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A QUANTITATIVE RISK ASSESSMENT OF A DOMESTIC PROPERTY CONNECTED TO A HYDROGEN DISTRIBUTION NETWORK

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ABSTRACT

The increased reliance on natural gas for heating worldwide makes the search for carbon-free alternatives imperative, especially if international decarbonisation targets are to be met. Hydrogen does not release carbon dioxide (CO_2) at the point of use which makes it an appealing candidate to decarbonise domestic heating. Hydrogen can be produced from either 1) the electrolysis of water with no associated carbon emissions, or 2) from methane reformation (using steam) which produces CO_2, but which is easily captured and storable during production. Hydrogen could be transported to the end-user via gas distribution networks similar to, and adapted from, those in use today. This would reduce both installation costs and end-user disruption. However, before hydrogen can provide domestic heat, it is necessary to assess the 'risk' associated with its distribution in direct comparison to natural gas. Here we develop a comprehensive and multi-faceted quantitative risk assessment tool to assess the difference in 'risk' between current natural gas distribution networks, and the potential conversion to a hydrogen based system. The approach uses novel experimental and modelling work, scientific literature, and findings from historic large scale testing programmes. As a case study, the risk assessment tool is applied to the newly proposed H100 demonstration (100 % hydrogen network) project. The assessment includes the comparative risk of gas releases both upstream and downstream of the domestic gas meter. This research finds that the risk associated with the proposed H100 network (based on its current design) is lower than that of the existing natural gas network by a factor 0.88.

Keywords: Hydrogen · Distribution Network · Quantitative Risk Assessment

1 Introduction

Worldwide, in 2018, the consumption of natural gas grew by 4.6%. This marks the greatest increase seen since 2010 (Iea, 2019). The increased consumption also resulted in an 83% increase in CO_2 emissions since 1990 levels (iea, 2018). In the UK the growth in natural gas consumption has been driven primarily by an increased reliance on natural gas for domestic heating, which now services around 85% of households (Dodds & Demoullin, 2013; IET, 2019). It is therefore crucial to find an alternative way of providing carbon free, cheap, and reliable heat to society (BEIS, 2017). Hydrogen is an energy vector which can provide carbon-free heating (BEIS, 2017; Dodds & Demoullin, 2013).

An extensive amount of literature exists showing how hydrogen can be integrated into the energy network alongside other decarbonisation technologies such as compressed air energy storage (Ball & Weeda, 2015; Bünger et al., 2015; Dodds & Demoullin, 2013; Mouli-Castillo et al., 2019, Mouli-Castillo et al., 2021). Recent technical advances in Proton Exchange Membrane (PEM) electrolyser technology and fuel cells, as well as well-established alkaline electrolysis capabilities, makes the technical feasibility of hydrogen uptake, over the coming decades, more likely. To enable this shift to take place, demonstration projects will also have to de-risk the technology from a regulatory and commercial standpoint (Ball & Weeda, 2015). De-risking will require a clear understanding of the risks and safety measures of all parts of the hydrogen value chain (Mohammadfam & Zarei, 2015).

Most research into the safety aspects of hydrogen value chains focus on industrial production, transport, storage, and end uses. Work relating to consumer and/or public risk has been centred on quantitative risk assessments (QRAs) at fuelling stations (Mohammadfam & Zarei, 2015; Tsunemi et al., 2019). Furthermore, safety assessments of hydrogen transportation in piped networks focus mainly on either hydrogen and natural gas blends, or high pressure systems (J. Kim & Moon, 2008; Stolecka, 2018). Only one study by Lee et al. 2015 was found to investigate the safety aspects of a low-pressure hydrogen distribution network in South Korea (Lee et al., 2015). This is in the town of Ulsan (South Korea) which aims to become a hydrogen hub. The majority of work at Ulsan has been in support of the rollout of hydrogen for the transport sector and fuel cell technologies. Currently, combusting hydrogen for heat does not appear to be the main focus of the plans at Ulsan. Thus, there is a major gap in published research into the safety of transporting high purity hydrogen within a low-pressure distribution network to consumers, specifically for domestic use in combustion appliances e.g. boilers, cookers, fires.

SGN is one of the UK gas distribution companies, providing gas to some 5.9 million homes and businesses across Scotland, the south of England and Northern Ireland. SGN own and operate the Local Transmission System and Distribution network which link the pressure reduction station to the emergency control valves (ECVs) at the consumers' meter. SGN is undertaking the Hydrogen 100 (H100) project that seeks to deliver construction and demonstration of a 100% hydrogen distribution network to supply domestic heat. The project will deliver hydrogen to approximately 300 homes on a voluntary basis. The project uses existing knowledge, and supports new research, to develop a strong evidence base. A primary risk mitigation method in terms of gas distribution is the use of odorants. Mostly sulphur based such as Mercaptans, but also free of sulphur. This distinction is important as fuel cells are damaged by sulphur compounds, requiring desulphurisation of the gas. Odorisation in hydrogen and natural gas has been studied in the context of the hydrogen transition, in particular for its use in distribution gas networks. Mouli-Castillo et al. 2020 undertook standardised olfactory characterisation of widely used odorants. Mouli-Castillo et al. *in press* have conducted a comparative assessment between hydrogen and methane odorisation and concluded that Odorant New Blend, standby-Odorant 2, and THT used in the UK and mainland Europe would allow a comparable detection of hydrogen leaks to that of natural gas. Hence, this aspect of risk mitigation is not explicitly considered here as it is would neither increase nor reduce the comparative risk.

Quantitative risk assessments (QRAs) are a formalised methodology for evaluating human, economic, personnel and community risk levels, which enable comparison to regulatory risk standards. QRAs can be described as the formal and systematic method to determining potentially hazardous events, assessing the likelihood and consequences of such events, and presenting the findings as risk to people, the environment or infrastructure (Vianello & Maschio, 2014).

Here we present a comprehensive and multi-faceted QRA tool for the comparative assessment of a 100% hydrogen distribution network to the current natural gas network. We demonstrate its value by applying it to the proposed H100 demonstration, which is scheduled for operation in the early 2020s. We show how this novel QRA framework supports the rollout of hydrogen in the UK by drawing on the comparative approach taken by the Health and Safety Executive (HSE), a UK safety authority. This approach requires the demonstration that any new network is 'as safe as' the current natural gas one. In this paper, we describe systematically how each key part of the gas network and parameters leading to fatalities can be quantitatively characterised. For each we propose a quantitative 'most-likely' estimate using first hand operational data from gas industry and regulatory body records, as well as the results from an extensive experimental programme combined with modelling. In section 4, we go on to calculate the risk 'most-likely' comparative risk factor between the current and future H100 hydrogen networks. Finally, we undertake a sensitivity analysis to identify the maximum uncertainty allowable for each of the parameters for the 'as safe as' regulatory guideline to be met for the H100 network.

2 Quantitative Risk Assessment methodology of a low pressure gas distribution system methodology

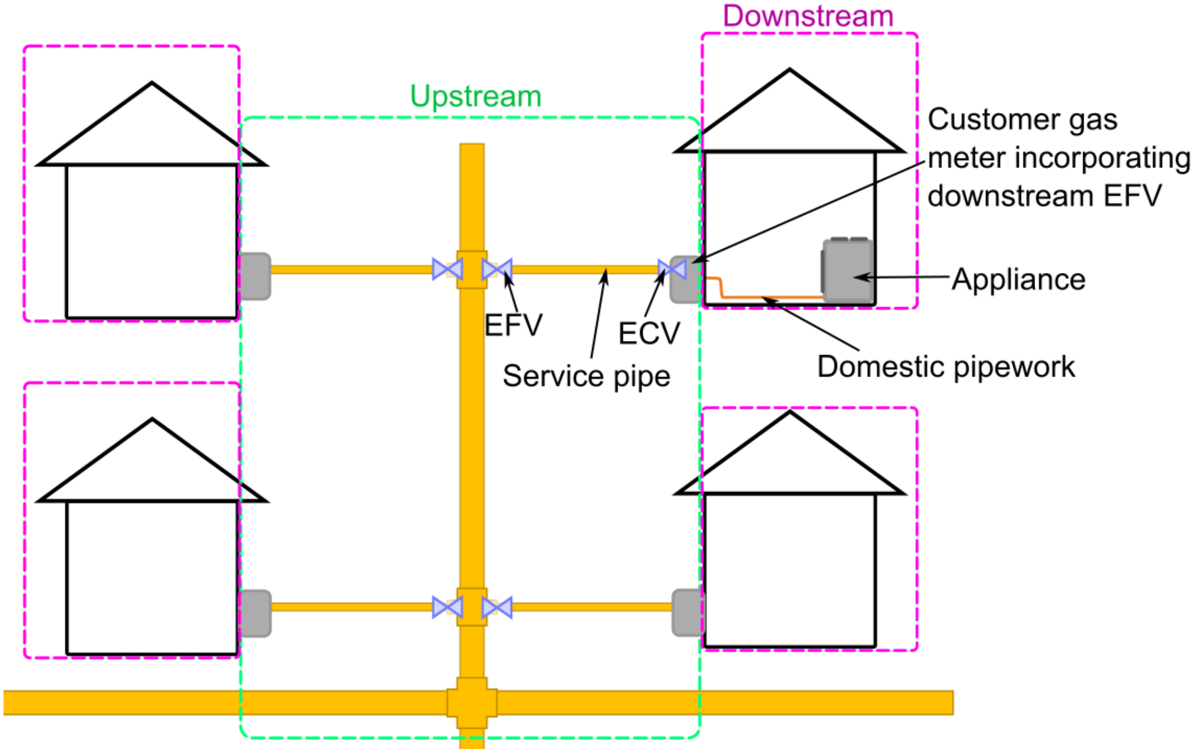


Figure 1: H100 schematic showing the various components of the system. EFV stands for Excess Flow Valve which stops the flow when it reaches a certain level, and ECV for Emergency Control Valve allowing to safely isolate the customer's pipe from the network.

