HyDelta

WP1A – Safety and hydrogen

D1A.1 – Results of the UK Hy4Heat and H21 studies translated to the Dutch situation

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Executive summary

This report is part of the national hydrogen research programme HyDelta Work Package 1A Safety. It focuses primarily on creating the framework conditions for safely applying hydrogen in urban areas. Extensive research has been carried out in recent years in the United Kingdom concerning the safe application of hydrogen in urban areas. This report summarises the most important results of the H21 and Hy4heat studies that have been published in the United Kingdom. The key question in this report is as follows:

What are the safety risks associated with the distribution of hydrogen in the distribution network and in indoor installations with regard to the nature and extent of leakages, dispersion and inflow into other areas, the risk and consequences of ignition and what measures are suitable in this regard.

This question has been answered by translating the results of the aforementioned British studies to the Dutch situation. In addition to the aforementioned reports, several other Dutch reports have also been included in order to reflect the latest available knowledge.

As part of Work Package 1A Safety, a report will also be published on the first adjustments to the risk models that were established in the United Kingdom for hydrogen as well as any possible mitigating measures for pilot projects in the Netherlands. For this, please see HyDelta D1A2 [1]. This report focuses on research conducted in the United Kingdom (UK) and its application for the Netherlands, including possible mitigating measures in the UK. The two reports therefore supplement each other.

Scope

H21 and Hy4Heat were very extensive programmes that spanned a period of three years at £25 million per project. Much of what has been published has led to follow-up research programmes in the UK. The publications describe references to literature, historical data and experiments carried out up to and including the most recent experiments in 2020. This report is limited to urban areas – distribution pipes in the street – connecting pipes to low-rise housing and the gas installations in low-rise housing with a heat demand of < 70 kW.

Risk of leakage: nature and extent

Hydrogen will not affect the existing natural gas grid; using hydrogen instead of natural gas will not cause more leaks. The volume of hydrogen that is released in the event of a leak is, however, larger than with natural gas. For small leaks (max. 1 litre per hour) that amounts to about 30% more volume, and for larger leaks it is up to 190% more (also referred to as a factor of 1.3 to a factor of 2.9). In addition, permeation through the pipe wall can be up to 5 times higher. However, in absolute volumes this is very low.

- The low-pressure distribution network in the United Kingdom is constructed in part using the same materials as in the Netherlands, although in different proportions in terms of length. The exception to this is that in the Netherlands, (impact-resistant) PVC is mostly used in the 100/200 mbar distribution network. The Netherlands is unique in this respect. Leakage tests conducted in the UK on the same materials are therefore applicable to the Netherlands. The H21 study shows that parts of the distribution network that are leak tight for natural gas are also leak tight for hydrogen. When natural gas leaks were repaired, this also proved effective for hydrogen. The main source of distribution leaks was found in the UK's cast iron distribution network. H21 therefore recommends replacing cast iron in the distribution network with the more modern polyethylene (PE) pipe material. In addition, H21 also recommends using a gas stopper in the branching of the connecting pipe as an extra precaution.
- Hy4heat has conducted research on leakages in indoor installations (the part downstream of the gas meter set-up). In the United Kingdom, gas meters are usually installed outside or in a kitchen cupboard. Installation in meter boxes as in the Netherlands (in combination with the electricity meter) is not done in the UK. This makes the research results less directly applicable to the Dutch situation in some cases. It also holds true for indoor installations that hydrogen does not lead to more leaks. Installation errors in the pipes in particular are the cause of the largest leaks. This applies in the Netherlands just as it does in the United Kingdom. No fitting types were found that leaked hydrogen but not natural gas. No fittings were found to be unsuitable for hydrogen in Hy4Heat. This is not directly applicable to the Netherlands because other fittings are used here. Research has been conducted in the Netherlands that supports the leakage rate found in Hy4heat: An existing leak with natural gas results in an approx. 30% higher flow rate with hydrogen for fittings.

Dispersion and inflow into other areas

As far as the dispersion of hydrogen in the open air is concerned, i.e. as a result of leakages in the distribution section, it holds true that, due to the lower density, the gas will rise more quickly than natural gas and will therefore not lead to higher risks in the open air. In general, it can be said that hydrogen does not disperse further in the soil than natural gas does. Inflow from leaks into an enclosed space can lead to unsafe situations in particular. However, this also applies to natural gas.

Dispersion in spaces was examined in Hy4heat, Hyhouse and the Gas Dispersion Analysis report (sub-report of Hy4heat). Here, the primary argumentation was based on a leak in the pipework in the indoor installation. In the case of a hydrogen leak, homogeneous gas concentrations first form at the top of the room (gas stratification). The volume of hydrogen from leakage in a pipe is 1.2 to 1.8 times that of natural gas. The influence of ventilation openings is considerable, see also Hy4heat reference [29] page 39 ff, and significantly greater than, for example, mechanical ventilation. At the highest tested leakage rate of 78.6 m^3/hour, the addition of natural ventilation ensured that the concentration at the top of the room was reduced from ~60% full gas to ~40% full gas. This kept the mix ratio within the explosion limits and closer to the stoichiometric ratio. Please note that this tested leakage rate does not occur in reality in a domestic environment in the Netherlands. The maximum leakage rate of natural gas when a gas cooker pipe is penetrated is approximately 10 m^3 per hour; for hydrogen this would be 20-30 m^3 per hour. If hydrogen spreads to other rooms, the hydrogen concentration will quickly decrease due to natural ventilation. Formation of an explosive mixture with the most common small leaks (<10 m^3/h) and normal ventilation does not appear to be realistic. In the event of a hydrogen leak in a room without ventilation, in accordance with building regulations and closed/door windows, a very high hydrogen concentration may be formed at the site of the leak, depending on the pressure, leakage and volume of the room where the leak is located. The most effective measure for preventing an explosive mixture from forming is to combine box ventilation (e.g. air vents in meter boxes of at least 0.01 m^2) with room ventilation from the adjacent room. As a comparison, the NEN2768 now prescribes an upper and lower grid for a meter box of net 0.02 m^2 each, which is already more than the aforementioned requirement of 0.01 m^2. The flammability limit in the source space (where the leakage occurs) is not achieved and by ventilating the space this is likely to be further reduced. In addition, with natural gas the vast majority of leaks are noticed due to the odour present and are subsequently repaired before a dangerous quantity of gas is able to escape and ignite. UK research therefore suggests that odourisation is an effective tool for hydrogen as well, in addition to flow protection such as an EFV or gas stopper adjusted to the maximum consumption of an appliance.

Risk of ignition

The risk of ignition for hydrogen is different from that of natural gas. At the same gas pressure, hydrogen can ignite at distances that are up to 25% further [2] from the gas outlet. In practice, this means that the presence of ignition sources at a greater distance may cause ignitions. Various studies have been conducted on the influence of ignition sources on ignition in urban areas. Mechanical extractors and light fixtures do not cause ignition in hydrogen under normal operating conditions. This is important, because these potential ignition sources are often located at the top of the physical space, where the hydrogen concentration first accumulates. When testing white goods (various household appliances present in the kitchen, but also outside this area: freezers, hair dryers, hoovers, etc.) as ignition sources, no difference was found between the risk of ignition for natural gas and for hydrogen. In addition, the risk of igniting hydrogen concentrations is further reduced by the fact that the ignition source is often located at a low level in the room, while the hydrogen gas rises quickly and is first concentrated at the top of a space. The risk of ignition is then further reduced by ventilation in the box/cupboard or room. The studies in the UK have focused on kitchen areas as gas meters may be present in a kitchen cupboard, several gas appliances may be installed in the kitchen, and several ignition sources may be present. For the Netherlands, the most relevant room is the meter box because of the presence of electrical distribution boards, followed by the kitchen where a central heating appliance may be installed.

Consequences of ignition

Combustion of gas, and therefore of hydrogen, releases flue gases and heat that may cause a build-up of pressure in an enclosed space. If this combustion gas is unable to escape, the pressure will continue to build up. In the UK, studies have been conducted into the consequences of ignition of hydrogen and natural gas.

The results are shown in “ISO damage charts”. The data have been further developed into several different concentration bands, expressed in the percentage of gas in air (GIA).

A summary of the results of the data obtained on ignition of the gas is broken down into concentration bands, with the comparison between natural gas and hydrogen and the consequences in general terms:

1. 0 – 10 vol% - Hydrogen may be less severe than natural gas
2. 10 – 15 vol% - Comparable damage between hydrogen and natural gas
3. 15 – 20 vol% - Hydrogen may be more severe than natural gas

4. 20 – 25 vol% - Hydrogen is likely much more severe than natural gas
5. >25 vol% - Hydrogen is likely much more severe than natural gas

Consequences of the aforementioned bands are subject to experimental conditions / environments

In the open air and at low concentrations, a fire will first occur at a gas concentration of >LFL value. Then a hydrogen fire is possible without overpressure. In closed areas (indoor installation situations) or at higher concentrations, an explosive ignition can occur with potentially more far-reaching consequences, as indicated in the 5 points mentioned.

- A hydrogen fire with the same energy outflow as natural gas has equal or lower heat radiation. The heat radiation of hydrogen becomes equal to that of natural gas if dust/earth are also present in the flame.
- A hydrogen explosion may, under the same conditions, cause greater consequential damage than a natural gas explosion due to the higher burning rate. At low gas concentrations (<10 vol%) the consequential damage with hydrogen is lower; starting from 15 vol% it is more severe. In the case of an explosion with a stoichiometric (30 vol%) hydrogen mixture, pressure build-up can cause an overpressure of over 100 mbar and, in non-ventilated spaces, up to 7 bar. This could lead to walls collapsing or houses being destroyed

Assessment of the overall risks and appropriate control measures

From the UK studies, the following overall risk assessments from fires and explosions are apparent: the overall risks from hydrogen may be higher than from natural gas, with higher risks of explosion, though this is partly offset by lower risks of fires. However, in the UK, the risks from the incomplete combustion of natural gas, which produces carbon monoxide, have not been taken into account. Unfortunately, in the UK the use of natural gas causes a significant proportion of casualties due to carbon monoxide (approximately 20 incident reports with casualties per year). This is also the case in the Netherlands (39 natural gas incidents with carbon monoxide poisoning out of a total of 69 downstream of the gas meter between 2010-2020). When using 100% hydrogen, these casualties will no longer occur because 100% hydrogen does not release carbon monoxide.

In the UK, the total risk is calculated in the quantitative risk models and compared with the field data for natural gas. The risk from natural gas distribution is shown as the potential number of casualties per year: Potential loss of life (PLL). As an illustration: in air traffic, the number of casualties per X million flights is used. On average, it is claimed that per 30 million flights worldwide each year, there are approximately 600-1000 unfortunate casualties. In the Netherlands, we do not work with this kind of an approach, because there are hardly any casualties, which is certainly the case when carbon monoxide is not taken into account. In the UK, the results of the calculated PLL values for natural gas are also higher than actually measured, which is why the results of these models are considered conservative.

The main differences between the UK and the Netherlands are as follows:

- In the UK there are proportionally more steel and cast iron pipes in the low-pressure distribution network than in the Netherlands. In the Netherlands, approximately 80% of the distribution network is already made of plastic. Both countries have replacement programmes for the ageing network sections made of materials such as cast iron. Using plastic materials instead of cast iron reduces the PLL. The ongoing replacement programmes in both countries are therefore contributing to a lower PLL.
- In the UK, 50% of gas meters are placed in kitchen cupboards and 50% are placed in the exterior facade. In the Netherlands, indoor gas meters are currently placed in the meter box (during the large scale introduction of natural gas in the 60’s/70’s there was more variation here), which also houses the electricity distribution board, meaning that the risk could be different.
- In the UK, there are proportionally more older houses as compared to the Netherlands. As a result there are more cracks, less mechanical ventilation as well as ventilation that does not comply with the existing regulations in the UK. Ventilation has a major impact on the PLL.

The PLL for hydrogen in 2032 in the UK is 1.88 times higher than the PLL for natural gas in 2020, with 83% of the risk attributed to the metal networks that remain in the grid even with the current replacement plans in the UK. If all remaining iron pipes in the UK low-pressure and medium-pressure networks are replaced, the PLL for hydrogen could fall to 0.18.

Due to the above mentioned differences between the UK and the Netherlands, the total risk as described for the UK cannot be translated into the same figure for the Netherlands. This will be further explored in HyDelta 2. [1].

