Would different training would be required for each variation?
c. What evidence limitations exist in seeking to answer these questions and how might they be addressed?

14. What risks and barriers would exist and how could they be overcome? [7.2]

15. What could be done to minimise these risks/barriers? For example what could be done to minimise the disruption of a transition for consumers? [7.1]

16. What trade-offs and sensitivities would exist? [7.4] For example:
a. What factors would influence the cost of a transition?
b. What could be done to minimise the timescales of a transition?
c. Would it be cheaper to transition suburbia than city centres?
d. How would the costs and logistics change depending on different scales and speeds of transition? For example how might the costs and logistics change if 100, 1000, 10,000, 20,000 or 30,000 homes were converted per day and what would be the impacts on the required workforce size?
e. Would the logistics and costs vary across different parts of the country?

17. What assumptions have been made in conducting this work and in reaching conclusions? [A.4]

18. What are the data limitations? [A.4]

19. What evidence gaps exist and how might they be addressed? [9].

[5] BEIS ITT - Hydrogen Appliances -v2 03May17.docx

A2 Stakeholder Questionnaire

The questionnaire developed to support the 1-2-1 stakeholders is reproduced as follows:

Interview Questionnaire Structure

Project:	BEIS Hydrogen Logistics	**Client:**	BEIS
Location:	Enter meeting location	**Date and time:**	Enter meeting date Enter time
From:	Enter name of person, job title and the company they represent		
Subject:	Stakeholder Interview Questionnaire		
Purpose:	To gain industry expert knowledge on the practical logistics of switching from NG to H2		
Document no:	57239/102873V	**Issue no:**	1
Document classification:		Not protectively marked	

Participant ID:	*Participant ID*
Interview Date:	*full date*
Interviewer(s):	*name of interviewer*
Interviewees:	*names of interviewee(s)*

Introduction

- Introduce yourself and FNC [very brief]
- State that this research has been commissioned by BEIS [no need to provide more detail than this]

Purpose of study:

- Overall objective of the study is to develop an understanding of the logistical challenges associated with a hydrogen switchover downstream of the meter.
- Considers domestic properties only.
- Findings will provide BEIS with crucial data to facilitate further studies about the viability of a hydrogen switchover moving forwards.

Interview Outline:

- Length of interview – 1 Hr
- Interview Structure
  - Process – Tasks & Coordination Involved
  - Personnel – Workforce Aspects
  - Risks & Opportunities
  - A.O.B & Close
- This is not in any way an assessment of their current capacity to deliver on a hydrogen switchover.
- The research is a scoping exercise designed to get a better sense of the logistical requirements associated with such a switchover, and the more honest about limitations and challenges that participants can be, ultimately the more helpful the research will be.

Data handling and privacy:

Ref: 57239/102873V/1

Interview Questionnaire Structure

Please read out: "The findings from this interview will be used for research purposes only. We will not pass on your details to other organisations outside of the research team. Any interview findings that we use in the research may be linked to other surveys or datasets but the information you provide will be anonymised before inclusion in published outputs. We will keep any information that you share with us confidential and store it securely, in accordance with the Data Protection Act" "The findings from this interview will be used for research purposes only. We will not pass on your details to other organisations outside of the research team. Any interview findings that we use in the research may be linked to other surveys or datasets but the information you provide will be anonymised before inclusion in published outputs. "To support the analysis of the interview data, BEIS will be provided with a summary of this interview. This information will not be shared beyond BEIS. We will keep any information that you share with us confidential and store it securely, in accordance with the Data Protection Act. "The Data Protection Act will be replaced on the 25th May of this year (after the delivery date for this research) with new regulations called the General Data Protection Regulations. These new regulations build on existing regulations but require that you give 'valid, freely given, specific, informed and active' consent for us to be able to recontact you in the future. The purpose of any follow-on research would be to dive deeper into the logistics of a hydrogen transition with a research participant who had been previously identified, is familiar with the topic, and could provide access to further contacts for additional follow-up research. The purpose of follow-on research would not be to ask or probe about specific individual responses given to this (current) research. "Do you consent for BEIS - or an independent research organisation appointed by BEIS - to recontact you within 12 months of completion of this research (ie: by the close of April 2019) to perform follow-up research as outlined above? "To support the analysis of the interview data, BEIS will be provided with a summary of this interview. This information will not be shared beyond BEIS." [do not ask for explicit consent to this, but if participant says they would prefer for any element of the transcript not to be shared with BEIS, record this, tell them that we will respect this wish, and proceed with interview anyway] - Emphasise that there are no wrong or right answers. We want to hear their opinions and views. We want to hear what they have to say, in their own words
Ask if interviewee has any questions before you start?
Response:
Applicant background
Confirm role in the gas supply chain during interview. "I understand that your company is involved with the installation and servicing of domestic gas supply and appliances. Is this correct?" If not: Ask participant to briefly explain what their company's role is