Internationally there are no existing quantitative safety standards for hydrogen distribution networks to domestic users (Energy Networks Association, 2018; Lee et al., 2015). As such, the UK Health and Safety Executive (HSE) (government agency responsible for the regulation and enforcement of safety practices) operates an 'as safe as' policy. In effect, it has to be demonstrated, using a robust safety case, that a future hydrogen network is 'as safe as' the current natural gas distribution network. For this reason, the QRA presented here is a comparative assessment between the accepted safety levels of the current natural gas distribution network in the UK, and planned hydrogen networks. We use the H100 project as a case study for its application (Figure 1). Thereafter the term 'upstream' will refer to the gas distribution network and service pipes upstream (before) the ECV, located after the customer's gas meter. Similarly, the term 'downstream' will refer to the pipes and appliances inside the domestic property (after the ECV). In addition to the ECV, Excess Flow Valves (EFV) are also installed on the network to prevent uncontrolled release of gas in the event of a rapid pressure drop downstream of the valve.

The aim of the QRA is to understand how the differences in hydrogen and natural gas characteristics affect the risk profile of the network. This comparison involves the consideration of five essential elements:

1. The probability of gas release from network piping. This includes the distribution of sizes of the holes through which a gas release could occur, and estimates of gas release rates. (Section 2.1)
2. The movement of flammable gas in the event of a gas release upstream of the ECV and the likelihood of gas entering a domestic property. (Section 2.2)
3. The build-up of flammable gas within a domestic property when a gas release enters the property, or originates from a gas release within the property to levels over 20% of the Lower Flammability Limit. (Section 2.2.1)
4. The probability of ignition in the event of a flammable atmosphere occurring. (Section 2.3)
5. The consequences of an ignited release. (Section 2.4)

These elements will now be discussed sequentially.

2.1 Release Probability

The first step of the QRA is to compare the likelihood of a gas release from a future hydrogen network to that of the current natural gas network i.e. the recognised acceptable safety standard.

Table 1: SGN Public Reported Escape Events (2016/2017) and Reduction Factor for 100% PE Network. The Reduction Factor calculation assumes the data originated from a network composed of approximately 74% PE and 26% non-PE assets (Allan & Lewis, 2019).

Network Related PREs	PE Asset (73.6%)	Non-PE Asset (26.4%)	Total	100% PE PREs	Reduction Factor
Mains Pipe	215	1,677	1,892	292	6.5
Mains Joint	149	3,218	3,367	202	16.6
Mains Other Components	577	1,590	2,167	784	2.8
Total Mains Related PREs	**941**	**6,485**	**7,426**	**1,279**	**5.8**
Service Pipe	4,524	4,916	9,440	6,147	1.5
Service Joint	242	150	392	329	1.2
Service Other Components	542	3,235	3,777	736	5.1
Total Service PREs	**5,308**	**8,301**	**13,609**	**7,212**	**1.9**
Total Network PREs	**6,249**	**14,786**	**21,035**	**8,490**	**2.5**

Impacts of a Polyethylene network on public releases

This section characterises the relative difference in public reports of gas escapes (PREs) occurring from the polyethylene (PE) sections of the current distribution network to those from metal sections. A PRE occurs when a member of the public calls the national gas emergency service number (HSE, 2019). Since H100 will use an all PE network we use data from a mixed material current network to infer the PREs from a 100% PE network. Sub-components of the physical network e.g. pipes, mains joints, service pipes etc (see Table 1 for SGN sub-component categories) were considered in this study to ensure that any difference was due to the material used rather than a disproportionate Volume amount of sub-components. Components which contain more moving parts (e.g. valve) and joints at which there is a greater chance of poor workmanship (e.g. poor welding) tend to be more prone to leakage. Of course, mains and service pipe were also considered as they form the bulk of the distribution network.

This data (Table 1) indicates that the PE part of the current network leads to significantly fewer PREs than the non-PE sections. The current SGN network is composed of approximately 74% PE and 26% metal components. By extrapolating the reported PREs proportions to a 100% PE network, the total number of PREs for a 100% PE network would be 8,490. That would amount to a reduction factor of 2.5 compared to the current mixed (74% PE and 26% metal) network 21,035 PRE events. We note that using the same assumption, all mains related PREs would drop by a factor of 5.8 and all services related PRE events would drop by a factor of 1.9. We also note that most mains PRE events are related to metal joints. For service related PRE events, the Steel service pipes cause the most gas escapes.

Our analysis assumes a proportional reduction in PREs based on the network material composition fraction. This implies that the number of PREs are independent of the gas transported (i.e. only a function of the network composition). This assumption is reasonable because the increased proportion in PREs associated with joints and components are due to gas being released through interstices caused by joint failure. Other phenomenon discussed in the literature, such as hydrogen permeation through PE (Melaina et al., 2013) is less than gas escapes by volume through physical gaps as studied here. More specifically, the rate of permeation is a function of pressure, hence its effect are insignificant when considered for the service pipe or property with ventilation meeting the UK regulatory criterion of 10 m3/h/m2, as is considered in our study (Crowther et al., 2015). Melaina et al., 2013 state that these losses could be 3-5 times greater for 100% by volume, hence less important in terms of energy. This is echoed in a study by The UK’s Health and Safety Executive indicating that the permeation rates from PE pipe were extremely small compared to the leakage from small defects in pipework and that the leakage rates are insignificant from a safety point of view (J. Hodges et al., 2015). Similarly, at the 7 barg or lower pressure used in the distribution networks, increased gas releases resulting from hydrogen embrittlement of steel has not been demonstrated (Dodds & Demoullin, 2013; JP Hodges et al., 2015; Melaina et al., 2013). And although uncertainty remains as to the threshold pressure at which hydrogen embrittlement becomes a concern, a report by the UK's Health and Safety Executive reported that there was little evidence to suggest material degradation at operating pressures of 7 bar and below found in low pressure distribution networks (Frazer-Nash Consultancy, 2018). Furthermore, it has been shown experimentally that hydrogen gas releases at the same rate as natural gas in typical low-pressure gas infrastructure (Hormaza Mejia et al., 2020).

Impacts of a Polyethylene network on Gas in Building Events

Another dataset from SGN, gathered over the period 2005-2008, indicates both the number of 'Gas in Building' (GIB) events and network material they are associated with. A GIB event is an event that leads to a flammable gas concentration that is > 20% of the Lower Flammability Limit (LFL). The LFL corresponds to the lowest concentration of gas in air required for an ignition to be possible. The safety limit in the UK is set to 20% of that LFL. This is equivalent to 1.0% of Natural Gas in air, and 0.8% for hydrogen.

The dataset contains 261 GIB events. 55 (21%) of which are related to PE assets, whilst 206 (79%) are related to non-PE assets. If the reported GIB event proportions are extrapolated to a 100% PE network, then the total number of GIB events for that network would be 75. That would amount to a reduction by a factor of 3.5 compared to the 261 reported GIB events from the current mixed material network (which forms the current safety standard).

Benefits of a 100% Polyethylene network

The reduction by 2.5 in PREs and by 3.5 in GIB events when up scaled to a 100% PE network (in comparison to the current mixed network) are of the same order of magnitude. For the purpose of the QRA the 3.5 (71%) reduction in GIB events is retained. This is because GIB events are more representative of risk than PREs since they account for flammable accumulations inside buildings.

The use of a PE network upstream of the meter has no influence on releases occurring downstream of the meter (i.e. from a gas release inside the building). As such, the use of PE in the network does not reduce the probability of a release occurring downstream of the meter. This is particularly important when considering that 15% of all reported GIB events in 2014/15 to the UK Health and Safety Executive occurred downstream of the meter (HSE, 2015). These 15% of GIB events would not have been avoided by switching over to full a PE network upstream of the meter.

2.2 Gas Mobility (escapes)

The next step in studying the differences in risk induced by hydrogen releases compared to natural gas upstream of the ECV is to determine the variation in gas mobility between the gas release and the target building. Okamoto and Gomi (2011, 2014) have carried out a series of experiments (Okamoto et al., 2014; Okamoto & Gomi, 2011). In their work they inject hydrogen and methane into a back filled pit considered representative of the type of material where a gas network might be buried. The backfill is mostly composed of sand, covered by 15 cm of crushed stone and 5 cm of asphalt. The experimental work matches analytical models of flow in porous media. Their work is investigates test scenarios which focus on low leakage pressures (lower than that of a UK gas distribution network). To ensure quantitative results applicable to the H100 case study, an extensive set of experimental testing, based on their methodology, was performed at the Health and Safety Laboratory's test facility in Buxton, UK (SGN, 2019). These tests evaluated different scenarios using operating pressures representative of a UK gas distribution network presented in Figure 2. The first scenarios considered gas migration from a buried cavity through a low and a high porosity ground. This was then followed by scenarios with the presence of a channel with higher permeability relative to the surrounding ground and covered by an impermeable layer (similar to road surfacing). Finally, a scenario was considered with only a partial impermeable cover. Low permeability refers to a wet sand with a value of 8.5 x10^{-13} m^2, whilst high permeability refers to backfill material or loose sand with a value of 1 x10^{-11} m^2. The term cover refers to a surface material deemed impermeable or near-impermeable such as a road surface. The 'easy route' represents a linear high permeability channel of back-fill material.