There are control measures available to bring the risks posed by hydrogen in urban areas to the same level as for natural gas. These have been considered for the Dutch situation from the UK’s proposed measures:

- Nature and extent: lowering the gas pressure of the network is possible and would reduce the PLL by 0.02 per year. The use of a different medium does not cause more leaks to occur.
- Nature and extent: in the case of hydrogen, the risk of leakage appears to be greater. Therefore, more frequent searches for leaks could be undertaken to reduce the number. The QRA models indicate which parts of the network (material as well as pressure) contribute most to leakages and could therefore be checked more often.
- Nature and extent: the installation of excess flow valves (EFV) would barely reduce the PLL in the main distribution network (i.e. the section before the connecting pipe and meter set-up), because most of the hydrogen leaks to be

expected in a main network with older materials will have already been managed after the replacement programmes. Using a gas stopper in the branching between the main pipe and the connecting pipe will ensure a significant reduction in the risk associated with damage caused by excavations. There would also a risk reduction in the event of failure of the gas installation in the house, including the gas meter set-up, as a result of fires in the house involving a leak in the 100 mbar connecting pipe. Depending on the set values of the gas stopper, the UK has recommended using a gas stopper when the building is entered. Discussions are ongoing with smart gas meter manufacturers for integrating gas stoppers in gas meters.

- Nature and extent: replacement of cast iron and ageing iron assets (pipes and components) with plastic pipe material reduces the likelihood of leakage in the UK. These replacement programmes have been active in the Netherlands for years (replacement of cast iron and steel connecting pipes, for example).
- Dispersion in spaces: most leaks in connecting pipes, meter connections and indoor pipes occur as a result of work activities. Odorization allows for early detection of leaks (this would be very effective, as in the case of natural gas) and could reduce the extent of the leakage and therefore prevent the formation of an explosive mixture.
- Dispersion in spaces: installing gas meters outdoors reduces the PLL by 0.01 per year in the UK (this is already the case for half of the situations). However, as this would constitute a major change in the Netherlands, it is uncertain whether this control measure is realistic for the Dutch situation.
- Dispersion in spaces: pipes that are leak tight when used with natural gas appear to be so for hydrogen as well. When a new natural gas installation is installed, a leak tightness test is carried out. It is only logical to do this for hydrogen as well, together with a visual inspection for existing pipe systems.
- Dispersion in spaces: ventilation is a very effective measure. Applying box ventilation (grating in the meter box) and room ventilation (air vents, etc.) in accordance with the applicable building regulations ensures sufficient ventilation, so that the formation of a mixture that could catch fire or explode is prevented or significantly delayed. Just as with natural gas: ensure that there is sufficient ventilation in basements, crawl spaces or other enclosed spaces where gas can accumulate. Or apply other control measures here.
- Ignition prevention: there is little difference in the risk of ignition sources (fittings, fans, white goods) between hydrogen and natural gas. The most effective control measure is again ventilation in the box/cupboard or room. In addition, hydrogen can be ignited up to 25% further away from the ignition source than natural gas. Where possible and feasible, potential ignition sources in the vicinity of a gas installation should be avoided or combined with adequate room ventilation.
- Consequences of ignition: the risk of ignition (consequential damage) is clearly reduced by the above measures. If an ignition does occur, the pressure has to be released. In practice this happens when the explosion forces a door or window open (sometimes even walls and/or a ceiling). The intensity of the explosion can be reduced by lowering the pressure wave of the explosion. Again, sufficient ventilation is the most effective solution.

In addition to the control measures mentioned (see also Hydelta WP1a D1a.2 Part 3), general control measures (which also apply to the use of natural gas) are also applicable. This includes adequately competent staff, procedures and measuring equipment, training and independent monitoring during large-scale pilot projects in order to establish additional control measures.

Contents

1 Rationale

1.1 General

This research has been carried out within the framework of the national HyDelta 1.0 research programme. The programme focuses on the safe integration of hydrogen into the existing gas transport and distribution infrastructure and aims to remove barriers that hamper innovative hydrogen projects. The complete research programme is divided into work packages. For an explanation of the various work packages, please visit www.hydelta.nl.

1.2 Problem definition

The Netherlands has made the safety of the transport, distribution and use of natural gas a top priority. The Netherlands is preparing for a new transition: the use of 100% hydrogen in place of natural gas. This development is also taking place elsewhere in Europe with the United Kingdom (UK) as the frontrunner with extensive field studies. As part of the HyDelta work programme of WP 1A - Safety, this study describes the relevant outcomes of research in the UK and translates them to the Dutch situation.

1.3 Objective

To provide insight into the safety risks involved in the distribution of hydrogen within the distribution network and in gas indoor installations with regard to: the nature and extent of leaks, dispersion and inflow into other spaces, the risk of ignition and its consequences and which measures are appropriate in this regard. All of this has been described using the publications from the UK's H21 and Hy4Heat research programmes, which were published in July 2021.

1.4 Procedure

First of all, this work package started with an inventory of the most important characteristics of the natural gas system in urban areas in the Netherlands: the distribution network in the street, domestic connecting pipes, the meter set-ups and gas set-ups in the house. In addition, an overview has been made of the literature consulted and the results of recent research programmes in the Netherlands in this area of work.

The studies have been evaluated and control measures have been proposed accordingly. This is followed by an explanation of the additional research that is required for the Dutch situation. To this end, the following steps were taken:

- Workshops with stakeholders in the Netherlands with the aim of:
    1. Creating an overview of the 'knowledge gaps' related to this specific topic
    2. Classifying these knowledge gaps into the categories of nature & extent, dispersion, ignition and consequences
    3. Identifying pilot projects in the Netherlands and UK that can provide more information
- Mapping out the most important recent reports in the Netherlands and the UK
- Analysing these reports (including H21, HyHouse and Hy4Heat) and translating them to the Dutch situation based on the categories mentioned
- Gaining insight into the remaining gaps in knowledge where follow-up research is necessary.

The risk assessment models for hydrogen, as prepared in the UK, have been used as a basis. These form a very solid foundation. The data and information from the studies described in this report are based on data from all the reports that are available from this work package via the websites. The underlying reports are extremely comprehensive and not all of them are publicly available. The decision was made to include references to the underlying reports in the chapters wherever possible.

1.5 Summary

In view of the scope of this report, a summary has been provided in blue boxes in each chapter. The chapters themselves provide additional explanations while allowing readers to go further in-depth, as references are included where possible.

- Chapter 2 describes the general characteristics of the natural gas supply, incident reporting, buildings and population in the UK and in the Netherlands. This concerns the current situation. The various relevant reports with their references, which are used throughout the remaining chapters, are also mentioned.
- Chapter 3 explains the risk models used upstream and downstream of the meter from the UK.

- Chapter 4 discusses the nature and extent of leaks in both the distribution network and leaks behind the meter. The use of natural gas and hydrogen is compared here and the results from the UK are translated to situation in the Netherlands.
- Chapter 5 builds on the nature and extent of leakages by indicating the possible dispersion.
- Chapters 6 and 7 discuss the likelihood of ignition and the potential consequences thereof respectively.
- Chapter 8 discusses the calculations made with the QRA models including anticipated mitigating measures in the UK distribution network, as well as the mitigating measures now proposed for the roll-out of pilot projects specifically for the UK. In HyDelta Work Package WP1A.2 Part 1 Quantitative risk assessment of hydrogen in the distribution network with additional experiments and recommendations for measures [1], a start was made with applying the QRA model to the Dutch situation based on field tests and calculations. This will be further developed during HyDelta 2.
- Chapter 9 incorporates the previous chapters into proposals for control measures for pilot projects in the UK. The differences for the Dutch situation are indicated. A total overview of possible mitigation measures for the Netherlands is provided in Report D1A2 [1]. Where there is no clear insight into mitigation measures, follow-up research is mentioned.

1.6 Research used in NL and UK

In both the UK and the Netherlands, the knowledge necessary to ensure the safe use of hydrogen has already been acquired. The table below provides an overview of the most important research reports consulted. In addition, references are provided throughout this report as included in Chapter 10

Table 1 Overview of relevant hydrogen reports in NL and UK

Name of report	**Contents**	**Client**	**Publicly available?**
H21 phase 1 Technical Summary Report May 2021 [3]	Field research into the most critical factors in the natural gas distribution network and using them for testing with 100% hydrogen. An extensive summary is available	HSE Science Division	https://www.h21.green
H21 QRA Model for Hydrogen Gas Distribution Networks, Northern Gas Networks, report 10078380-2 rev.0, October 2020 [4]	Conversion of the existing risk model (Conifer) to a model that can calculate the transition from natural gas to hydrogen. An overview of the data collected on the current distribution network of natural gas is translated into a distribution system for 100% hydrogen. Including calculations to quantify the risks and to translate this from natural gas to hydrogen		Not publicly available.
Hy4heat July 2021 Hy4heat Work Packages: WP1 Programme Management WP2 Hydrogen Quality Standard WP3 Appliance Certification WP4 Domestic Appliances WP5 Commercial Appliances WP6 Industrial Appliances WP7 Safety Assessment	Research into all safety aspects behind the ECV (emergency control valve). In short: gas installation in houses and commercial properties up to a gas consumption of 100kW. WP 7: the Safety Assessment and Conclusions Report including the QRA gives an overview of the many experiments conducted with 100% hydrogen as compared to natural gas and/or 100% natural gas.	HSE Department for Business, Energy & Industrial Strategy	https://www.hy4heat:info/WP7. All sub-reports that are in the public domain can be accessed via this website. Safety Assessment: https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/60e763269bb1f3226065b716/1625776936518/Precis.pdf Safety Assessment: Conclusions Report (incorporating Quantitative Risk Assessment) https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/60e399b094b0d322fb

WP8 Demonstration Facilities WP9 Community Trial Preparation WP10 Developing Hydrogen Gas Meters [5]			0dadc4/1625528759977/conclusions+inc+QRA.pdf Safety Assessment: Consequence Modelling Assessment https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/60e397ad0755a209e0d2c8a4/1625528245029/consequence+modelling.pdf Safety Assessment: Gas Ignition and Explosion Data Analysis https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/60e3a4e885053e2e862c55c5/1625531632133/ignition+and+explosion+data+analysis.pdf Safety Assessment: Gas Dispersion Modelling Assessment https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/60e3a625f86cfd7f0fceabbc/1625531945539/gas+dispersion+modelling.pdf Safety Assessment: Gas Dispersion Data Analysis https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/60e3a58f9c8a9a5ec2da2c2f/1625531805625/Gas+dispersion+data+analysis+.pdf Safety Assessment: Gas Escape Frequency and Magnitude Assessment https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/60e3a95389577a20e6436597/1625532765474/gas+escape+freq+and+mag.pdf Safety Assessment: Experimental Testing - Domestic Pipework Leakage https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/60e3a9d06bc0cc26a450d2b4/1625532893145/Exp+test+domestic+pipework+leakage.pdf Safety Assessment: Experimental Testing – Commercial Pipework Leakage https://static1.squarespace.com/static/5b8eae345cfd799896

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Hydrogen in natural gas on Ameland island [6]	Field research into the effect of hydrogen admixtures on existing natural gas networks, central heating and cooking appliances	Netbeheer Nederland	https://www.netbeheernederland.nl/_upload/Files/Waterstof_56_d2bb410cce.pdf
Future gas distribution networks (risk assessment) [7]	Theoretical study into the suitability of the current natural gas network for hydrogen distribution	Netbeheer Nederland	https://www.netbeheernederland.nl/_upload/Files/Waterstof_56_2341e11b42.pdf
Flaring and venting hydrogen [8]	Field research into efficient venting, depressurisation and degassing	Netbeheer Nederland	https://www.netbeheernederland.nl/_upload/Files/Waterstof_56_ef89b43e02.pdf
Gasunie report (incl. risk assessment), GT-200311 [9]		Gasunie	Not publicly available
Flushing hydrogen pipes [10]	Field research into the required flushing speed when venting and gassing	Netbeheer Nederland	https://www.netbeheernederland.nl/_upload/Files/Waterstof_56_37ec4c47da.PDF
Report on sectioning hydrogen networks [11]	Theoretical research into the possibilities of safe and efficient sectioning	Netbeheer Nederland	https://www.netbeheernederland.nl/_upload/Files/Waterstof_56_85705cbfed.pdf
The dispersion of natural gas and hydrogen in the soil [12]	Field research into the dispersion of hydrogen in the soil as compared to natural gas	Netbeheer Nederland	https://www.netbeheernederland.nl/_upload/Files/Waterstof_56_d37df4d760.pdf

Behaviour of hydrogen in the event of leakages in the gas distribution network [13]	Theoretical research on hydrogen dispersion during leakages in the distribution network		https://www.netbeheernederland.nl/_upload/Files/Waterstof_56_770e4ce970.pdf
Kiwa/Gastec UK 2015: Safety Issues Hydrogen as an energy storage vector [14]	Field research into the dispersion of hydrogen in the event of leakages in indoor installations	Department of Energy & Climate Change	https://www.researchgate.net/profile/James-Thomas-24/publication/336319834_Energy_Storage_Component_Research_Feasibility_Study_Scheme_-_HyHouse_-_Safety_Issues_Surrounding_Hydrogen_as_an_Energy_Storage_Vector/links/5d9c6d02458515c1d39e8289/Energy-Storage-Component-Research-Feasibility-Study-Scheme-HyHouse-Safety-Issues-Surrounding-Hydrogen-as-an-Energy-Storage-Vector.pdf
H21 Leeds City Gate [15]	Feasibility study on using the current natural gas grid for hydrogen distribution	Leeds City Gate	https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf

2 Characteristics of the distribution network, residential construction and incident reporting in the UK and in the Netherlands

This chapter describes the general characteristics of network construction, residential construction and incident reporting in the UK and the Netherlands and concludes to what extent the studies mentioned in Chapter 1 in the UK are applicable to the Netherlands. A summary of this chapter is included in the last section.