Interview Questionnaire Structure

1.	Part 1: Process
1.1	Based on previous conversions the following approach has been adopted. Do you consider the following four categories of Gas Work to be a logical sequence: • Servicing of existing NG appliances and pipework • Fault Finding & raising no compliances – Pre-conversion • Installation – New pipework / Appliances / ventilation • Commissioning – New Hydrogen Appliances and Pipework. Handover to customer. Prompts: • Households • Pipework • Equipment • Regulations / Standards Note: Depending on where the meter is located this may include pipes both in the home and outside.
	Response:
1.2	Considering a hypothetical home conversion from Natural Gas to Hydrogen – A detached house in a rural area, Built in the 1980's with no building modifications (i.e. in line with building regulations). The property has a Combi Boiler, Gas hob/ oven and a gas fire in living room. • How long would it take to transition this home from the meter and downstream? • When and how long would this home be without gas/ hydrogen? • What would be the typical Day Cost for this work? Prompts • Break out tasks involved. • How long will each task take? • Resource required - Experienced Gas Fitter or up-skilled worker? • Replacement Materials / equipment required? • Use 'town gas" conversion flowchart as a guideline.
	Response:
1.3	Would there be any variation depending on the type of household? Prompts • Property type (e.g. flats vs houses) • Age of property • Type of Ownership (e.g. freehold vs leasehold) • Type of Occupant (e.g. owner occupied vs rented vs social housing). • Are there any other factors that may influence cost/ time of a conversion?
	Response:
1.4	Are there any steps/ processes you feel is missing or are there additional activities that would be beneficial?
	Response:

Interview Questionnaire Structure

2.	**Part 2: Personnel**
Consider the workforce that would be required to deliver this transition?	
2.1	What is the current Workforce size?
	Response:
	Can you explain what this response is based on? Experience / research / visibility of industry
	Response:
2.2	What additional workforce would be required in order to deliver this? Prompts: • Where are the shortfalls in workforce? Age / Skillset / Training / Experience.
	Response: Why do you believe this to be the case: (Experience / research / visibility of industry)
2.3	What additional qualification / training would be required? Prompts: • Current training requires 10 weeks training • Practical demonstration • Theoretical knowledge • Change-over qualification
	Response: Why do you believe this to be the case: (Experience / research / visibility of industry)
2.4	What is the capacity of training currently available within the UK? Prompts • Number of reputable training centres • Turnaround period of Trainees / Course lengths • Grants / Funding available • Apprenticeships • On the job training
	Response: Why do you believe this to be the case: (Experience / research / visibility of industry)

Interview Questionnaire Structure

3.	**Part 3: Opportunities and Risks**
3.1	Are you aware of any opportunities to combine other works with these switch over to minimise disruption for the occupier? Prompts: • Energy Efficiency measures • Upgrades • Electrical Supply
	Response: Why do you believe this to be the case:
3.2	Considering current practice in domestic natural gas works, what are the biggest challenges you see in transitioning UK domestic properties from natural gas to hydrogen from the meter and downstream? Prompts: • Workforce • Equipment / technology available • Coordination / management • What factors may have the greatest impact?
	Response: Why do you believe this to be the case:
3.3	What are the general risks and barrier you see with transition a household from natural gas to hydrogen? Prompts: • Revisit conversion process discussed in section 1.1
	Response: Why do you believe this to be the case:
3.4	What immediate issues might arise during the first few weeks/ months following the transition and what overhead and training might be required to address these?
	Response: Why do you believe this to be the case:

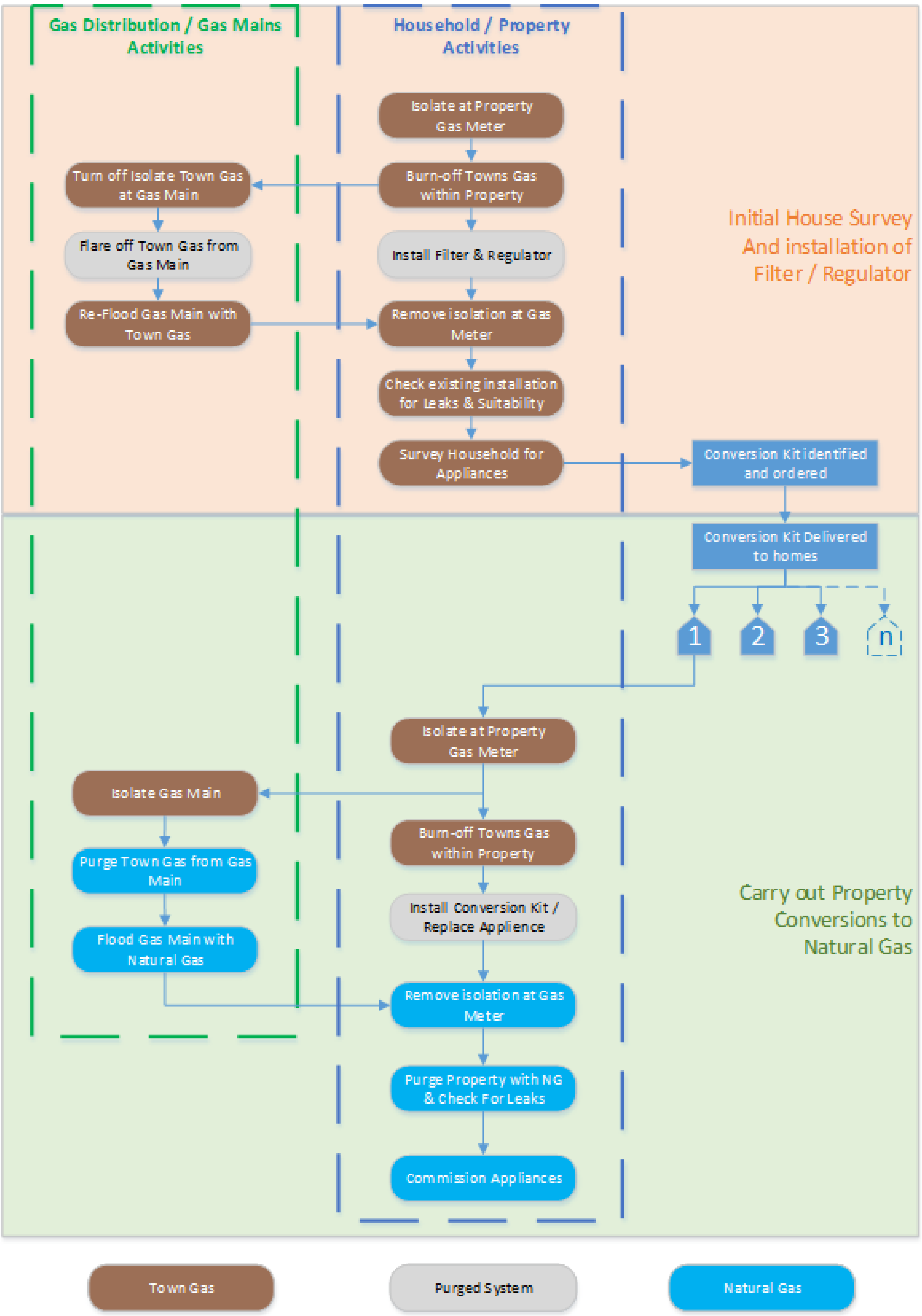
Interview Questionnaire Structure

3.5	What could be done to minimise these risks/barriers? For example what could be done to minimise the disruption of a transition for consumers? Prompts: • Explore response to previous question • Minimise Time • Minimise access • Alternative accommodation / heating / portable gas supplies.
	Response: Why do you believe this to be the case:
3.6	What trade-offs and sensitivities would exist? For example:
	a. What factors would influence the cost of a transition?
	Response: Why do you believe this to be the case:
	b. How would the costs and logistics change depending on different scales and speeds of transition? For example how might the costs and logistics change if 100, 1000, 10000, 20000 or 30000 homes were converted per day and what would be the impacts on the required workforce size?
	Response: Why do you believe this to be the case:
	c. What could be done to minimise the timescales of a transition?
	Response: Why do you believe this to be the case:
	Would the logistics and costs vary across different parts of the country (Northern/Southern/devolved, rural/urban)?
	Response: Why do you believe this to be the case:
	Would it be cheaper to transition suburbia than city centres and what impact does housing density have on the performing a transition?
	Response: Why do you believe this to be the case:
3.7	Do you think the transition from Natural Gas to Hydrogen is a good move for the UK?
	Response: Yes No Why do you believe this to be the case:

Interview Questionnaire Structure

4.	**Part 4: A.O.B & Close**
4.1	Ask if interviewee would like to say anything else, or whether they have any question for you
	Response:
	• Thank the participant for their time. • Reiterate that their anonymity will protected in our final reporting. • Tell them they are welcome to contact members of the study team to ask questions at a later date if they wish
4.2	*"We plan to summarise the output from this interview and shared the output with BEIS to allow them to carry out quality assurance of the research. A copy of this write up can be made available to you upon request. Prior to inclusion within the final published report, any reference to stakeholder identity will be removed and any findings will be included in the report anonymously. Are you happy for this interview to be shared with BEIS for these purposes?"* Response: YES NO