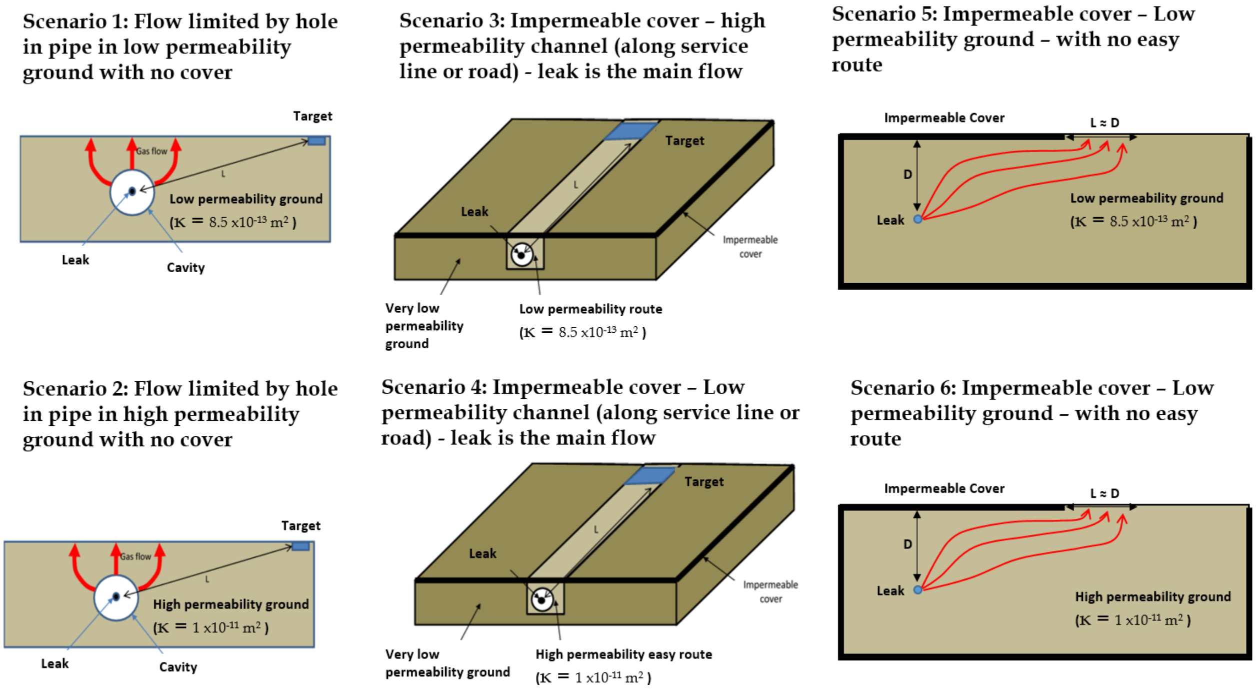


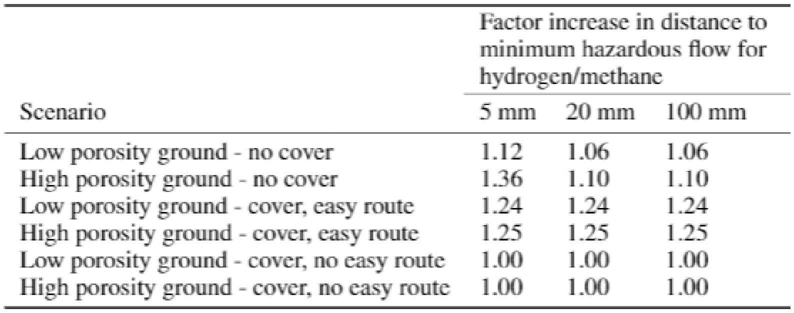
Figure 2: Leakage scenarios considered in this study. L is the length to the target, or for Scenarios 5 & 6 the distance reached by the leaking gas outside the edge of the impermeable cover. D is the depth of the leak.

The key findings of these tests (see Table 2) indicates that:

1) when gas migration occurs in ground without an impermeable cover there is an increase of between 6 and 36% in the distance travelled by hydrogen compared to methane.
2) For the hole sizes tested, gas migration in lower porosity ground travels close to 2 meters from the source of the gas release in the horizontal direction.
3) For large and medium releases in low porosity ground, hydrogen travels 6 % further than methane; whilst for small releases it travels 12% further.
4) The largest relative increase in distance travelled is of 36% for small leaks in high porosity ground without an impermeable cover. The absolute distance however remains in the region of 2 to 4 meters away from the source horizontally.
5) However when an easy route is present, such as a duct or pipe, the increase in hydrogen travel distance compared to methane is both relatively (25%) and absolutely (10s of meters) significant.

Consequently a 1.25 factor increase of hydrogen travel distance (based on the 25% difference) is used in this assessment. To allow for some uncertainty a normal distribution with a mean of 1.25 and a standard deviation of 0.016 was used in the final risk calculations (see 4 Risk Calculation).

Table 2: Increased Distance of Travel Factor for Hydrogen



	Factor increase in distance to minimum hazardous flow for hydrogen/methane		
Scenario	5 mm	20 mm	100 mm
Low porosity ground - no cover	1.12	1.06	1.06
High porosity ground - no cover	1.36	1.10	1.10
Low porosity ground - cover, easy route	1.24	1.24	1.24
High porosity ground - cover, easy route	1.25	1.25	1.25
Low porosity ground - cover, no easy route	1.00	1.00	1.00
High porosity ground - cover, no easy route	1.00	1.00	1.00

The industry has a good theoretical understanding of gas movement from above ground releases. A commonly used industry standard software *Phast* has been used in this study to assess the gas cloud that would result from a large gas release (hole-in-pipe diameter of 100mm). Wind speeds of 2 m/s and 5 m/s are used, corresponding to a ‘Light Breeze’ and a ‘Gentle Breeze’ respectively on the Beaufort Scale, and corresponding to the Pasquill-Gifford categories 2F and 5D. The model results are detailed in Supplementary Figures 1 & 2. The results show that the gas clouds from a large gas release for methane and hydrogen do not reach in excess of 3 m horizontally downwind of the gas release at the LFL concentration. Distribution networks are buried hence gas releases to the open air occur when the network is exposed. This exposure usually happens during servicing or street works. As such, it is assumed that personnel would be present to detect the gas release, and initiate emergency procedures. As this work is explicitly focused on the risk to individuals inside buildings, the case of above ground releases will not be considered further.

2.2.1 Gas Concentrations in Buildings

Whether a gas release into a building originates from upstream of the ECV or downstream, its capacity to lead to a flammable gas accumulation needs to be established. There is limited research which involves direct comparison between the build-up and dispersion of hydrogen and methane (Barley & Gawlik, 2009; Lowesmith et al., 2009; Matsuura, 2009). For this reason this study aims to bridge that knowledge gap by focusing on estimating the relative difference between hydrogen and methane gas build up and dispersion.

This work used the results of experimental work undertaken as part of the HyHouse project (Crowther et al., 2015). The HyHouse project involved the release of hydrogen and natural gas inside a domestic property. This work provides a comparable methodology in which equivalent energy flow rates, for both hydrogen and methane, are used to simulate gas releases into a property. This is representative of the switch to domestic hydrogen supplies i.e. the energy output from the network to the customer would remain the same as natural gas. Because hydrogen has a mass density close to 7.3 times lower than methane at the conditions at which it is delivered to consumers, and an energy density per kilogram close to 2.6 times greater, the volumetric flow rate would have to increase by a factor of 3 to maintain an equivalent energy supply rate.

Table 3: Hole size distribution scenarios, for gas releases from pipework downstream of the meter.

Scenario	Small(%)	Medium(%)	Large(%)
1: Base Case	69	23	8
2	89	10	1
3	33.3	33.3	33.3
4	25	50	25
5	0	0	100

Table 4: Gas concentrations in building from HyHouse (Crowther et al., 2015).

Hole Size	Gas concentration in kitchen (%)						Gas concentration in bedroom above kitchen (%)					
	Natural Gas			Hydrogen			Natural Gas			Hydrogen		
	Low	Med	High	Low	Med	High	Low	Med	High	Low	Med	High
Small	2.2	4.3	5.5	0.3	6.2	8.0	5.5	5.5	5.5	8.0	8.0	8.0
Medium	3.8	5.2	6.2	2.4	8.8	10.9	6.2	6.2	6.2	10.9	10.9	10.9
Large	5.4	5.9	7.0	5.7	12.7	15.0	7.0	7.0	7.0	15.0	15.0	15.0

The experimental work undertaken at HyHouse involved releasing gas into a ground floor kitchen for 2.5 hours. The property had below average ventilation conditions of 3.46 $m^3h^{-1}m^{-2}$ (Crowther et al., 2015). This is below the 10 $m^3h^{-1}m^{-2}$ indicated in UK building regulations and close to the 'zero carbon home standard' of 3 $m^3h^{-1}m^{-2}$ (Billington et al., 2017; NHBC Foundation, 2009). Gas concentration levels were recorded at 1) close to the floor level, 2) at medium height, and 3) close to the ceiling. This allowed gas stratification due to the effects of buoyancy to be monitored. The experiment recorded the gas concentrations both in the kitchen area and in the bedroom above amongst others. HyHouse provides a good basis on which to evaluate the risk caused by the gas release, not only the location within the house, but also in the rooms above where gas is likely to accumulate.