2.1 General data on distribution networks in the UK and in the Netherlands

An overview of the materials, pipe lengths and pressure ranges used in the UK distribution network is described in the document H21 Part E QRA Results, Section 3.2 (not publicly available) [16]. In the UK, the following materials have traditionally been applied in the distribution network for both the distribution pipe and the connecting pipe:

- Cast iron (CI)
- Ductile iron (DI)
- Spun iron (SI)
- Steel
- The above materials have had PE inserted
- PE

The distribution pressures applied in the UK are as follows:

- Low-pressure: 19-75 mbar
- Medium-pressure: 75 mbar- 2 bar
- Intermediate pressure: 2-7 bar

H21 translates the overview of applied materials, pipe lengths and pressure ranges in the Northern Gas Networks distribution network into the proportional composition of the UK-wide distribution network (reference H21 QRA Model for Hydrogen Gas Distribution Networks, report no. 10078380-2 rev.0, October 2020) [4]. This publication is not publicly available. The pipe materials used in the Netherlands are listed in Table 2. The gas pressures applied in the Netherlands are comparable to those in the UK.

Table 2 Overview of applied materials, pipe lengths and pressure ranges in the Dutch distribution network, report page 10 [17]: Pipe length of the distribution network in the Netherlands in km divided into material and pressure range: 1990 to 2019 (ref. CoData, regulator ACM)

Material	Pressure	1990	1993	1998	2012	2013	2014	2015	2016	2017	2018	2019
PE	0,03-0,1	5714	6396	7866	11852	12090	12240	12419	12609	12629	12825	12976
u-PVC	0,03-0,1	20765	19949	18730	20945	20774	20642	20520	20922	20728	20506	20308
HI-PVC	0,03-0,1	33063	37463	43922	55832	56785	57594	58401	58586	59301	60128	60779
Steel	0,03-0,1	6562	6584	6522	5023	4935	4840	4725	4595	4469	4352	4222
Cast iron	0,03-0,1	9669	8657	7523	5224	4743	4280	3924	3616	3315	2990	2702
Ductile iron	0,03-0,1	2404	2477	2066	1096	1047	1013	976	951	924	890	866
Asbestos cement	0,03-0,1	2165	1982	1982	1507	1381	1217	1119	1017	899	794	732
Other	0,03-0,1				41	87	95	96	109	119	117	123
Unknown	0,03-0,1				109	0.2	0	0	0	0	0	1
PE	1,0- 4,0	5127	5755	6139	7176	7169	7167	7184	7162	7186	7124	7108
Steel	1,0- 4,0	980	909	952	995	961	948	911	898	869	849	807
Cast iron	1,0- 4,0	320	278	292	114	88	73	65	62	57	48	45
Ductile iron	1,0- 4,0	941	628	316	288	257	231	209	193	185	178	174
Other	1,0- 4,0				2	2	2	2	3	2	2	2
Unknown	1,0- 4,0				5	0	0	0	1	2	2	2
PE	8			559	901	976	1053	1102	1178	1257	1325	1372
Steel	8	11400	11666	12363	12832	12838	12810	12798	12793	12769	12755	12700
Ductile iron	8	874	821	704	509	487	477	465	453	443	425	429
Unknown	8				11	0	5	1	1	0	0	0
Unknown	Unknown				10	0	0	0	0	0	0	0
	total	99983	1035483	109936	124472	124623	124688	124917	125148	125153	125321	125347

It is worth noting that in the Netherlands, the majority of the distribution network has been constructed using plastic pipe materials and that most of the metal distribution network has been replaced over the decades by PE and impact-resistant PVC, while in the UK the majority of the distribution network is still constructed using metal.

2.2 General data on residential constructions and gas meter installations in the UK and the Netherlands

Table 3 summarises the important data on residential construction and gas meter installations in the UK and the Netherlands.

Table 3. Overview of residential constructions and gas installations in the Netherlands and in the UK as of 1 January 2020

	United Kingdom	**The Netherlands**
Population size	70 million	17.5 million
Number of household gas connections	24 million	7.2 million
Type of natural gas	H-gas	L-gas
Type of odourant	Mercaptan	THT
Residential constructions	- Housing stock 23.5 million, primarily through landlords and private occupancy. - A relatively high number of poorly insulated houses, Percentage of housing units - year of construction: 21% < 1919; 38% 1919-1946; 42% 1946-2000, 9% >2000, see page 26, [18]; - Gas meter not installed in a meter room with an electricity meter. - Gas meter installed in a box outside on a facade. Or installed inside the house: installed separately under a staircase or in a kitchen cupboard. Estimated that 50% is located outside and 50% inside the house, see reference page 32 [4] - Central heating unit set-up: upright, usually in the kitchen. - "ECV (emergency control valve)" installed just outside the facade of the house.	- Housing stock 7.5 million, primarily through housing corporations, care institutions and private occupancy. - Post-insulation of houses since 1970s oil crisis. - Gas meter installed with electricity meter and/or water meter in meter room. - The manual shut-off valve is usually in the meter box upstream of the gas pressure regulator. - Central heating unit set-up: hanging. In multi-storey buildings this is usually in the kitchen, in low-rise buildings it is usually in the loft. - Emergency control valve for gas close to the gas meter (ECV)
Requirements for installers	Mandatory certification for installers: personal certification, partial certificates for each type of device, repeated testing, qualifications of technicians.	Certification on a voluntary basis. In January 2023, the 'CO vakmanschap' professional certification will enter into force. This certification applies to installation and maintenance work on a central heating unit up to and including the flue gas discharge. Installation work on pipes is not covered by this certification system.
Incident reporting	Mandatory central reporting and incident investigation by order of the Ministry of Health and Safety Executive (HSE).	Mandatory central reporting as part of 'CO vakmanschap' due to mandatory certification by 1/1/2023, it is not yet known to which body incidents must be reported and by which body investigations will be carried out. Distribution incidents up to the gas meter according to Dutch State Supervision of Mines (SodM) criteria and subsequent investigation under the authority of SodM.

In both the UK and the Netherlands, odourants are used for the distribution of natural gas, although the odourants are different. This had no influence on the research conducted into the desirability of applying odourants.

In the UK, there are many relatively poorly insulated houses as compared to the Netherlands, reference page 3 [18]. In the UK, research has been conducted into the degree of accumulation of hydrogen in houses. Due to the higher degree of particularly modern houses in the Netherlands, the results from the UK on this matter cannot be applied 1:1 to the Dutch situation.

In addition, gas meters in the UK are not placed in the same room as the electricity meter. Gas meters are placed in boxes outside on the facade, under a staircase or in a kitchen cupboard. The meter boxes used in the Netherlands in accordance with NEN 2768 are not used in the UK. This means that research into accumulation and ignition in an enclosed space, as conducted in the UK, cannot be applied 1:1 to the Netherlands.

In the UK, the ownership of rental housing is regulated differently to a certain extent as compared to the Netherlands. 19% of rental housing is owned by municipalities. This means that the responsibility for complying with regulations concerning, for example, the ventilation of rooms with combustion appliances also rests partly on the same municipality. In the Netherlands, this responsibility rests on private landlords or housing corporations. An overview of ownership ratios is given in Table 4.

Table 4. Details of houses in the Netherlands and in the UK as of 1 January 2020

	Quantity NL Million	**% NL**	**% total rentals NL**	**Quantity UK Million**	**% UK**	**% rentals**
Total number of houses	7.5	100	-	23.6	100	
Of which owner-occupied	4.3	58	-	15	64	
Of which rental properties	3.1	42	100	8.6	36	100
% Owned by municipalities		0	0		7	19
% Owned by housing corporations		29	69		10	28
% Private rentals		13	31		19	53

2.3.1 Incident reporting in the UK in natural gas distribution networks

In the UK, incidents are reported centrally by the Department of Health and Safety Executive (HSE). The number of incidents resulting in injury and/or death is reported publicly. The following overview does not distinguish between incidents upstream and downstream of the gas meter. It does not include work-related incidents.

The total overview of natural gas incidents in the UK can be found in Table 5 [19].

Table 5 Details of natural gas incident reporting in the UK leading to injuries. (Note: there may be several injuries per incident).

Incident / Severity	**Incident type**	**2016/17**	**2017/18**	**2018/19**	**2019/20r**	**2020/21p (Note A)**
Incidents	**All**	**154**	**129**	**136**	**150**	**100**
Incidents	Carbon monoxide poisoning	122	100	99	96	62
Incidents	Other exposure, e.g. to unburnt gas	4		6	13	13
Incidents	Explosion/fire	28	29	31	41	25
Fatalities	**All**	**0**	**2**	**3**	**8**	**3**
Fatalities	Carbon monoxide poisoning	0	1	2	0	1
Fatalities	Other exposure, e.g. to unburnt gas	0	0	0	0	0
Fatalities	Explosion/fire	0	1	1	8	2
Non-fatalities	**All**	**263**	**193**	**246**	**201**	**131**
Non-fatalities	Carbon monoxide poisoning	222	154	196	151	87
Non-fatalities	Other exposure, e.g. to unburnt gas	5	0	12	15	14
Non-fatalities	Explosion/fire	36	39	38	35	30

The UK also provides figures on the number of reports per km of pipe for the various diameters and materials, broken down into 2 types of causes: spontaneous and external (such as damage due to excavations). The data collected in H21 for this purpose are not available in a public document, therefore these data cannot be presented [16](H21 report Annex E). In general, it can be said that the categorisation according to cause is very similar to that of the Netherlands.

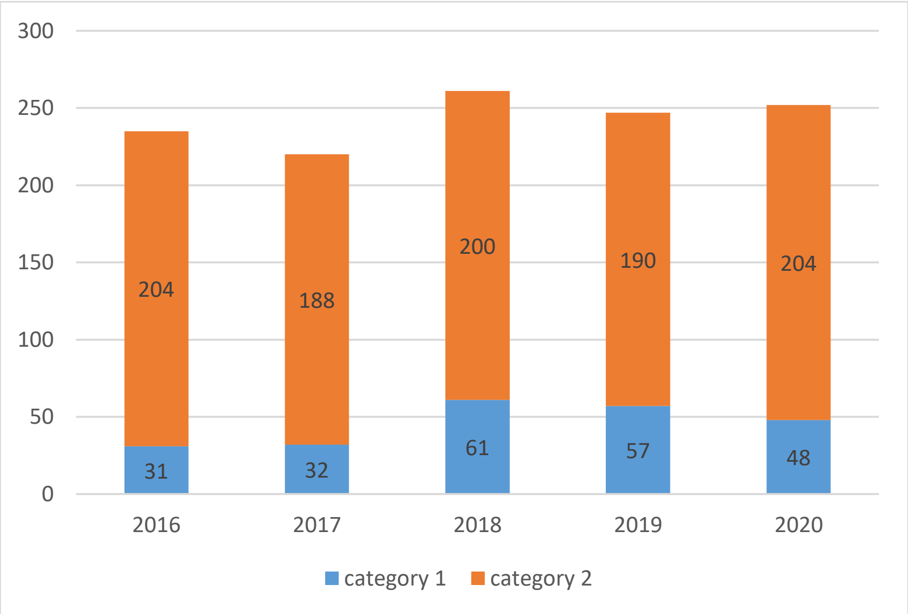
2.3.2 Incident reporting in natural gas distribution networks in the Netherlands

In the Netherlands, gas distribution incidents are reported in accordance with the criteria of SodM (Dutch State Supervision of Mines). These include incidents involving and not involving injuries. The criteria are adjusted on a regular basis, which limits the ability to make accurate comparisons over the years. It is possible for the number of incidents to increase dramatically due to changes in the criteria. The reporting criteria used in this report are those defined by SodM. The most recent reporting criteria are those of 1 June 2020, as shown below.

Table 6 SodM reporting criteria for incidents

An incident is considered a Category 1 incident if one of the following criteria is met: - Have there been deaths or injuries? - Has there been a gas fire/explosion primarily caused by the gas in the RNB's (regional network operator) asset? - Does it involve the evacuation of more than 250 persons? - Are more than 250 users involved?
An incident is considered a Category 2 incident if one of the following criteria is met - Has an indoor gas fire been caused by another fire? - Does it involve the evacuation of more than 10 people? - Are more than 10 users involved? *SodM reporting criteria as of 01/06/2020*

Figure 1 Overview of the number of Category 1 and Category 2 incidents according to the SodM reporting criteria in force at that time. From the reference Gas distribution incidents annual review 2020, page 19 [20]



Due to the categorisation of the SodM criteria, incidents involving injuries are always counted as Category 1. By way of illustration, the following table provides an overview of the total number of reported third party casualties, both fatalities and injuries, as well as the number of work-related casualties (casualties among employees fall under health and safety legislation). Each incident is reported separately, but these are not publicly available.