4.3	Check if they are happy to be contacted for future research on the hydrogen logistics
	Response: YES NO

A3 Town Gas Conversion



A4 Data Limitations and Assumptions

The stakeholders consulted in the study had a significant background in natural gas systems but many have had limited active involvement in the hydrogen gas systems. Consequently, their input has been primarily based on their practical background in natural gas system installation, fault-finding and training. Their input generally has therefore comprised expectations based on their professional judgement and were keen to emphasise that this has not been underpinned by detailed analysis or testing.

Data Limitations

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

- The information collected has been based on multiple, consolidated opinions with expertise in natural gas appliances but little or no direct involvement with the development of hydrogen gas systems.
- There is a considerable body of evidence on hydrogen in industrial applications (at considerably greater pressure). There is very little knowledge of hydrogen at the low pressure used in domestic pipework.
- Stakeholders were not asked to share commercially sensitive information.
- The current industry is not used to innovation or radical change and therefore has limited experience to draw from.

Assumptions

This study has involved the following assumptions:

- Domestic gas systems comprise the gas meter, pipework, pipework joints and local isolators near appliances. It does not include the main isolation of the property or the regulator used to drop the pressure to 20 mbar.
- Only domestic pipework systems have been considered. Commercial and industrial pipework has been omitted.
- Heat generated from any hydrogen appliances will be from combustion. Fuel-cells and other technologies are beyond the scope of this project.
- The analysis has concentrated on a hydrogen concentration of 100%. The feasibility of using hydrogen in lower concentrations blended with natural gas has not been considered.
- The energy market for domestic natural gas appliances is assumed to stay relatively constant in the short to medium term (up to 2030). The impact of radical changes in the market such as electric heating or heat pumps has not been considered.

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