One key control of the gas concentration resulting from a gas release is the size of hole causing the release (Crowther et al., 2015). This size is different from the size distribution for upstream releases which are only relevant to determine the gas displacement and likelihood of a GIB event upstream of the meter. HyHouse uses three hole size for releases corresponding to 16, 32 and 56 kW downstream of the meter. These hole sizes are 3.30 mm (termed "small"), 4.65 mm (termed "medium") and 6.00 mm (termed "large") respectively. At HyHouse, gas was released at a pressure of 20 mbar.

For this study, the distribution of those hole sizes is necessary to perform the risk estimation using the gas release sizes from HyHouse. A "base case" distribution of 69%, 23% and 8% of small (16 kW), medium (32 kW) and large gas releases (56kW) respectively, has been assumed in this work. This assumption is based on release data from small bore (<2") industrial gas pipe data for hole sizes in the range of 1 to 50 mm ((OGP), 2010). In order to evaluate the sensitivity of that assumption, four additional cases were evaluated (Table 3). The results of these tests are reported in Table 4.

2.3 Ignition probability of Gas in Building events

Following the evaluation of the likelihood of a gas accumulation to develop within a building, it is necessary to determine the likelihood of ignition of the air and flammable gas mixture. An understanding of the ignition energy required to ignite the flammable gas mixture, along with the potential ignition sources is required to determine the ignition probabilities of GIB events.

2.3.1 Ignition energy

For an air-flammable gas mixture to ignite, a certain amount of energy is required to be discharged into the mixture. The amount of energy required is dependent on the gas type (i.e. hydrogen or methane) and its concentration in the mixture. This concentration has to be within the flammable range of that specific gas.

Mathurkar (2009) investigated the potential for ignition of hydrogen and methane mixtures as well as for pure hydrogen and pure methane. The work involved establishing ignition energy over the flammability range of the gases. A comparison with four other studies (Bjerketvedt et al., 1997; H. J. Kim et al., 2004; Lewis & Elbe, 1987; Ono et al., 2007) provides confidence in the observed trends. For the purpose of this QRA, the lowest of the ignition energy from the five studies at the corresponding HyHouse concentration was used.

2.3.2 Ignition sources

For an ignition source to result in the ignition of a flammable gas-air mixture, it has to be triggered. Since this is a comparative QRA, only ignition sources likely to present different ignition probabilities between natural gas and hydrogen are considered. Although occupants are equally likely to trigger an ignition source (e.g. flick a switch), the likelihood of ignition (in the case of a gas release) will be lower for methane as it has a lower ignition threshold than hydrogen (i.e. requires less energy to ignite). Therefore it is necessary to consider all possible sources of ignition, and frequency of use, to build up a statistically representative picture of the likelihood of ignition. Below is presented a list of domestic ignition sources for consideration in this assessment:

- Thermostats are assumed to trigger once per hour during the coldest 6 months of the year.
- Fridge/freezers are assumed to trigger once per hour throughout the year.
- Washer/dryers are assumed to be active twice a week for three hours throughout the year.
- Other ignition sources such as static discharge and light switch activation are assumed dependent on the presence of an occupant in the room. More specifically, on the presence of an occupant in the building and its location.
- Light switch activation is only assumed to occur during the night (8 hours per day). A single activation of one of the light switches in the room is assumed.
- The kitchen wall light switche is always used when an occupant is in the lounge.
- The probability of each bedroom light switch to be triggered is spread evenly between all light switches available when an occupant is in the bedroom.

- In 50% of all releases where an occupant is present in the property a static discharge is assumed. These types of events can occur when an occupant in the lounge enters the kitchen causing a static discharge with the door handle, or when an occupant wakes up in the middle of the night to investigate a smell of gas (e.g. causing static discharge from bedding and/or carpet). Not all static discharge will release sufficient energy to allow an ignition.

We note that conditional probability of ignition has been considered to account for the fact that a gas cloud can only be ignited once. The ignition energy required to ignite the gas concentration occurring at HyHouse and presented in Table 4 were determined based on several studies presented in Mathurkar (2009). To account for these studies, for each ignition source a normal distribution in the range of 0.04 to 1.20 mJ with a mean of 0.08 mJ was used. It was assumed that all the ignition sources followed this rule. This represents the uncertainty in the energy released when an ignition source is triggered. This allowed the comparative assessment to focus on the ignition range over which ignition of a hydrogen-air and natural gas-air mixture would differ the most.

2.3.3 Ignition Modelling

Calculations in Microsoft Excel™ were performed to determine the ignition probabilities of hydrogen and natural gas releases in the event of a gas build up event in a domestic property. Using the assumptions and data presented above, the calculations produced the ignition probabilities (shown in Table 5) for the Base Case scenario (presented in Table 3). Table 6 presents the ratio of both hydrogen ignition probability and natural gas ignition probability.

The results show that without mitigation measures in place, ignition of gas in building events from hydrogen releases has a higher probability by a factor of 2 to 4.6 than those from natural gas releases. Mitigation measures and their impact on the evaluation are presented in section 2.6 Mitigation Measures Evaluation.

Table 5: Ignition probabilities from Ignition modelling in Excel, were 1 is equivalent to 100% chance of ignition.

Ignition Probability			
Gas Type	Small Releases	Medium Releases	Large Releases
Natural Gas	0.05	0.06	0.23
Hydrogen	0.17	0.39	0.47

Table 6: Ignition risk factor for different hole size distributions.

Scenario Number	Small(%)	Medium(%)	Large(%)	Ratio of Hydrogen Ignition Probability/ Natural gas Ignition Probability
1: Base Case	69	23	8	4.0
2	89	10	1	3.7
3	33.3	33.3	33.3	3.9
4	25	50	25	4.6
5	0	0	100	2.0

2.4 Consequence Analysis

Assessing the consequences of an ignition of a natural gas or hydrogen accumulation within a domestic building at the concentrations observed at HyHouse is challenging. This difficulty is caused by multiple factors, including gas concentration which can influence the outcome of the ignition. Other factors include:

1. Homogeneity of the gas accumulation
2. Geometry of the room
3. Location of the ignition source
4. Availability of ventilation
5. Energy released by ignition source
6. Degree of obstruction from furniture and other obstacles

In this study we conducted a literature investigation to understand the consequences of gas accumulation ignition at the concentrations encountered at HyHouse. The literature search identified investigations conducted in environments comparable to HyHouse to ensure applicability. As such, for the quantitative component of this new QRA approach to settings other than HyHouse, such as the H100 project, further research would be required on the unique environmental conditions of that particular setting once a specific site is selected for the demonstration network. For H100 such site specific investigations are ongoing as part of the H100 Fife subsequent project.

A threshold value of 0.14 bars was selected as representative of the overpressure resulting from an explosion leading to the partial collapse of the walls and roof of a typical domestic building (Mannan, 2012), thereafter referred to as ‘significant structural damage’. In this context, the ‘overpressure’ refers to the transient and localised increase in pressure caused by the explosion’s shock wave.

To enable a direct comparison of the consequences of a hydrogen gas explosion at HyHouse, for the hydrogen in air concentration levels observed, hydrogen explosion test results from rooms with similar dimensions were used (Bauwens et al., 2012; Ma et al., 2014). Similarly, incident investigations of natural gas explosions were also used to assess the consequences of the natural gas concentrations reached in the experimental releases conducted at HyHouse. Both the experiments carried out by Bauwens (Bauwens et al., 2012) and Ma (Ma et al., 2014) used rooms of 4.6 m by 4.6 m by 3 m (64 m^3). A vent of 2.7 m^2 representative of a standard size window was located on a side wall. Those dimensions are comparable to those of the kitchen used at HyHouse. Indeed, from the HyHouse report (Crowther et al., 2015) floorplan and images the kitchen volume is calculated at 65±2 m^3. Hence, results are considered representative for this specific case. A recently published model (Sinha & Wen, 2019), which was validated against 23 experimental investigations, considered both idealised and more realistic experimental set-ups to investigate the consequences of methane, propane, natural gas and hydrogen ignition. This model (Sinha & Wen, 2019) was used to validate the other sources (listed above) in this study to determine the concentrations at which an ignited mixture would lead to an overpressure > 0.14 bar (the threshold) would be reached. The results are presented in Figure 3.