Table 7 Overview of the number of gas incidents in the distribution domain resulting in injury (fatalities or injuries in the Netherlands)

	fatalities	injuries (bystanders/residents)
2020	0	0
2019	0	10 (Jan v.d. Heijdenstraat)
2018	0	1 (+1 doubtful as to whether it was caused by the gas)
2017	0	2
2016	0	8
2015	0	8 (of which 2 were due to a meter box fire of unknown cause)
2014	2	10 (+6 inhalation of gas +10 inhalation of smoke)

In the Netherlands, the detailed reporting provides good insight into the cause of Category 1 and 2 incidents, see Figures 2 and 3.

Figure 2 Distribution of the causes of all Category 1 incidents in 2020

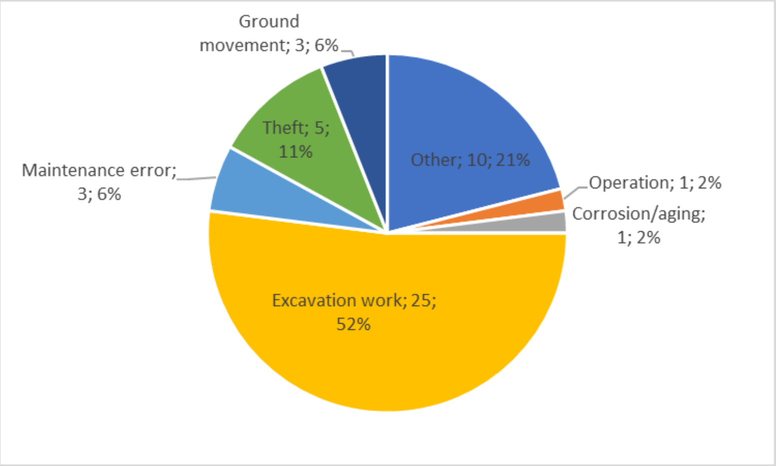
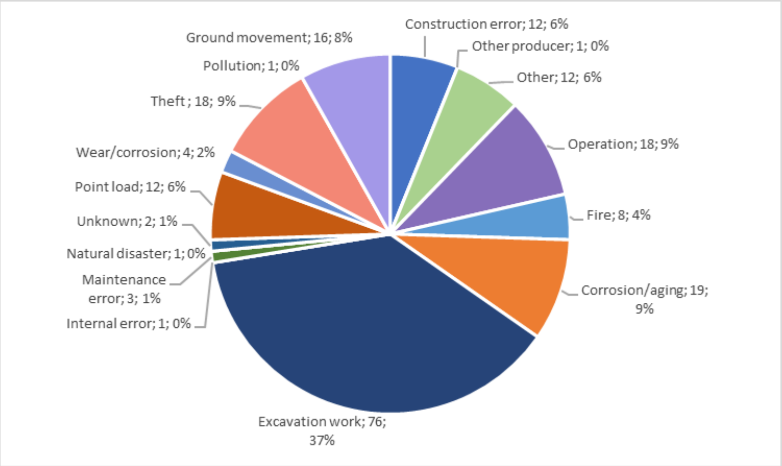


Figure 3 Overview of the various causes of the Category 2 incidents in 2020.



Thanks to this method of reporting and the information about the existing natural gas network, it is possible to use the causes to calculate what control measures can be taken to further reduce the risk of leakage in the Netherlands.

This means that in the Netherlands, the main focus is on preventing damage caused by excavation work. This is frequently brought to the attention of the public through publications on websites. It is also repeatedly brought to the attention of the various parties involved.

2.3.3 Incident reporting in the UK, behind the meter

The natural gas incidents relating to carbon monoxide are not further considered when discussing the risks with hydrogen.

In the UK, gas incidents are reported, investigated and indexed through RIDDOR (Reporting of Injuries, Diseases, and Dangerous Occurrences Regulations). There are approximately 24 million domestic gas meters in the UK, leading to approximately 400,000 gas-related reports annually. This results in about 260 RIDDOR forms, of which 20 are incident reports with casualties. In the UK, 62 incidents in the house (excluding carbon monoxide poisonings) resulting in injuries have been reported over the past 4 years. Incidents involving only property damage are not included.

An overview of the cause and numbers (numbers in brackets) in the house:

- Third party damage (18)
- Corrosion (5)
- Defective appliances – often no FFD (flame failure device) present (27)
- House fire (4)
- Unknown (7)

This is too little information to make a quantitative risk assessment based on the above data. Based on the incident investigations carried out in the UK, only qualitative conclusions can be drawn. This is the reason why the reports of the FCO (first call operatives, in the Netherlands the 112 control room) were also examined. Also see the section on gas leaks 4.2. The frequency of occurrence can be determined from these data.

2.3.4 Incident reporting behind the meter in the Netherlands

Kiwa Technology has been reporting the natural gas accidents that occur behind the gas meter in the Netherlands for several decades. These data are published in annual overviews on the website of Netbeheer Nederland. Kiwa Technology collects this information through media reports, through existing contacts and through research assignments. There is no obligation to report this kind of incident behind the gas meter.

Gas accidents behind the gas meter are classified in the categories carbon monoxide poisoning (CO poisoning), explosion (with or without fire) and fire.

In addition to these gas accidents, Kiwa also reports cases where gas is deliberately released. In the aforementioned accident reports [21], these intentional cases are not included. Intentionally inflicted damage or injury is in fact not an accident. In this HyDelta report, cases of deliberate use of natural gas that have emerged from the reports have been included. See Table 1. Incidents of this kind have a major impact on society, see Table 7.

Table 8 Overview of incidents involving natural gas in the Netherlands downstream of the meter (2010-2020) translated into an average number per year. Probability per connection (≤G6), related to 7.2 million connections. Each incident may involve several casualties.

Type of incident downstream of the gas meter	Number of natural gas incidents	Probability of incident per gas connection x 10^{-6}	Number of fatalities	Number of injuries *	Number of major damage claims #)	Probability of injury or fatality per gas connection x 10^{-6}
Carbon monoxide poisoning	39.5	5.5	2.64	138.2	-	0.37 (fatality) 19.2 (injury)
Fire and/or explosion (excluding intentional cases*)	14.5	2.0	0.45	7.8	14.5	0.06 (fatality) 1.1 (injury)
Intent* resulting in fire and/or explosion	9.8	1.4	2.18	6.5	9.8	
Intent* not resulting in fire or explosion)	4.9	0.7	-	-	-	
TOTAL	**68.7**	**9.6**	**5.27**	**152.5**	**24.3**	

**) Intent: vandalism, pipe theft, deliberately releasing a large quantity of natural gas, etc.*
#) Major damage: more than €10,000.
**) Injured: People treated after an incident and/or transported to hospital for further treatment*

Not all incidents that have occurred will be included in table 8. This is because not every incident makes the news and Kiwa Technology is often not informed. As far as fires and explosions are concerned, the more serious or sensational the incident, the more likely they is to feature in the media. An explosion, for example, will almost certainly be reported by the media. But if someone suffers minor burns, it usually doesn't make the news.

In order to analyse gas incidents, we distinguish between accidents and cases of intent. We also discuss the intensification of an already existing fire.

Accidents caused by natural gas

During the period between 2010 – 2020, the number of reported fatalities from carbon monoxide was 2.6 per year and 0.5 per year from fire and/or explosions. That's around five times as many deaths from carbon monoxide as from fire or explosions. The number of registered CO injuries is 138 per year.

When switching to hydrogen, the risk of fire or explosion may increase due to the higher combustion rate, the lower minimum ignition energy and the wider ignition limits. On the other hand, the effect of hydrogen igniting is possibly less intense due to its earlier ignition moment. Furthermore, the flame with hydrogen is smaller and the radiation heat of the flame is lower (it is only hotter than with natural gas very close to the flame). On balance, it is impossible to tell from the data of the consulted sources which effect is decisive.

With hydrogen there is no risk of carbon monoxide poisoning, as no carbon monoxide is released during the (partial) combustion of hydrogen. Looking at the Netherlands as a whole, this means 2.6 **fewer deaths** and 138 **fewer injuries** compared to natural gas. Based on the estimate from the Dutch Safety Board, the actual numbers of carbon monoxide deaths and injuries are a multiple of these figures, see page 50 of [22]. There are indicators that the actual number of injuries or fatalities is three to five times higher. These casualties would be prevented with the use of hydrogen.

Fire, intensified by collapse of gas installation

According to the current gas installation regulations (NEN 1078, NEN-EN 1775), if a fire breaks out in a building - for whatever reason - the presence of a gas installation is not allowed to result in a significant intensification of this fire. This means that either the pipe must not collapse or, if it does, the "extra" fuel supply (the gas) in the building must not contribute significantly to aggravation thereof. Existing gas installations that were installed based on older regulations will not always comply.

If the existing installations are maintain for the supply of hydrogen, the probability of aggravation will be about the same as for natural gas. Indeed the emitting flow rate is (due to turbulent flow) about three times higher than with natural gas, but the calorific value is about three times lower.

Intent

Intent is understood to mean the deliberate release of a large quantity of gas. As the overview shows, this did not always lead to a fire or explosion in the past.

Reports from the 112 control room in the Netherlands

In the Netherlands, the reports do not distinguish between the type of gas or fuel involved in the incident. For this reason, these data have not been analysed further.

2.3 Conclusion on applicability of UK residential construction and incident studies

In the UK and in the Netherlands:
The gas pressures used are not identical, but are in line with each other;

- The natural gas has an alarming odour (odourant), although a different odour is used;
- Most gas incidents are caused by damage from excavation work with gas escaping into the open air;
- In almost all of these cases, there are people present who are able to intervene immediately;
- The number of fatalities in the distribution area is very low;
- Most fatalities downstream of the meter (i.e. indoors) are caused by carbon monoxide poisoning.

In the Netherlands:

- The majority of the distribution network consists of plastic material, while in the UK it is made of metal. In both countries, replacement programmes for cast iron and asbestos cement are in progress;
- In the distribution network, every pipe is checked for leaks once every 5 years and leaks are repaired (non-urgent in 6 months, urgent within 24 hours). This systematic check does not exist in the UK;
- Gas incidents downstream of the meter (i.e. indoors) are not routinely reported, whereas in the UK they are;
- In comparison to the UK, many houses are well insulated, which affects the level of natural ventilation;
- The gas meter is placed in the same room as the electricity meter (the meter box); in the UK these are placed in different rooms and approximately 50% of the gas meters are placed outside of the house.

The differences in pipe material in the distribution network, systematic leak detection programmes, the degree of insulation and incident reporting mean that the effects of a hydrogen leak in the UK may be different from that in the Netherlands. The differences mentioned above also mean that conclusions from the UK studies, as applied to the total UK situation, cannot simply be applied 1:1 to the Netherlands.
At the same time, the studies give a clear direction on the effects, potential consequences and possible control measures. In general, this approach seems applicable to the Netherlands, but careful interpretation and application is necessary.

3 Risk assessment models

In this chapter, the two QRAs for both parts of the gas chain are explained, and the assumptions made in the UK are explained. A summary of this chapter is included in the last section.

In the UK, two parts of the gas chain are considered, which makes it appear that two risk models (hereafter referred to as QRAs) have been applied for describing risks related to natural gas and hydrogen. The input for each of the models is divided up into information from the pipe systems upstream of the gas meter and downstream of the gas meter. The WP1a report on the QRA model with Dutch parameters discusses the Dutch situation in detail.

The following QRA descriptions were used:

- For calculating the risks in the distribution domain, in other words upstream of the gas meter. This is based on the H21 project. It also includes a reference to an external leak – a leak from a distribution pipe in the street – which can eventually get into houses.
- For calculating the risks in houses, in other words downstream of the gas meter. This is based on the Hy4Heat project.

As in the Netherlands, there is no history of 100% hydrogen distribution in the UK. Therefore, in order to use the QRAs in the UK, the decision was made to translate the natural gas data as much as possible to a distribution system with 100% hydrogen, supplemented with the research already carried out in the UK, data from literature and, where necessary, any relevant assumptions. Therefore in the design of the QRAs as was implemented in the UK, the most recent research results from HyDelta 1 from the other work packages have not been included.

The HSE criteria for natural gas are related to the number of **gas connections** in the UK: [23] (page 33 ff).

The risk acceptance criteria in the UK are HSE requirements and are defined as the annual probability of fatalities, in other words the potential loss of life (PLL). The following categorisation has been made here:

1. Not acceptable: > 1 per 10,000
2. Acceptable, if ALARP (as low as reasonably practical): between 1 in 10,000 and 1 in 1,000,000
3. Widely accepted: < 1 per 1,000,000

These criteria are applied in the Netherlands, see for example the level of safety in gas distribution networks, reference page 64 [24].

Since there have been no incidents with fatalities behind the gas meter (with the exception of carbon monoxide poisoning), only the incidents described in Section 2.3.3 have been considered and classified into four categories with casualties. The term casualty can refer to both an injury and a fatality.

The data applied in the QRA model summarises the historical data on incidents into four injury categories. The term casualty is used to refer to both injuries and fatalities.

The four categories are as follows:

1. 0 casualties
2. 1 casualty
3. Between 1-3 casualties
4. More than 3 casualties

The data on the number of incidents by injury level per incident in relation to the estimated size of the leak is summarised in the following table.

Table 9 Number of incidents per casualty category divided into Large leak, Medium leak, Small leak and Unknown size leak [25] (Section 1.5.2) & ref. HyDeploy incident review data [26]

	Number of incidents			
Number of injuries	**Large leak**	**Medium leak**	**Small leak**	**Unknown size leak**
1	13	3	5	12
Between 1-3	10	3	1	6
>3	4	0	1	2
Unknown	0	0	1	1

The risk model applied uses two cases: A natural gas base case and a hydrogen base case that has been derived from it.

Natural gas base case

The natural gas base case assessment is intended to validate the QRA model on actual incident data of natural gas and to convert the results into a prediction of risks for natural gas.

To obtain a measure of reliability, the safety assessment for the use of natural gas is compared with historical incident data, so that the model matches observed incidents. The approach chosen is to obtain a 'conservative best estimate' for natural gas, rather than assuming the 'worst case scenario'. This allows a comparison to be made with the hydrogen assessment.

Development of the hydrogen gas base case

The hydrogen gas base case uses the model built for natural gas as the starting point. Assumptions that are specific and variable for each gas were then updated in the model. These assumptions include:

- Assumptions relating to leakage frequency
- Assumptions relating to gas dispersion
- Assumptions relating to ignition
- Assumptions relating to damage and injury level

This case assesses the risks associated with the transport of hydrogen in the current natural gas system as it currently stands. This base case does not take into account the addition of risk reduction measures that are not present in the natural gas base scenario.

In Sections 4 ff, the nature and extent of leakages applied for input into the models has been provided. The UK input data are briefly summarised here. Where possible, the Dutch data have been included. In addition, the identified and calculated risks in the UK have also been added, as well as a consideration of what this might mean for the Dutch situation.

The relationship between these risk models in the natural gas infrastructure is shown below in Figures 4 and 5. One difference in the infrastructure is relevant here. For the Netherlands, the ECV (emergency control valve) or manually operated shut-off valve (main control valve in Figure 5) for the gas is usually located in the house in front of the gas regulator in the distribution domain, but within the house facade.

Figure 4 Gas infrastructure from the pipe in the street to the gas installation in the house in the UK, indicating the scope of the H21 and Hy4Heat research programmes

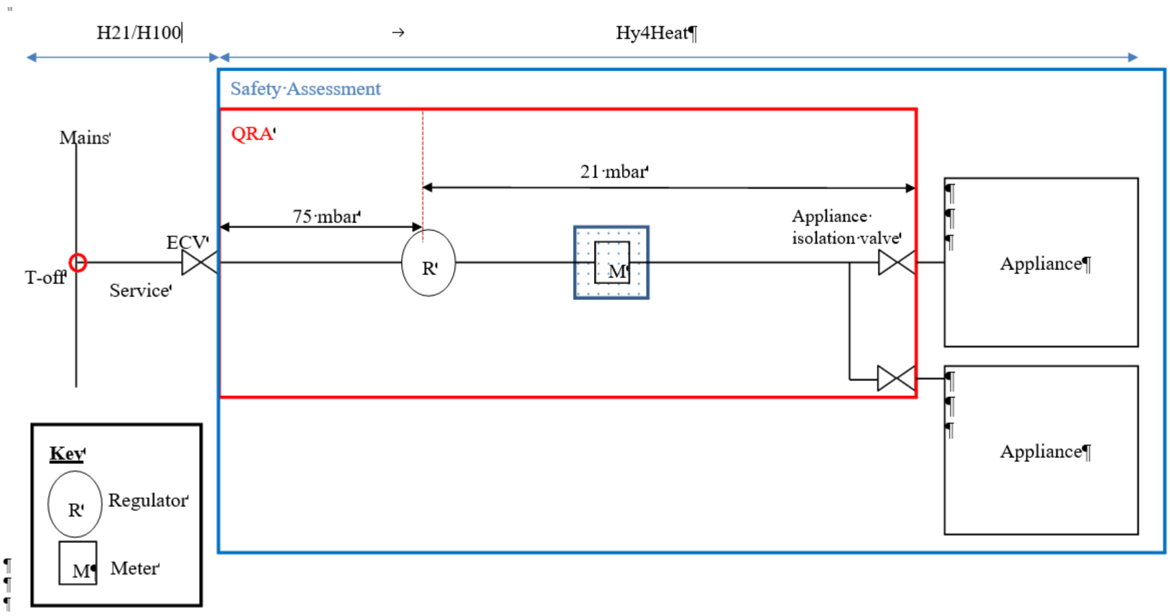
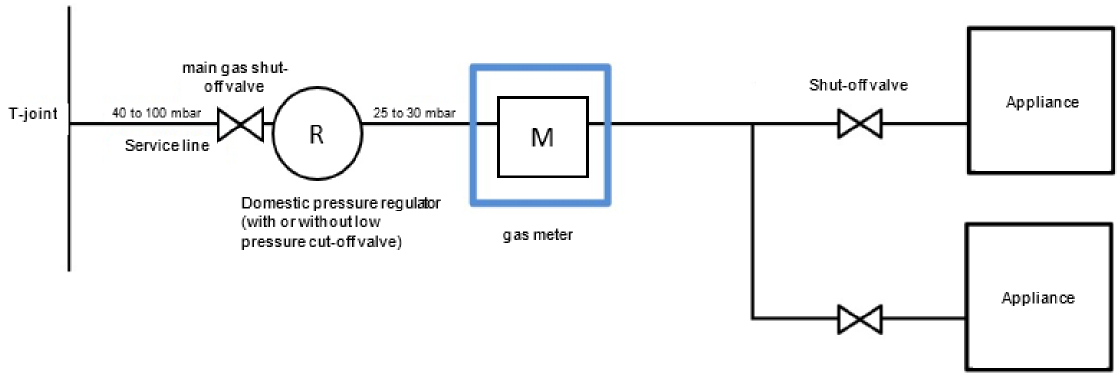


Figure 5: Gas infrastructure from the gas pipe in the street to the gas installation in the house in NL; main valve is ECV in the UK

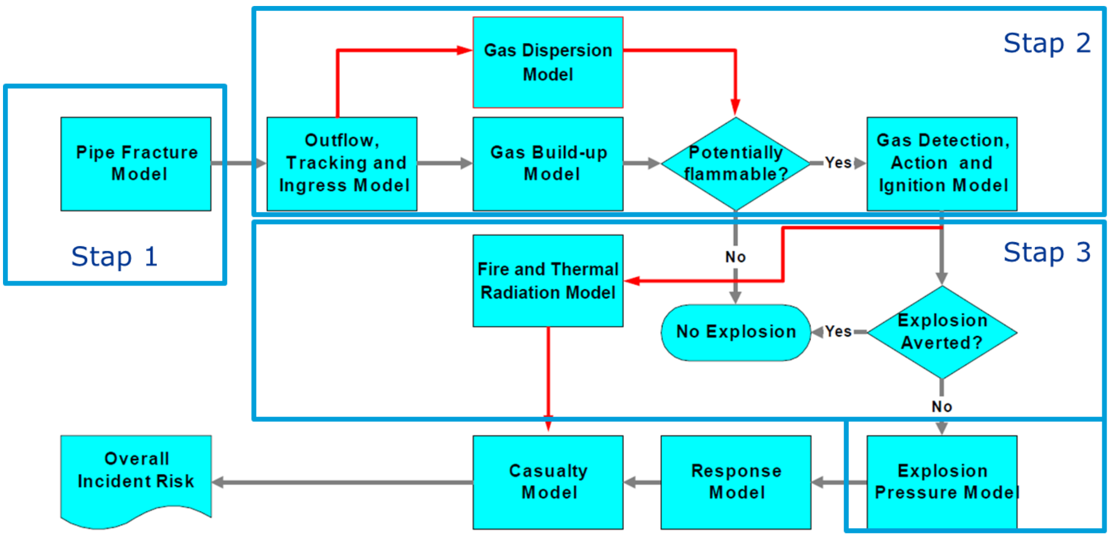


3.1 Distribution domain – H21 Phase 1

The H21 project uses a standardised risk assessment method developed for gas leaks. This methodology has been described in detail for natural gas systems, reference page 4 ff [13]. The model can be used for leaks due to external causes (root growth, soil erosion, etc.), but also for leaks caused by the failure of the infrastructure itself. Even though these causes are treated differently, both can lead to fires above ground, or dispersion of the gas through the subsoil to enclosed spaces (e.g. houses), and possibly explosions. The findings from this model include risks to people as well as the likelihood of fires or explosions.

The model was originally developed as a risk assessment model for the UK gas network to prioritise cast iron pipes for replacement, reference page 8 [13]. The model is based on incident data, measurement data and validated model data. As part of the H21 project in the UK, this model is being tested and adapted for hydrogen transport systems. For this purpose, the existing calculation model CONIFER (Calculation of networks and installations fire and explosion risk) was fine-tuned. A literature review was carried out in order to do this and additional tests were performed to map out the behaviour of hydrogen. The model is modular and consists of a number of components. Much of the information required has been mapped out in a report that is not publicly available, but that could be used within this study (reference H21 QRA Model for Hydrogen Gas Distribution Networks, report no. 10078380-2 rev.0, October 2020) [4].

Figure 6   The H21 risk model for natural gas distribution networks

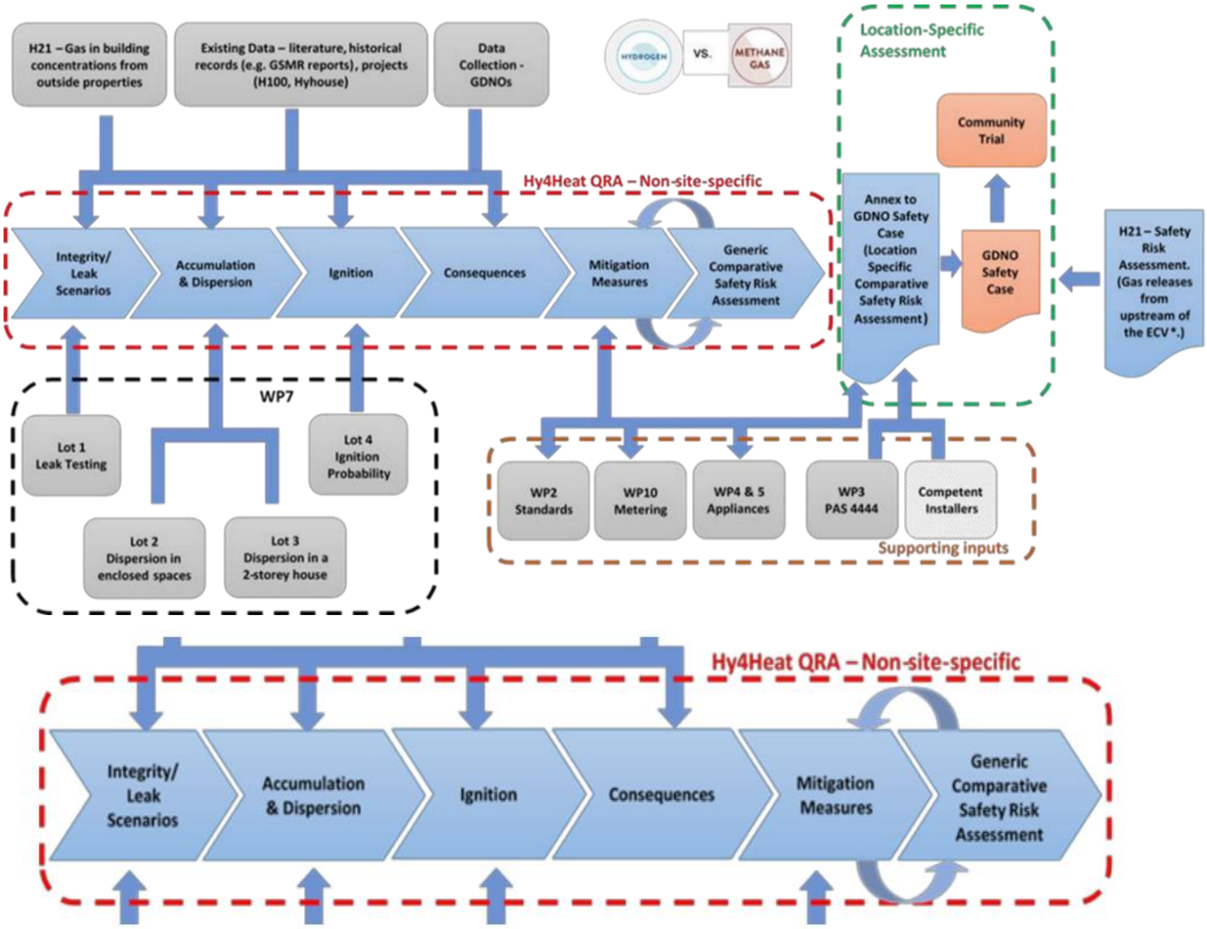


Detailed information is not publicly available. A comprehensive review of experimental data has taken place as well as validation and modification of the QRA model and methodology used.