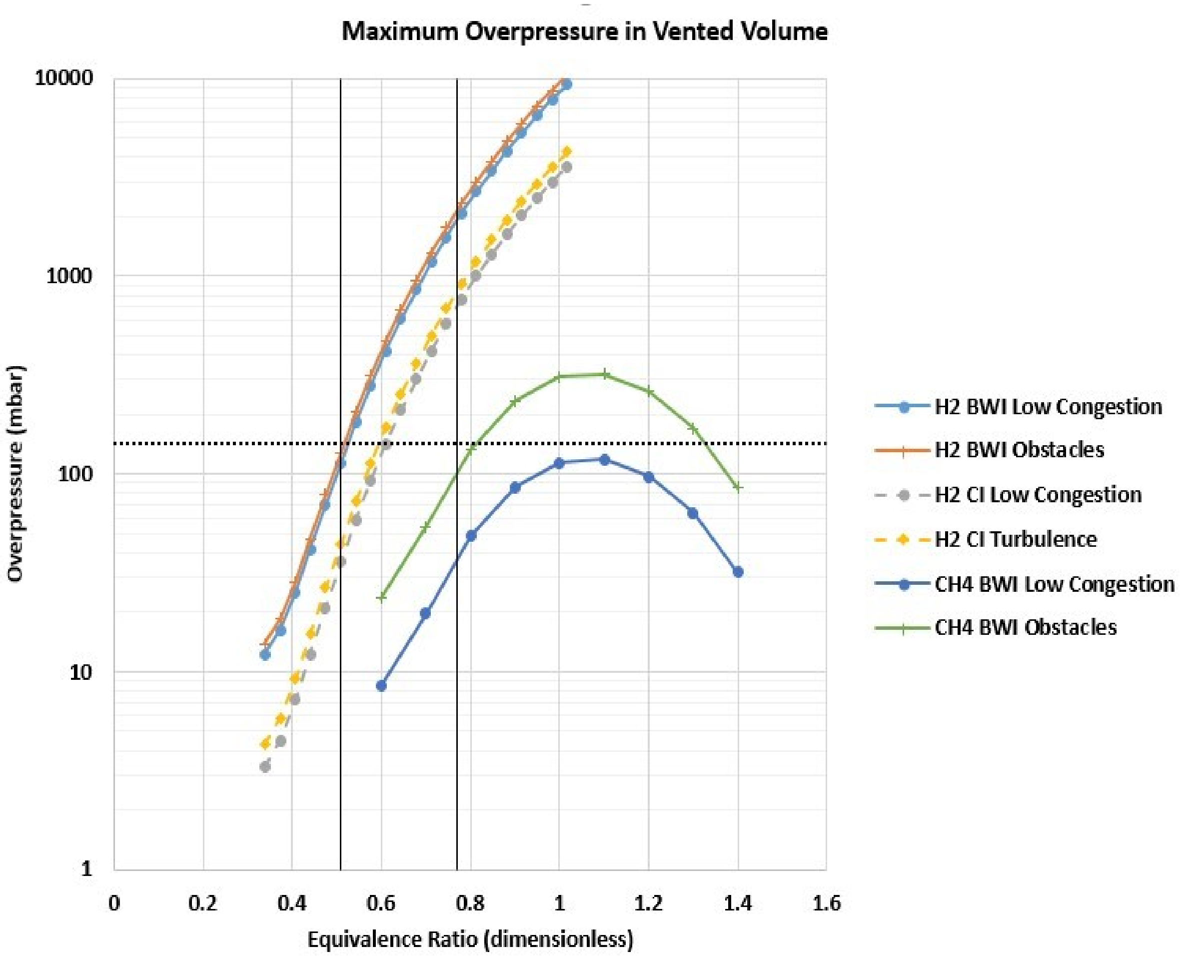


Figure 3: Overpressure caused by the ignition of hydrogen-air or methane-air gas mixture in a 61 m^3 volume with a 2.7 m^2 vent. Various scenarios are considered, including back wall ignition (BWI), central ignition (CI), low congestion cases, cases with a total obstacle area of 3.36 m^2 representative of limited furniture, and a case with initial turbulence.

The experiments carried out by Bauwens (Bauwens et al., 2012) and Ma (Ma et al., 2014), along with the modelled scenarios illustrated in figure 1, indicate that the overpressure resulting from the ignition of a flammable gas cloud is extremely dependent on the scenario considered. This is true even for a fixed volume and vent size. For this reason it is important to select a conservative concentration threshold below which overpressures are unlikely to reach or exceed 0.14 bar. These thresholds are chosen to be 15% and 8% gas in air for hydrogen and methane respectively. These thresholds are illustrated using vertical lines in Figure 3. The equivalence ratio is used in the figure to normalise the results. It is defined as the gas concentration in air divided by the stoichiometric gas concentration in air. As shown in figure 3, at concentrations below the chosen threshold, the overpressure never exceeds the 0.14 bar threshold (horizontal dashed line) in any of the modelled scenarios. This is in accordance with experimental observations from Bauwens (2012) and Ma (2014).

The greatest gas concentrations recorded at HyHouse are 15% for hydrogen and 7% for natural gas (Table 4). These concentrations resulted from the gas accumulations from ‘large gas releases’. This indicates that the levels of flammable gas concentrations reached at HyHouse are close to, or just below, the concentration thresholds above which, if ignited, significant structural damage could occur. We also note that at these concentrations, the consequences from the ignitions related to overpressure would be comparable for both methane and hydrogen. At HyHouse, the ‘small’ and ‘medium’ releases both resulted in flammable gas in air concentration lower than the 15% and 8% thresholds defined above for hydrogen and methane. As such, ignition of accumulations from these releases should not lead to significant structural property damage.

We highlight that the results discussed here are based on the HyHouse experimental setup and building shape, gas release rates, and gas in air concentration levels. These results might diverge in other conditions. For example, if similar release rates are encountered in a smaller volume room with poor ventilation, higher concentrations of flammable gas would occur, and this could lead to an increased contrast in overpressures between hydrogen and methane ignitions.

2.5 Risk Evaluation

Using the work reported above it is possible to evaluate the risk levels for HyHouse for both natural gas and hydrogen. Key conclusions and their implications in the risk evaluation are now presented.

- Upstream Release Probability: The release probability of hydrogen and natural gas is assumed to be independent from the gas properties, and dependent on the network material. For a 100% PE network the release rate can be reduced by around 71%. This benefit is only applicable to upstream releases, and when comparing existing mixed material networks with 100% PE networks.
- Upstream Gas Mobility: In the case of an upstream release, it was found that hydrogen travels on average 1.25 times further than methane. As such it is assumed that the likelihood that an upstream hydrogen release would reach a given property increases by a factor of 1.25.
- Downstream Release Rate: The theoretical release volumetric flow rate from hydrogen releases in a domestic property is around 3 times greater than that of natural gas. This is due to the volumetric flow rate (from a gas release in a domestic building) being governed by the inverse of the square root of the gas density. The density of methane is around 9 times greater than that of hydrogen. The release probability is assumed to be the same for both gases, as it is primarily

controlled by the pipe material and jointing techniques employed , and other external factors (e.g. accidental damage), which are assumed to be comparable for current downstream installation's and the H100's future set-up.

- Gas build-up and concentrations: The concentrations resulting from the release of hydrogen at HyHouse were found to be on average about 1.6 times greater than the concentrations resulting from methane releases (Table 4).
- Ignition Likelihood: Based on the concentrations from HyHouse, and the hole-size distribution assumptions discussed above (section 2.3), the ignition likelihood of hydrogen (for the same energy release rate) was greater than methane by a factor of 4. When only large releases were considered this factor reduced to 2. This difference in ignition probability is primarily due to the ignition energy being approximately one order of magnitude lower for hydrogen than for methane.
- Consequences: The concentrations observed at HyHouse are shown not to lead to flammable gas concentration that would result in an overpressure high enough to results in severe structural damage if ignited. In the case of severe structural damage (overpressure > 0.14 bar) serious injury and fatality of occupants is likely (Ogle, 1999). Due to large releases from both hydrogen and methane resulting in concentration likely to induce a similar overpressure if ignited, the associated consequence in terms of potential to cause 'severe structural damage' to the property is shown to be comparable.

In this study it is assumed that overpressure causing severe structural damage is the main cause of fatality resulting from the ignition of a flammable gas mixture. Other sources of damage exists, namely, in this context, the risk from thermal radiation and toxic chemicals released during combustion. However data compiled under the Gas Safety (Management) Regulation of the UK from 2005-2018 indicates that downstream events resulting in injury are over 6 times more likely to be caused by explosions, than by fires (Health and Safety Executive, 2019). Flash-fires require unconfined combustion to occur, otherwise they develop into a vented explosion. Hence, flash-fires are much more likely outdoors (Lautkaski, 1998). Which means people inside a building would benefit from the protection of the building itself (Rew, Spencer and Maddison, 1998). Hence, when assessing the risk of fatality from the ignition of a flammable mixture inside a confined space with many obstacles (like a domestic dwelling), it is reasonable to consider explosions resulting in severe structural damage as a proxy. The risk of an explosion, which results in structural damage to a building, can be characterised based on the findings summarised in the list above. The likelihood of an explosion causing significant structural damage would be increased by a factor of 2 for large hydrogen releases, in comparison to similar methane releases, under the HyHouse test conditions. This factor increase is caused by the increased probability of ignition of hydrogen. This increase results from hydrogen's lower ignition energy compared to that of natural gas, at the concentrations observed at HyHouse.

When all the release categories (small, medium and large) tested at HyHouse are considered, the likelihood of an ignited event increases by a factor of 4 for hydrogen compared to natural gas. Yet, most of these events would not results in overpressures likely to cause significant structural damage. This distinction is important as it is assumed that gas explosion events, which result in significant structural damage, accounts for most of the consequences of an explosion that would result in fatalities. In which case, for the HyHouse test conditions, the risk of fatalities is primarily associated with large releases. Hence, this risk of fatalities is found to increase by a factor of 2 for hydrogen.

2.6 Mitigation Measures Evaluations

The risk evaluation performed in the previous section assumes that the gas release frequency and hole size distribution are the same for both hydrogen and natural gas. Previous studies such as HyHouse also make the same assumption (Crowther et al., 2015). This assumption is deemed reasonable as the gas releases considered are a result of accidental damage, appliance failure, or poor workmanship on the pipe-work; all of which are independent of the gas properties. This assumption is also demonstrated to be valid downstream of the ECV (Hormaza Mejia et al., 2020). For the reasons above, the gas release frequency for hydrogen and methane are assumed equivalent leading to a two-fold increase in the risk of fatality from structural collapse from hydrogen explosions. To mitigate against this increased risk, the H100 network will be a purpose built 100% PE network. As presented in section 2.1, this will reduce the likelihood of releases upstream by 71%. In addition, mitigation measures will also be implemented downstream of the meter.