3.2 Risks in houses - Hy4heat

As part of Hy4Heat, WP7 addresses the risk model in houses based on gas leakage scenarios. This risk model is shown below in the blue blocks. The literature used, field data, results of previous studies and related research as used in Hy4Heat are shown in the grey blocks.

Figure 7 Model for describing the safety components shown schematically.



For the modelling of leak hole size, historical data and test results from the Steer Energy report have been used: Safety Assessment Suitability of Hydrogen in Existing Buildings May 2020, page 13, [27]. Also see Chapter 4.2.

For calculating the dispersion of the gases, see the Hy4Heat Gas Dispersion Modelling Report, reference page 6 ff [28]. The model calculates the final concentration of the gas, given a specific hole size of the leakage in a particular room and depending on a ventilation level. The rooms included were a kitchen with a volume of 28.8 m^3 and a ground floor of the house with a volume of 76.8 m^3. Also see Section 5.1.

For the modelling of explosions and the underlying literature references used, please refer to the detailed report from WP 7: Hy4Heat Consequence Modelling Report, reference page 6 ff [29].

With the information described above, the effects of damages and injuries were estimated based on different scenarios for both natural gas and hydrogen (see pages 77 to 79 WP 7: the Safety Assessment and conclusions report incl. QRA) [25]. Ultimately, choices were made in Hy4Heat for implementing the first sets of different calculations for the UK.

3.3 Applicability of UK risk model in the Netherlands

The risk models above are based on the construction of the gas distribution network in the UK. The gas distribution network in the UK is different from that in the Netherlands (in terms of pressures, diameters, materials used and kilometres of the network). As a result, these risk models are not directly applicable to the Netherlands, meaning that the same control measures cannot automatically be adopted. These kinds of models need to be filled in with data from the Dutch distribution network and the corresponding parameters and assumptions.

The UK compares the current natural gas distribution network in 2020 with the distribution network for hydrogen in 2032. In 2032, the UK's cast iron distribution network replacement programme will have been completed. It was started in 2020. This will change the composition (see applied materials) of the network, so that much more PE will also be used in the UK.

For the Netherlands, the risks for the natural gas distribution network in 2020 can also be compared with a distribution network for hydrogen in the (near) future and the projected replacement of materials can be included in this.

In the UK, the follow-up research programmes include the description of risks upstream and downstream of the gas meter in one model. The work on this started in 2022. The aim is to be able to calculate the total risk for the various situations. Input parameters and assumptions made must then be accurately described.

The Hy4Heat risk model is applied in the UK for:

- Standard single-family houses: terraced, semi-detached or detached. All existing buildings with building characteristics that comply with current building regulations regarding ventilation and installation of appliances. Houses using mechanical (or forced) systems for background ventilation have been excluded for the transition to hydrogen in Hy4Heat's consideration;
- Commercial properties: only where buildings are similar to residential constructions, provided that the total gas consumption (i.e. the total use of all appliances, including those used in the course of business operations) does not exceed 100 kW;
- Housing not exceeding two storeys in height, but that may include, for example, a basement and/or a loft conversion;
- Housing supplied by connecting pipes with a maximum operating pressure of 75 mbar.

In addition, a number of assumptions have been made in applying the risk models used in the UK:

- The indoor installation pipes and fittings for hydrogen gas are the same as for natural gas;
- The gas meter is indoors in 50% of cases: in a kitchen cupboard or in an unlocked room under the stairs;
- The causes of an initial leakage (e.g. pipe damage, third party interference) remain unchanged from natural gas to hydrogen gas. This is because these factors are independent of the gas being transported;
- Consumer behaviour is assumed to remain unchanged from natural gas to hydrogen gas. This also applies to responses to a suspected leak, as the same odorant will be used for hydrogen. This ensures that the familiar smell that people are used to reacting to remains unchanged;
- Gas appliances are all safety certified in accordance with relevant legislation and with guidelines from PAS 4444 and contain FFDs (flame failure devices) fitted to all appliances. This reduces the likelihood of appliances being left on unattended and/or if the flame has been extinguished, help avoid unburnt gas from continuing to flow out, such as from a gas burner on a cooker. In addition, gas appliances are always designed by manufacturers to prevent flames from entering the inner pipe;
- A conversion to 100% hydrogen requires the replacement of all household appliances. This automatically means that appliances without FFDs will be removed from the system;
- Competent installers are all Gas Safe certified for hydrogen. This will ensure that every hydrogen system is installed to the same safety standards as the current natural gas standards require;
- Principles from the IGEM Hydrogen Reference Standard should be applied in each pilot project as these standards outline the key differences in hydrogen gas as compared to natural gas and how these can be handled safely. For the summary of the UK pilot projects see Annex I of this report. The original English texts have not been translated into Dutch;
- All gas pipes suitable for hydrogen should be installed in accordance with current natural gas standards to ensure compliance with the current recommended safety standards;
- No dye is added to hydrogen.

The above means that the risk models cannot be applied to the Netherlands on a 1:1 basis, because:

- Approximately 67% of the number of houses in the Netherlands consists of low-rise housing/single-family houses, the year of construction of which varies greatly;
- In the Netherlands, different ventilation requirements apply to single-family houses, which cannot be used for comparison as each country has its own building regulations;
- In the Netherlands, gas meters are mostly located in meter boxes, where the electricity meter and the electrical switch installation are also located;

- In the Netherlands, energy-saving measures are taken in existing buildings and new constructions, which may have an influence on ventilation. These include mechanical ventilation and forced ventilation with heat recovery units;
- In the Netherlands, houses are supplied through service lines (domestic connecting pipes) with a maximum pressure of 100 mbar; additional pressure reduction takes place directly before the meter to approximately 30 mbar;
- In pilot projects in the Netherlands, H2-compatible devices are used with a declaration of conformity, but no CE mark. This is not in accordance with the assumption regarding regulations for gas burning appliances as applied in the UK risk model;
- In the Netherlands, certification of installation companies and their employees is voluntary. There may be a requirement for personal certification for technicians working on 100% hydrogen systems, but a decision has yet to be made on this. This is different from the Gas Safe certification in the UK;
- The principles of the IGEM "Hydrogen Reference Standard" are not applied in the Netherlands. Appendix I includes an overview of the measures. These refer to a website of IGEM where the underlying documents can be obtained for a fee. Comparable to NEN in the Netherlands;
- For each pilot project in the Netherlands, a risk inventory is drawn up with the parties involved;
- For now, it is assumed that the installation regulations used for natural gas pipes (NEN 1078 and NPR 3378 series), including the strength and leak-tightness tests, apply to hydrogen. Note: the pressure surge test (for new construction) still needs to be considered in more detail. From 2022 onwards, several projects will be carried out to determine how existing standards for natural gas in the Netherlands and in Europe should be supplemented for admixtures with up to 100% hydrogen. For the distribution domain, work is being done on safety work instructions for hydrogen distribution that deviate from hydrogen on certain points;
- In the Netherlands, certification of distribution gas pipe systems up to 100% hydrogen is subject to inspection requirement 214 [30]. This inspection requirement is currently being supplemented by requirements for gas pipe systems. This inspection requirement will be published in mid 2022.

3.4 Conclusions on the applicability of risk models

In the QRAs, the risks are described in terms of the number of fatalities per year, or the potential loss of life (PLL) in 4 injury categories (both injuries and fatalities): 0 casualties, 1 casualty, between 1-3 casualties or more than 3 casualties.

Just as in the Netherlands, in the UK there is no statistical history of the risks of hydrogen distribution. The QRAs for hydrogen are therefore translated from natural gas as a starting point. In the hydrogen models, 4 gas specific assumptions have been revised: leakage frequency, dispersion, ignition and damage/injury level. The model does not take into account control measures if these are not in use for natural gas.

H21: for the distribution network, a standard risk model has been used as a basis for prioritising the replacement of cast iron pipes. This model was then adapted for hydrogen using literature and field research, see later chapters in this report.
Hy4Heat: for the risks downstream of the gas meter (i.e. indoors), historical data has been used, supplemented by literature and field research.

The risk models are based on the network structure in the UK. This differs from the Dutch network in terms of materials, diameters and pipe lengths, which means that direct application to the Netherlands is not appropriate. The risk models must be filled in with data from the Dutch distribution network in order to determine risk-reducing measures directly from the risk models.
However, for the risk modelling in the UK, extensive research into the behaviour of hydrogen has been carried out, which provides insight into potential control measures. The behaviour of hydrogen is similar in the Netherlands, which makes a reasoned application of comparable control measures highly feasible.

4 Nature and extent of leaks

This chapter examines the nature and extent of gas leaks in the UK and the Netherlands, both in the distribution network and downstream of the meter (i.e. indoors). A summary of this chapter is included in the last section.

The expected nature and extent of leaks in hydrogen is based on the data from natural gas translated to a distribution system with 100% hydrogen and supported by data from the literature and information from experiments performed. For hydrogen, there is no historical data available.

For the sake of completeness, previous studies (see ref. [7], [9], [31], [14] into the nature and anticipated extent of hydrogen leaks have already concluded that:

- Hydrogen will not affect the existing natural gas network. Using hydrogen instead of natural gas will not cause more leaks;
- The volume of hydrogen that flows out of the pipe through a leak is higher than the volume of natural gas:
    - With a small leak (roughly one litre per hour or less), the flow can be laminar and about 30% more hydrogen flows out in terms of volume. The energy outflow is 50 to 60% less;
    - For larger leaks, the flow becomes turbulent and 190% or approximately 3 times as much hydrogen flows out than natural gas (in terms of volume). For low-calorific gas, the energy outflow is roughly the same on an upper value basis and slightly lower on a lower value basis;
    - Other leakages:
        - If there is no pressure difference, hydrogen can move 210% more volume through diffusion
        - Permeation can occur through the pipe wall. This is 5 times faster, but the absolute quantities remain very small.

4.1 Distribution domain

As part of H21 [3], research has been conducted into anticipated leakage reports. A sample of assets was taken that is representative for the assets (different types of pipe material and relevant components such as regulators) present in the UK gas network if it is converted to hydrogen on a large scale from 2032 onwards. Of the 215 assets tested, 41 were found to be leaking, of which 19 assets provided sufficient data to compare the leaks of hydrogen and natural gas. The following was concluded:

- The pipes and components (assets) in the distribution network that were gas tight with natural gas were also gas tight with hydrogen;
- The assets (including repaired assets) that leaked with natural gas, also leaked with hydrogen;
- None of the PE assets leaked. Cast iron, ductile iron and spun iron leaked at similar rates (approximately 26- 29% of all iron assets leaked) and the proportion of steel assets leaking was slightly less (14%);
- The volumetric leakage rate for hydrogen and natural gas varied between 1.1 and 2.2, depending on the type of laminar or turbulent flow;
- Four types of compounds were responsible for the most leaks at joints: a photo has been attached. In the English version, the following terms are used: Hook bolts, lead yarn, screwed and bolted gland;
- All repairs to natural gas leaks were also effective when tested with hydrogen.


Hook Bolts


Lead Yarn


Screwed


Bolted gland

In the UK, data on gas leaks from the so-called FCO calls (first call operatives, in the Netherlands the 112 reports) were also analysed. From approximately 1,300 investigations from the FCO, 900 gas leaks downstream of the gas meter, i.e. in the house downstream of the ECV (emergency control valve), were identified. These reports were further analysed:

- Most of the gas leaks would have been below the maximum permissible leakage rate (MPLR) for natural gas, some would be above the MPLR for hydrogen. These gas leaks would not create a flammable atmosphere with natural gas or hydrogen;
- A small minority of leaks (approximately 3%) could create a flammable atmosphere with natural gas or hydrogen if allowed to continue indefinitely;
- Large spontaneous gas leaks are extremely rare. Failure modes are usually gradual over time and odorization is effective as a preventive mechanism for detection;
- A large proportion of gas leaks are detected during gas meter replacements.

The information described above can be translated to the Dutch situation. Reports show that most leaks in natural gas distribution networks occur in connecting pipes, followed by gas meter set-ups, i.e. in and around houses. Incidentally, by far the largest proportion of these leaks are detected by third parties through reports of a smell of gas.