Table 7: Effectiveness of Mitigation Measures

Mitigation Measure	Gas in Building events prevented (out of 50)
Enhanced Flame Failure Device	14 (45%)
Crimp Fittings	6 (20%)
Meter located outside	5 (16%)
Removal of lead pipework	2 (6%)
Stronger flexible pipe	2 (6%)
Chained cooker with Rawl bolts	2 (6%)
Flow Limiting Valve (20m^3 of H_2/hr)	Limits the release rates to the maximum used at HyHouse

The mitigation measures considered here are based on a study of 50 GIB events, which are provided in as Supplementary Table 1. For each event it was determined whether the event could be prevented with a risk reduction measure, and if so, what that measure could realistically be.

Key mitigation measures for downstream releases are:

- Enhanced flame failure device (FFD) for cookers and fires,
- Installing the gas meter outside of the property,
- Using mechanical crimp fittings instead of the much weaker and more vulnerable to fire soldered joints,
- Removing any lead pipework within the property as it is vulnerable to fire,
- Installing a stronger flexible pipe at the rear of the cooker to limit the likelihood of damage when the cooker is displaced,
- Fixing the cooker to the wall using a chain and Rawl bolts to limit the loading on the flexible cooker connection, and
- Add a flow Excess Flow Valve (EFV) upstream of the gas meter.

An expert assessment conducted by Environmental Resources Management found that the implementation of these measures, whether individually or in combination, could have prevented 31 out of the 50 considered GIB events (i.e. 62%) (Table 7). We assume that the measures would not be 100% effective in every instance, and a 90% effectiveness was therefore instead assumed. As such, it was assumed that the mitigation measures would actually result in the prevention of 28 instead of 31 incidents (i.e. a reduction of 56%). The 50 GIB events and associated mitigation measures can be found in Supplementary Table 1.

The effectiveness of the mitigation measures displayed in Table 7 indicate that the enhanced flame failure device on appliances e.g. cookers and gas fires, are the most effective in preventing GIB events. It should be noted that the incidents resulting from releases which can be prevented by flame failure devices are usually of a lower severity in terms of the potential for overpressure. In terms of risk, it is therefore probable that other mitigation measures e.g. locating the meter outside, and using crimp fittings, will have a greater effect in preventing explosions and will therefore also prevent overpressures which could cause significant structural damage. This relative importance cannot however be entirely assessed and quantified from the data available.

3 Risk Calculation

Our assessment has analysed the comparative likelihood of:

1) Release from the distribution network (see section 2.1)
2) Ingress into a property from upstream releases resulting in a Gas In Building event (see section 2.2)
3) Releases downstream of the excess flow valve at the customer meter (see section 2.2.1)
4) The occurrence of a Gas In Building event from downstream releases considering mitigation options (see section 2.6)
5) Ignition of a Gas In Building event from large gas releases (≥ 64 kW) (see section 2.3)
6) Ratio of upstream to downstream events (see section 2.1 and (HSE, 2015))

Each of these likelihoods are presented in Table 4 which presents the relative decrease or increase in likelihood compared to the existing natural gas network. These likelihoods are derived from experimental and modelling studies as well as historical data from the current gas network. These likelihoods should be considered a ‘most likely’ value based on the available data at the time the assessment is performed. An assessment of uncertainty in those parameters is presented subsequently. The final risk modification factor is the weighted sum of the products of those likelihoods.

The results (Table 4) indicate that the current gas network has a relative risk of 1 (i.e. constitutes the reference from the HSE’s perspective). The relative risk from switching to hydrogen without any mitigation measures in the current network results in an increase in the risk of fatalities resulting from severe structural damage of an occupied property of 2.08.

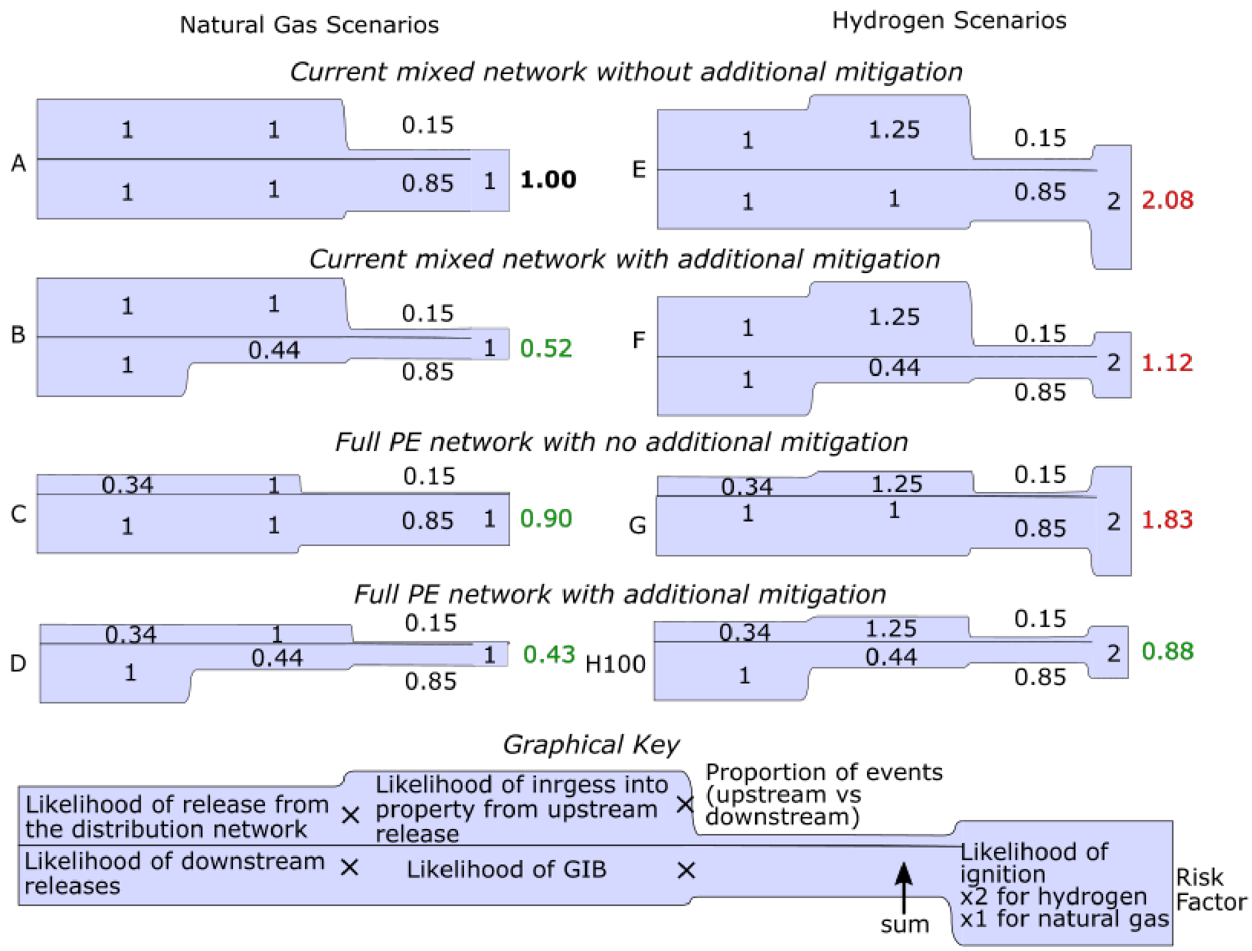
The benefits from a 100% PE network alone (i.e. with no mitigation measures downstream of the network) are not sufficient to produce a comparatively lower risk between methane and hydrogen. Indeed, a full-PE network would result in a fatality risk reduced by 0.9 for methane (Table 4, scenario C), whilst the risk would be increased by 1.83 for hydrogen (Table 4, scenario G). This demonstrates the need for additional mitigation measures to be implemented to bring the risk from switching to hydrogen to less than 1.

When the mitigation measures discussed above are implemented downstream of the meter the likelihood of a GIB is reduced by a factor of 0.44 (i.e. a 56% reduction). These measures on their own (i.e. without a 100% PE network upstream of the meter) are also not enough to reduce the risk of fatality from a hydrogen network. Alone these measures would lead to a risk factor of 1.12 for hydrogen (Table

4, scenario F). This is much lower than the value of 2.08 without these measures (Table 4, scenario E), but still not enough to meet the ‘as safe as’ requirements. We note that if these measures were to be deployed on the existing gas network the risk factor would be reduced to 0.52 (Table 4, scenario B). This raises the question that if these mitigation measures were rolled out downstream of the network prior to its conversion to hydrogen, then the overall risk on the network would likely be lower than it is for the current network. This would result from a much wider reduction where those measured are implemented and natural gas maintained, compared to the less extensive areas where hydrogen could be rolled out with a risk factor of 1.12 (Table 4, scenario F). Care should be taken during any transition to avoid uneven risk profile changes across the areas due to be converted to hydrogen.

Finally we note that the combined approach taken by H100, of building both a new 100% PE network and implementing mitigations measures downstream of the meter, does result in a comparative fatality risk lower than the current network by a factor of 0.88 (Table 4, scenario H100).

Table 4: Risk factor calculations based on the likelihoods of events determined in our assessment. Scenarios A,B,C and D are Natural Gas scenarios, and scenarios E,F,G,H100 are Hydrogen scenarios. Scenario A is the current network (i.e. the status quo). Scenario H100 is representative of the H100 100% hydrogen network.