In the distribution network, in relation to the number of kilometres of pipe material, most leaks occur in materials such as cast iron (CI) and ductile iron (DI), asbestos cement (AC) and steel. With the exception of steel, these materials are no longer being newly constructed and are being actively replaced. Therefore the most leak-sensitive material is disappearing from use. As a result, it can be cautiously concluded that the replacement programmes in the distribution networks with PE and impact-resistant PVC may lead to fewer leaks [32].

Leaks in the Netherlands are classified into 2 categories: Leakage class I and Leakage class II.

Figure 8 Overview of the different leakage classes in the Netherlands.

Leaks - Urgent or Non-urgent?

A leak reported by a **customer** is always urgent. In the case of a leak that is detected during leak search programs, the size and/or location of the leak determines whether it is urgent or not. There are two leak indication classes

- Leak indication class I: possibly a leak that must be secured within 24 hours at the latest. These include:
  - an audible, tactile, smellable and/or visible leak;
  - a leak indication with a reading of 10,000 ppm and above, regardless of its location;
  - any leak indication (a reading of 10 ppm and above) within 0.5 meters of buildings;
  - a leak indication with a reading of 100 ppm and higher, within 2 meters of buildings;
  - a leak which, given the local conditions, entails the risk of a build-up of gas. Think of sewage systems, switch boxes and such;
- Leak Indication Class II: Possibly a leak that can be dealt with on a scheduled basis. These are all leak indications that do not fall under leak indication class I.

As in the UK, the leakage frequencies in the distribution system are monitored in the Netherlands. Table 10 shows the leakage detection data per year based on the total number of kilometres of main pipes and pipes being inspected, expressed in kilometres and as a percentage of the total.

Table 10 Leak detection data period 2014 - 2019 in the distribution network

	2019	2018	2017	2016	2015	2014
Total km main pipe	125,304	125,321	125,153	125,148	124,917	124,688
Number of km searched	33070	27,233	29,550	29,529	31,085	29,206
Number of leaks found	4192	3300	3575	3976	3900	3708
Avg. Leaks/km searched	0.13	0.12	0.12	0.13	0.13	0.13
Percentage searched	26%	22%	24%	24%	25%	23%

In recent years, searches for leaks have been carried out on average more often than the basic frequency of once every five years (on average, 20% of the network length is searched each year). This percentage has fluctuated around 24% over the past five years.

Figure 9: Leakage frequencies of main pipes in the gas distribution system, averages over 2014 to 2018 (reference Natural Gas Emissions for Gas Distribution 2018, Apeldoorn 2019) *[33]*

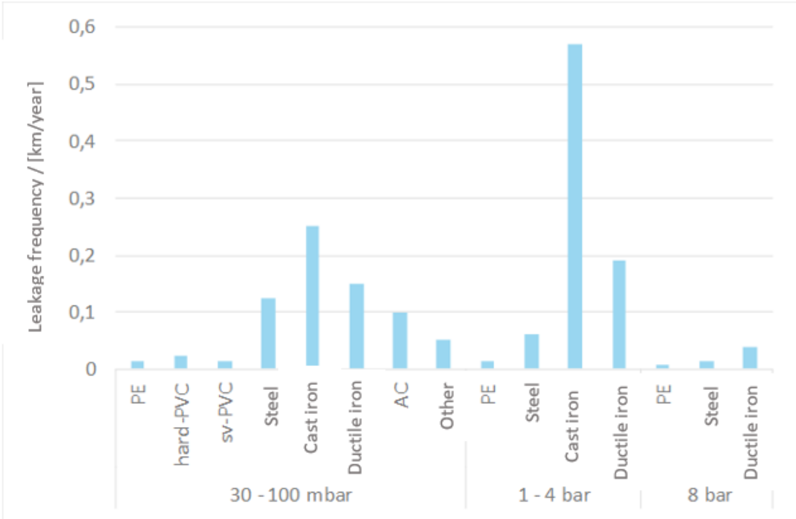


Figure 9 shows the leakage frequency in the main pipes in the gas distribution system in the Netherlands, defined as the number of leaks per kilometre that occur per year, divided over the various pressure regimes and the various materials used.

In addition to incident reporting, fault reporting also takes place in the Netherlands. A distinction is made between faults outside the facade (main pipes + connecting pipes) and inside the facade (connecting pipes + gas meter set-up ≤ G6). In 2020 the following numbers were reported:

- 55,074 faults including class II leaks
- 49,283 faults excluding class II leaks
- 3,053 faults where safety was at stake:
  - 759 main pipes
  - 1,898 connecting pipes (**295 pipes or connections within the facade**)
  - 314 GMS ≤ G6
  - Others are stations
  - Detection by customer/third party

If we zoom in on the 314 GMS and 295 reports of pipes or connections within the facade, the distribution in cause of the leakage is as follows:

Table 11 Fault reports for pipes or connections within the facade in 2020.

Fault report	**Quantity**
Installation fault (in the past	26
Other, explanation in comments	22
Operation	1
Corrosion / ageing	100
Excavations	15
Installation error (present)	1
Product fault	2
Point load	2
Vandalism / theft	96
Effect of the soil	30
Total	295

Here, it is noticeable that corrosion/ageing accounts for a third of the number of reports, followed by the number of reports of vandalism/theft. According to the current gas installation regulations (NEN 1078, NEN-EN 1775), if a fire breaks out in a building - for whatever reason - the presence of a gas installation is not allowed to result in a significant intensification of this fire. This means that either the pipe must not collapse or, if it does, the “extra” fuel supply (the gas) in the building must not contribute significantly to aggravation thereof. Existing gas installations that were installed based on older regulations will not always comply.

Of the 314 GMS reports, the cause distribution is:

Table 12 Fault reports of gas meter set-up (GMS) in 2020.

Fault report	Quantity
Installation fault (in the past)	85
Other, explanation in comments	9
Internal defect	22
Product fault	2
Wear/ageing	186
Vandalism / theft	6
Effect of the soil	4
Total	314

It is worth noting here that the largest proportion of these reports are related to wear/ageing of the GMS.

Most significant gas leaks (large gas leaks of 20 m^3/h) can be eliminated by installing excess flow valves - flow restrictors, also known as gas stoppers. The location of a gas stopper can be chosen: 1) the position of the connecting pipe of the distribution pipe 2) position in the gas connecting pipe at the entry to a building 3) built into the smart gas meter 4) in the gas pipes for each appliance, just behind the gas meter. N.B. position 4 relates to the indoor installation.

As in the UK, it is assumed that the leakage frequency in hydrogen distribution will remain unchanged in the Netherlands. Depending on which parts of the distribution network in the Netherlands are first converted to 100% hydrogen, it is advisable to search for leaks more frequently in those sections, depending on the materials present. Depending on the findings, the frequency of leak detection searches may be adjusted.

The sample survey from the UK shows that where there is natural gas leakage, this will also be the case for hydrogen. The same proposed mitigation measure applies here. If, before the distribution of hydrogen begins, a survey of the situation from the connecting pipe in the house to the GMS is carried out, a large proportion of the potential hazards can be identified and then possibly eliminated through replacement. Potential hazards include corrosion, installation errors, wear and tear, and the absence of ventilation grilles in the meter box.

Network companies use the aforementioned reports to map out the risks for each network company for natural gas. These indicators make it possible to carry out actions to reduce the risks [34]. It would make sense to use a similar approach for hydrogen distribution.

4.2 Downstream of the meter – indoor installations

In the Hy4Heat research programme, research was conducted into leaks in indoor installations where the comparison between natural gas and hydrogen was made, reference page 18 [25]:

- A compound that does not leak with natural gas will also not leak with hydrogen. Hydrogen molecules are smaller than natural gas (kinetic diameter of hydrogen 0.289 nm versus that of natural gas 0.380 nm). However, this is still about 10,000 times smaller than a ‘small leak’. In other words, hydrogen will not suddenly lead to more leaks.
- For small leaks at seams, loose and damaged fittings, the degree of leakage and leakage rate is comparable. Larger leaks (see also Table 14) lead to a higher leakage rate and other differences, approximately 3 times as much hydrogen as with natural gas outflow.
- In addition, laminar, transitional and turbulent outflows occur in both gases. Laminar flow is characterised by a linear relationship between flow and pressure and a leakage ratio of 1:1.2 between natural gas and hydrogen. Turbulent flow is characterised by a square root relationship between flow and pressure and a leakage flow ratio of 1:2.8 between natural gas and hydrogen.
- Damage and other large defects leading to holes showed the largest leakages in the study. These were turbulent leaks with a leakage current ratio of 1:2.8 between natural gas and hydrogen.

- The majority of the leaking fittings tended to leak with a laminar flow regime and a leakage flow ratio of 1:1.2 between natural gas and hydrogen.
- Installation errors leading to leaks accounted for the largest number of leaks. Leaks that led to turbulent flow were the worst case scenarios, such as a compression fitting without a support sleeve or a steel wire, only screwed in hand-tight without a joint. This situation is possible, but unlikely in practice.
- Leaks resulting from accidents such as drilled holes or nail holes are large leaks with turbulent flow regimes and a volumetric leakage ratio of 2.8:1 hydrogen to natural gas.
- Leaks from loose and damaged fittings were small leaks with laminar flow regimes and volumetric leakage ratios of 1.2:1 hydrogen to natural gas. Many of the leaks observed on damaged fittings resulted in small leakage flows of less than 1 litre per hour (=$1x10^{-3}$ m^3/hour) in both gases. This is below the 5 litre per hour pass/fail limit of current gas tightness tests for domestic systems and light commercial systems (i.e. offices in houses or offices similar to a building with floors, power installed appliances combined <100kW). In addition, the NPR3378-1 states that this limit of 5 litres applies to the total pipe installation; per leak, the leakage flow may be 1 litre per hour. For undamaged fittings, the leakage rates observed for both gases were at the limit of the measuring equipment, in the order of $1x10^{-6}$ m^3/hour.
- None of the tests performed found any characteristic or type of fitting that leaked in hydrogen and not in natural gas. No fittings were found to be unsuitable for hydrogen.

In the QRA model for the UK, the following data have been incorporated:

- Causes of the leaks with the selection: third party damage and corrosion. Based on historical data (approximately 400,000 (FCO) reports of domestic gas leaks);
- Location of leakage: most likely to occur in the kitchen, as this is where potential leakage sources and potential ignition sources are most likely to be found. Scenarios assessed: 50% with the door open and 50% with the door closed;
- Air tightness of the house: this was independent of the type of gas used.

Causes of gas leaks: in 34% of cases, this was related to the gas pipe, 41% to the gas meter set-up and 17% to the connection valves of gas appliances. Leaks in the appliances (approximately 9% of cases) were not included, nor was deliberate damage to the gas pipes.

Most gas leaks in the house are detected due to the odorization of the gas and the subsequent appropriate action taken by the occupant. These kinds of cases resolve themselves and do not lead to emergency calls and/or incidents/hazardous situations. It is estimated that the addition of odorant is 99% effective in the case of leaks caused by human intervention (do-it-yourself or third party damage). After all, there is always a person present. The probability of detection has been estimated for various types of events. These probabilities are described in Table 13 [25] (page 66 ff).

Table 13 Probability that a gas leak in a house will be detected due to odorization of the gas (as assumed in the UK).

Description	Probability	Comments
Probability of gas detection by occupant (third party damage)	0.97	Leaks caused by people, therefore, inherently someone present. Small proportion of people wouldn't smell a leak
Probability of gas detection by passer-by (large leaks)	0.80	Large leaks (6.5-11mm) will be strong smelling and therefore, a neighbour, visitor or passer-by could smell gas and report it. This is known to happen from past incident data recorded through GSMR
Probability of gas detection by passer-by (very large leaks)	0.90	Very large leaks (>11mm) will be very strong smelling and therefore, a neighbour, visitor or passer-by could smell gas and report it. This is known to happen from past incident data recorded through GSMR
Probability of gas detection by occupant (other leak causes*)	0.6	This takes into account the proportion of time that people would be out of the house or asleep.

A presence factor has been added for occupants in the house. In the models, a presence factor (and the fact that the person is awake) of 60% was used. This factor was higher during the COVID period, as more work was done from house.

Leakage size

The most commonly used indoor pipe material in the UK is copper, followed by steel. Plastic systems are not used in the UK. In the following table, the sizes of the leaks are described based on hole size and the hole size applied in the QRA model.