4 Uncertainty Analysis

As presented earlier our comprehensive assessment of the gas network applied to the H100 demonstration project was distilled to ‘most likely’ values for the likelihood of various events (which contribute to the fatality risk) occurring. In this section we present an analysis of the maximum allowable uncertainty simultaneously affecting all the parameters considered.

This assessment is undertaken as a series of Monte Carlo analysis using percentage points uncertainty applied as a normal distribution for each parameter (e.g. likelihood of upstream release). Each Monte Carlo analysis results in a spread of risk factors for the combined effects of the full-PE network, mitigation measures, and ignition. And the percentage point uncertainty is gradually widened, by the same amount for all the parameters. Only the likelihood of a downstream release occurring is not modified and remains a fixed value of 1 (see Supplementary Table 2). As previously discussed, this is because the means of achieving these releases is independent from the gas itself, and the downstream pipes (i.e. inside the building) will remain unchanged.

Our analysis indicates that a ± 0.05 point uncertainty can be added to each likelihood whilst still meeting the regulatory criteria that the resulting H100 network will be ‘as safe as’ the current gas network (Figure 8). 100,000 realisations of the relative risk calculations were then performed. These findings are presented as a cumulative histogram in Figure 8.

Under that ± 0.05 point uncertainty the ignition risk for H100 is lower than that of the current gas network in 99.95% of realisations. More specifically, the risk of ignition events resulting in significant structural damage can be demonstrated to be reduced by over 7.1%, 90 % of the time, and by over 24.8%, 10% of the time, compared to the current gas network. This is applicable to the H100 full PE network with no metal components combined with downstream mitigation measures (such as using crimped fittings, excess flow valves, and installing the gas meter outside the building). A ± 0.05 point uncertainty over most of the parameters can hence be considered the maximum tolerable uncertainty to ensure a relatively lower risk for a new PE network. Therefore this work finds that, with appropriate care and safety measures, the H100 network can be considered ‘as safe as’ the current natural gas network under a ± 0.05 point uncertainty.

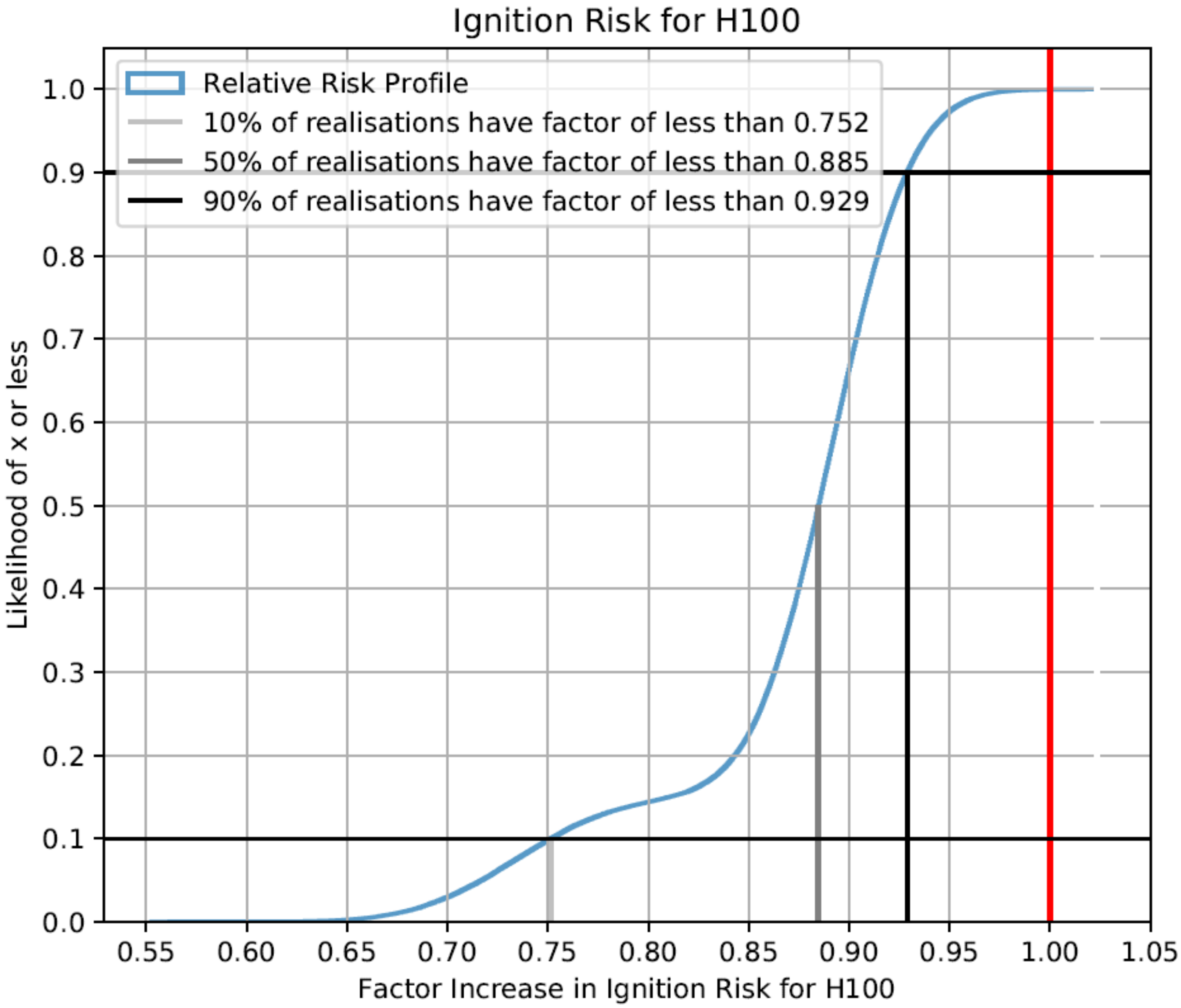


Figure 8: Ignition risk profile calculated for H100 using the values discussed in this work with a 10 percentage point uncertainty described by a normal distribution (see Table 8 for details of the inputs). The profile is established as the cumulative histogram of 100,000 realisations separated into 1000 even sized bins. We also note that the effects of the mitigation measures can only be quantified against the notion of 'Gas in Building Event'. However, we know that some of the mitigation measures are likely to also affect the likelihood of releases. However, in this assessment this effect cannot be quantified from the available data and has been quantitatively accounted for as reducing the likelihood of GIB events.

5 Conclusion

In this study, we have described how a QRA for future hydrogen distribution networks can be developed using novel experimental and modelling work, scientific literature, and findings from past large scale testing programmes such as HyHouse. This allows us to capture the different nature of concentration building up between hydrogen and natural gas, as well as its impact on ignition by allowing for ignition sources to be situated at different heights.

We demonstrate this approach on quantifying the risk modification factor from the current natural gas network compared to the proposed new, purpose built, PE distribution network for H100, assuming a detached house. Our QRA includes the impact of releases from both upstream and downstream of ECV at the domestic meter. We use our new approach to characterise the highest tolerable uncertainty in parameter probabilities.

We find that the proposed network for H100 can be considered 'as safe as' the current natural gas network as it will be 100% PE and implement mitigation measures downstream of the meter.

These findings are dependent on the assumptions stated throughout this work. Most notably that the results are applicable to the test scenarios used in the HyHouse project, which investigated the release of gas in a domestic dwelling in rural Scotland. The applicability of the results to other types of accommodation e.g. flats or bungalows, should only be done after careful consideration and investigation by a trained and suitably qualified professional. In addition, the house on which the QRA was based was assumed to be occupied and to contain a typical range of ignition sources. This is why SGN is undertaking a site specific assessment as part of H100 Fife to address the uncertainty arising from the assumptions in this work.

This method provides a novel framework to evaluate the risks of fatalities associated with proposed hydrogen networks and can be used in the early stages of the feasibility studies for demonstration projects. The approach is tailored to the 'as safe as' policy currently upheld by regulatory agencies in the UK and Europe. This alignment between research, industry projects and regulatory requirements is crucial to progress the decarbonisation agenda of nations worldwide.

6 Author Contributions

JMC reviewed the technical work reports, performed the literature review, and performed the uncertainty and overpressure modelling. KK designed and carried out the experimental program, and reported the result in a proprietary technical report. SH contributed to the technical review. MW and AM sponsored the work. All contributed to the manuscript.

7 References

Allan, J., & Lewis, D. (2019). *Annual Report and Financial Statements 2019.*

Ball, M., & Weeda, M. (2015). The hydrogen economy - Vision or reality? *International Journal of Hydrogen Energy*, *40*(25), 7903–7919. https://doi.org/10.1016/j.ijhydene.2015.04.032

Barley, C. D., & Gawlik, K. (2009). Buoyancy-driven ventilation of hydrogen from buildings: Laboratory test and model validation. *International Journal of Hydrogen Energy*, *34*(13), 5592–5603. https://doi.org/10.1016/j.ijhydene.2009.04.078

Bauwens, C. R., Chao, J., & Dorofeev, S. B. (2012). Effect of hydrogen concentration on vented explosion overpressures from lean hydrogen-air deflagrations. *International Journal of Hydrogen Energy*, *37*(22), 17599–17605. https://doi.org/10.1016/j.ijhydene.2012.04.053

BEIS. (2017). The Clean Growth Strategy: Leading the way to a low carbon future. *UK Gov*, 165. Retrieved from https://www.gov.uk/government/

Billington, M. J., Barnshaw, S. P., Bright, K. T., & Crooks, A. (2017). Conservation of fuel and power (Part L). *The Building Regulations*, 16.1-16.128. https://doi.org/10.1002/9781119070818.ch16

Bjerketvedt, D., Bakke, J. R., & Van Wingerden, K. (1997). *Gexcon - Gas explosion handbook 150.* Amsterdam: Elsevier.

Bünger, U., Michalski, J., Crotogino, F., & Kruck, O. (2015). *Large-scale underground storage of hydrogen for the grid integration of renewable energy and other applications*. *Compendium of Hydrogen Energy*. Elsevier Ltd. https://doi.org/10.1016/b978-1-78242-364-5.00007-5

Crowther, M., Orr, G., Thomas, J., Stephens, G., & Summerfield, I. (2015). *Energy Storage Component Research & Feasibility Study Scheme: HyHouse Safety Issues Surrounding Hydrogen as an Energy Storage Vector*.

Dodds, P. E., & Demoullin, S. (2013). Conversion of the UK gas system to transport hydrogen. *International Journal of Hydrogen Energy*, *38*(18), 7189–7200. https://doi.org/10.1016/j.ijhydene.2013.03.070

Energy Networks Association. (2018). *Gas Network Innovation Strategy*.

Frazer-Nash Consultancy. (2018). *Logistics of Domestic Hydrogen Conversion*. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760508/hydrogen-logistics.pdf

Hodges, J., Geary, W., Graham, S., Hooker, P., & Goff, R. (2015). *Injecting hydrogen into the gas network – a literature search*. *Health and Safety Laboratory*. Retrieved from http://www.hse.gov.uk/research/rrpdf/rr1047.pdf

Hormaza Mejia, A., Brouwer, J., & Mac Kinnon, M. (2020). Hydrogen leaks at the same rate as natural gas in typical low-pressure gas infrastructure. *International Journal of Hydrogen Energy*, *45*(15), 8810–8826. https://doi.org/10.1016/j.ijhydene.2019.12.159

HSE. (2015). *Major Hazard Safety Performance Indicators in Great Britain's Onshore Gas and Pipelines Industry Annual Report 2014 / 15*.

Health and Safety Executive. (2019) GSMR Report Data 2002-16. Retrievable from the HSE via a Freedom of Information Request.

HSE. (2019). Deferred repairs to public reported gas escapes. Retrieved November 28, 2019, from http://www.hse.gov.uk/gas/supply/deferred-repairs.htm#:~:targetText=Public reports of gas escapes,report a smell of gas.&targetText=prevent the escape of gas within 12 hours of PRE receipt.

iea. (2018). *CO2 Emissions from Fuel Combustion*.

Iea. (2019). *Global Energy & CO2 Status Report: The latest trends in energy and emissions in 2018*. Retrieved from https://webstore.iea.org/global-energy-co2-status-report-2018

IET. (2019). *Transitioning to hydrogen*.

Kim, H. J., Chung, S. H., & Sohn, C. H. (2004). Numerical calculation of minimum ignition energy for hydrogen and methane fuels. *KSME International Journal*, *18*(5), 838–846. https://doi.org/10.1007/BF02990303

Kim, J., & Moon, I. (2008). Strategic design of hydrogen infrastructure considering cost and safety using multiobjective optimization. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2008.07.028

Lautkaski, R. (1998). Understanding vented gas explosions. VTT Energy. Technical Research Centre of Finland. ISBN 951-38-5087-0. ISSN 1235-0605. https://cris.vtt.fi/en/publications/understanding-vented-gas-explosions

Lee, D.-G., Heo, D.-H., Lee, S.-K., Lee, J.-W., Lyu, G.-J., Lee, Y.-J., & Kim, H.-S. (2015). An Analysis of Safety Management Items for Low Pressure Hydrogen Facility below 0.1MPa in Domestic Hydrogen Town. *Journal of the Korean Institute of Gas*, *19*(6), 85–91. https://doi.org/10.7842/kigas.2015.19.6.85

Lewis, B., & Elbe, V. (1987). *Combustion, Flames and Explosions of gases* (3 rd editi). London: London Academic Press.

Lowesmith, B. J., Hankinson, G., Spataru, C., & Stobbart, M. (2009). Gas build-up in a domestic property following releases of methane/hydrogen mixtures. *International Journal of Hydrogen Energy*, *34*(14), 5932–5939. https://doi.org/10.1016/j.ijhydene.2009.01.060

Ma, Q., Zhang, Q., Pang, L., Huang, Y., & Chen, J. (2014). Effects of hydrogen addition on the confined and vented explosion behavior of methane in air. *Journal of Loss Prevention in the Process Industries*, *27*(1), 65–73. https://doi.org/10.1016/j.jlp.2013.11.007

Mannan, S. (Ed.). (2012). Chapter 17 Explosion. In *Lees' Loss Prevention in the Process Industries (Fourth Edition)* (Fourth Edi, pp. 1367–1678). Oxford: Butterworth-Heinemann.

https://doi.org/10.1016/B978-0-12-397189-0.00017-3

Mathurkar, H. (2009). *Minimum ignition energy and ignition probability for Methane, Hydrogen and their mixtures*. Loughborough University.

Matsuura, K. (2009). Effects of the geometrical configuration of a ventilation system on leaking hydrogen dispersion and accumulation. *International Journal of Hydrogen Energy*, *34*(24), 9869–9878. https://doi.org/10.1016/j.ijhydene.2009.09.044

Melaina, M. W., Antonia, O., & Penev, M. (2013). *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues*. https://doi.org/10.2172/1068610

Mohammadfam, I., & Zarei, E. (2015). Safety risk modeling and major accidents analysis of hydrogen and natural gas releases: A comprehensive risk analysis framework. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2015.07.117

Mouli-Castillo, J., Wilkinson, M., Mignard, D., McDermott, C., Haszeldine, R. S., & Shipton, Z. K. (2019). Inter-seasonal compressed-air energy storage using saline aquifers. *Nature Energy*, *4*(2), 131–139. https://doi.org/10.1038/s41560-018-0311-0

Mouli-Castillo, J., Bartlett, S., Murugan, A., Badham, P., Wrynne, A., Haszeldine, R.S., Wheeldon, M., McIntosh, A. (2020). Olfactory appraisal of odorants for 100% hydrogen networks. *International Journal of Hydrogen Energy*. Volume 45, Issue 20, Pages 11875-11884. https://doi.org/10.1016/j.ijhydene.2020.02.095

Mouli-Castillo, J., Orr, G., Thomas, J., Hardy N., Crowther, M., Haszeldine, R.S., Wheeldon, M., McIntosh, A. (In press). A comparative study of odorants for gas escape detection of natural gas and hydrogen *International Journal of Hydrogen Energy*.

Mouli-Castillo, J., Heinemann, N., Edlmann, K., (2021) Mapping geological hydrogen storage capacity and regional heating demands: An applied UK case study. *Applied Energy*. Volume 283, 1 February 2021, 116348. https://doi.org/10.1016/j.apenergy.2020.116348.

NHBC Foundation. (2009). *A practical guide to building airtight dwellings*. Retrieved from http://www.zerocarbonhub.org/sites/default/files/resources/reports/A_Practical_Guide_to_Building_Air_Tight_Dwellings_NF16.pdf

OGP, International Association of Oil and Gas producers. (2010). *Risk assessment data directory, report no. 434*.

Ogle, R. A. (1999). Explosion hazard analysis for an enclosure partially filled with a flammable gas. *Process Safety Progress*, *18*(3), 170–177. https://doi.org/10.1002/prs.680180310

Okamoto, H., & Gomi, Y. (2011). Empirical research on diffusion behavior of leaked gas in the ground. *Journal of Loss Prevention in the Process Industries*, *24*(5), 531–540. https://doi.org/10.1016/j.jlp.2011.01.007

Okamoto, H., Gomi, Y., & Akagi, H. (2014). Movement Characteristics of Hydrogen Gas Within the Ground and Its Detection at Ground Surface. *Journal of Civil Engineering and Science*, *3*(1), 49–66.

Ono, R., Nifuku, M., Fujiwara, S., Horiguchi, S., & Oda, T. (2007). Minimum ignition energy of hydrogen-air mixture: Effects of humidity and spark duration. *Journal of Electrostatics*, *65*(2), 87–93. https://doi.org/10.1016/j.elstat.2006.07.004

Rew, P.J., Spencer, H., Maddison, T. (1998). The sensitivity of risk assessment of flash fire events to modelling assumptions. ICHEME symposium Series NO. 144. https://www.icheme.org/media/10273/xiv-paper-22.pdf

SGN (2018) Gas Escape Events Reported to HSE 2002-2017. Proprietary Data.

SGN (2019) H100 Hydrogen Characterisation: Final Report. Report Number 0431389-02

Sinha, A., & Wen, J. X. (2019). A simple model for calculating peak pressure in vented explosions of hydrogen and hydrocarbons. *International Journal of Hydrogen Energy*, *44*(40). https://doi.org/10.1016/j.ijhydene.2019.02.213

Stolecka, M. (2018). Hazards of hydrogen transport in the existing natural gas pipeline network. *Journal of Power of Technologies*, *98*(4), 329–335.

Tsunemi, K., Kihara, T., Kato, E., Kawamoto, A., & Saburi, T. (2019). Quantitative risk assessment of the interior of a hydrogen refueling station considering safety barrier systems. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2019.07.027

Vianello, C., & Maschio, G. (2014). Quantitative risk assessment of the Italian gas distribution network. *Journal of Loss Prevention in the Process Industries*. https://doi.org/10.1016/j.jlp.2014.07.004

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