Table 14 Leakage sizes based on hole size and hole size applied in QRA model [25] page 72 described in detail in the Hy4Heat Gas Dispersion Modelling Report) [28]

Hole Size Description	**Hole Size Range**	**Hole Size Modelled**
Negligible	<1.5 mm	Not modelled
Very Small	1.5 - 2.4 mm	1.8 mm
Small	2.5 - 3.9 mm	3 mm
Medium	4 - 6.4 mm	5 mm
Large	6.5 - 10.9 mm	9 mm
Very Large	≥11 mm	13 mm

As an example,

Leak cause	**Leak hole size (hole diameter) mm**						
	< 1.5	**1.5 – 2.4**	2.5 – 3.9	4 – 6.4	6.5 – 10.9	≥11	
	Frequency distribution (% of total)						
Third party damage	5.1%	0.6%	0.6%	0.7%	0.4%	0.4%	7.7%
Corrosion/ degradation	11.0%	0.1%	0.1%	0%	0%	0.1%	11.3%
Loose Connection	3.3%	0%	0%	0%	0%	0%	3.3%
Unknown	11.4%	0%	0%	0%	0%	0%	11.4%
Totals	30.8%	0.7%	0.7%	0.7%	0.4%	0.6%	34%

Table 15-b Leakages at GMS

Leak **cause**	Leak size **(hole diameter) mm**						
	< 1.5	1.5 – **2.4**	2.5 – 3.9	4 – 6.4	6.5 – 10.9	≥11	
	Frequency distribution **(% of total)**						
Third party damage	10.8%	0%	0%	0%	0%	0.2%	11.0%
Corrosion/ degradation	11.6%	0%	0%	0%	0%	0%	11.6%
Flux damage	2.7%	0%	0%	0%	0%	0%	2.7%
Loose connection	4.3%	0%	0%	0%	0%	0%	4.3%
Unknown	11.3%	0%	0%	0%	0%	0%	11.3%
Totals	40.7%	0%	0%	0%	0%	0.2%	41%

Table 15 a/b/c shows the leakage frequency as a function of the hole size and as a function of the cause of the leakage at (a) the pipe material, (b) the gas meter set-up and (c) the appliance valve [25] (Section 5.2.3).

Tabel 15-a Leakage in pipes

Leak cause	Leak hole size (hole diameter) mm						
	< 1.5	1.5 – 2.4	2.5 – 3.9	4 – 6.4	6.5 – 10.9	≥11	
	Frequency distribution (% of total)						
Third party damage	5.1%	0.6%	0.6%	0.7%	0.4%	0.4%	7.7%
Corrosion/ degradation	11.0%	0.1%	0.1%	0%	0%	0.1%	11.3%
Loose Connection	3.3%	0%	0%	0%	0%	0%	3.3%
Unknown	11.4%	0%	0%	0%	0%	0%	11.4%
Totals	30.8%	0.7%	0.7%	0.7%	0.4%	0.6%	34%

Table 15-b Leakages at GMS

Leak cause	Leak size (hole diameter) mm						
	< 1.5	**1.5 – 2.4**	2.5 – 3.9	4 – 6.4	6.5 – 10.9	≥11	
	Frequency distribution (% of total)						
Third party damage	10.8%	0%	0%	0%	0%	0.2%	11.0%
Corrosion/ degradation	11.6%	0%	0%	0%	0%	0%	11.6%
Flux damage	2.7%	0%	0%	0%	0%	0%	2.7%
Loose connection	4.3%	0%	0%	0%	0%	0%	4.3%
Unknown	11.3%	0%	0%	0%	0%	0%	11.3%
Totals	40.7%	0%	0%	0%	0%	0.2%	41%

Table 15 -c leakage frequency as a function of hole size and cause of leakage at the appliance valve

Leak cause	Leak size (hole diameter) mm						
	< 1.5	**1.5 – 2.4**	**2.5 – 3.9**	**4 – 6.4**	**6.5 – 10.9**	**≥11**	
	Frequency distribution (% of total)						
Third party damage	0.1%	0%	0%	0%	0%	0%	0.1%
Corrosion/ degradation	7.6%	0%	0%	0%	0.%	0%	7.6%
Incorrect operation	0	0%	0%	0%	0%	0%	0%
Loose connection	0.3%	0%	0%	0%	0%	0%	0.3%
Unknown	8.5%	0%	0%	0%	0%	0%	8.5%
Totals	16.6%	0%	0%	0%	0%	0%	17%

The data from the aforementioned tables, among others, have been applied in the QRA model for both natural gas and hydrogen. There are therefore a considerable number of small leaks in indoor installations. It should be noted that most leaks larger than 4 mm are caused by third party damage. If this happens during a DIY action, the person responsible will probably take immediate action before a dangerous situation can arise. The historical data for natural gas can be considered representative of the distribution of the causes of leakage and hole sizes within the UK housing stock, regardless of whether the system transports natural gas or hydrogen. For a given hole size, the outflow/flow rate varies. For the method of determining flow rates for both natural gas and hydrogen gas, see the Hy4Heat Gas Escape Magnitude Report [35].

Various studies have been conducted in the Netherlands that support the UK findings above. There is no reason to assume that the distribution of causes of leakage and hole size in the Netherlands differs from that in the UK. The following can be added to the above based on experiments performed: for two pressure differences (25 mbar and 100 mbar), five leaks were created of roughly 0.1 l/h, 0.5 l/h, 1 l/h, 5 l/h and 10 l/h. An existing leak with natural gas results in a flow rate with hydrogen that is approximately 60% higher. In other words a leak of 1.0 l/h with natural gas will result in 1.6 l/h with hydrogen, regardless of the pre-pressure, page 2 [36]. In addition, there is insight into the numbers of gas leaks in indoor pipe installations in the Netherlands from 3 sources with field data [37]. Three sources of field data on natural gas leaks were studied:

a. Leakage rates measured during meter replacements (max. 1 dm^3/h)
b. Gas leaks in pipes from the housing stock of housing corporations (approx. 5 to 10 dm^3/h)
c. Gas accident database (up to approximately 10 dm^3/h)

It is clear from sources a, b and c that the chance of an accident due to a minor natural gas leak (up to 10 dm^3/h) is extremely small. The reason for this is because only a very small amount of ventilation is needed to keep the gas concentration below the lower flammability limit of natural gas (LFL=5.7%).

If we take a small kitchen measuring just 10 m^3 (2 m x 2 m x 2.5 m) with an extremely small ventilation rate (worst case) of 1/h with a natural gas outflow of 10 dm^3/h, the concentration will ultimately be just 0.1% gas, only a fraction of the LFL. An explosion can only occur at this natural gas flow rate if the space is much smaller. In this example, with a volume of less than 170 dm^3. This is already considerably smaller than, for example, the contents of a standard meter space (incidentally, meter spaces are designed for a much larger ventilation rate).

Hydrogen is lighter than natural gas and natural gas therefore spreads upwards faster. The lower flammability limit of hydrogen is 4%. The leakage rate will be 1.2 to 1.6 times greater than for natural gas (due to laminar flow). It can therefore be expected that the gas concentration will also be higher by a factor of 1.2 to 1.6 for an equal leak orifice and equal gas pressure. At the same ventilation rates, the concentration will then be correspondingly higher than for natural gas. However, as small leaks (comparable to a circular opening smaller than 2 mm in diameter) do not create sufficiently large combustible gas clouds to result in injuries, it is plausible that the probability of an incident resulting from a minor gas leak is not higher for hydrogen than for natural gas. Also see Chapter 6 on the risk of ignitions.

4.3 Conclusion on the nature and extent of leakages

Based on several studies, the following substantiated assumptions about the nature and extent of leakages can be made:

- The use of hydrogen instead of natural gas does not result in more leaks. For small leaks (up to 1 litre per hour), the volume outflow with hydrogen is +30% as compared to natural gas. For larger leaks, the volume outflow with hydrogen is up to +190%;
- Parts of the distribution network that are leak-tight for natural gas are also leak-tight for hydrogen and vice versa. Leak repairs that are effective for natural gas also appear to be effective for hydrogen. Note that this only concerns the degree of leak tightness and not the safety of working procedures or tools used;
- In the distribution network, most leaks occur in the connecting pipe and gas meter set-up. By far the most frequent means of detection is by smell;
- In the current distribution network, most leaks occur in pipes made of “old” materials such as cast iron and asbestos cement. This will not change with the use of hydrogen;
- Pipes downstream of the meter (indoors) that do not leak for natural gas, also do not leak for hydrogen. There were no fittings found that leaked hydrogen but not natural gas;
- Downstream of the meter, most leaks are caused by installation errors.

Looking ahead to Chapter 6 on the risks of ignition: it seems plausible that the probability of an incident involving a small gas leak (up to 1 litre per hour) indoors with hydrogen is no greater than with natural gas. For an equal leak size, the outflow of hydrogen is up to 1.6 times greater than natural gas. However, hydrogen is lighter and therefore spreads more easily in a room. With equal ventilation, no ignitable hydrogen cloud is created.

Both in the UK and in the Netherlands, the most gas leaks by far are noticed due to the alarming odour. This makes considering the use of odorant for hydrogen the logical conclusion as well.
Most leaks occur at the connecting pipe and gas meter set-up. Additional checks for leak tightness and possible replacement of connecting pipe and gas meter set-up when converting from natural gas to hydrogen is appropriate. Further reduction of gas leaks in pipe material can be achieved by fully implementing the replacement programmes for cast iron and asbestos cement for plastic.

In conclusion, based on the choice of materials, no more leaks are to be expected when using hydrogen, although there is more volume outflow in the event of a leak.

5 Dispersion and inflow into other areas

This chapter takes a closer look at the dispersion of hydrogen in the event of a leak. The comparison between natural gas and hydrogen has been made based on field research and literature reviews. A summary of this chapter is included in the last section.

5.1 Results of the UK studies

In the H21 project, research was conducted into the dispersion of hydrogen and natural gas in distribution networks [reference 6, pages 50-53, 58-62]:

1. Small leaks in the distribution pipe and connecting pipe underground - a total of 108 experiments
2. Small leaks found in gardens and houses - 85 experiments
3. Large leaks found in gardens and houses - 85 experiments.

These experiments were designed to obtain information on the dispersion of hydrogen in the soil as compared to natural gas. The results showed considerable spread and the reproducibility was not good, despite the test sites having been protected from the rain. Therefore, it is not possible to draw general conclusions.

Comparison of hydrogen and natural gas:

- For a given diameter and pressure, the leakage rate (volumetric flow rate) of hydrogen is higher than that of natural gas by a factor of 1.4 to 2.2. The higher values occur at pressures of 75 mbar and higher;
- Hydrogen does not migrate further through the soil than natural gas.

The results were further analysed and the detailed information obtained was used to adjust the models to better map the risks with actual measured values of gas leaks and displacement in the soil. A large number of reports were produced, which are not publicly available.

In addition, some insight has been gained into underground outflow and dispersion along the path of least resistance. This is described with the Darcy flow, reference Section 2.2.3 [31]. At equal pressures, it seems that hydrogen can cause crater formation earlier than natural gas. This may occur particularly at higher pressures in the gas distribution system (>200 mbar). Crater formation would be favourable if the hydrogen would then enter the atmosphere more quickly and not diffuse underground to closed areas.

Based on the work of Atkinson, reference Section 2.2.4 [31], it can be concluded that the greatest risks occur with outflows at higher pressures, unless crater formation occurs. In this situation, the distance that the gas travels underground is comparable for natural gas and hydrogen. Field tests (see recommendations for follow-up research) are required to confirm this. If the above theory of crater formation is correct, then it seems logical that underground outflow only causes a greater risk in the case of accumulation in closed areas, because accumulation takes place more quickly there (because there is more outflow) and the lower combustion limits for natural gas and hydrogen are approximately the same.

In Hy4Heat, experimental studies were carried out into the movement and dispersion of hydrogen in confined spaces such as kitchen cupboards. The inflow into other spaces has also been studied [5]. These studies were conducted in a test house and are therefore completely representative for actual urban areas. The experiments were carried out in a situation where the gas meter was placed in a kitchen cupboard and a situation where the gas meter was placed in a box accessible from outside. Some experiments with gas outflow in a basement were also carried out. The latter experiments were very limited, because such situations hardly ever occur in the UK. The data on the extent of leakage in the case of a leak outside (H21) have not been included.

The experiments were carried out with natural gas and hydrogen as a comparison and with multiple ventilation set-ups in 2 phases:

- In phase 1, 73 experiments were carried out with 39 hydrogen outflows and 34 natural gas outflows in kitchen cupboards and in a recessed meter box. The outflows were of holes varying from 0.6 mm to 7.2 mm in diameter with a pressure of 20 mbar at the outflow point. This pressure is typical of the pressure behind the gas meter in a house. The sizes of the leaks used in the experiments are much larger than the sizes of leaks found in practice (see Tables 14 and 15a to c);
- Phase 2 consisted of an additional series of 11 experiments (10 hydrogen and 1 natural gas) with some higher leakage rates and variations in combinations of ventilation openings in the box and the kitchen wall.

The following conclusions can be drawn from this study:

- Layers of nominally uniform gas concentrations (so-called stratification) developed above the gas leakage for both hydrogen and natural gas. These observed steady state concentrations could be reproduced in a simple model and were reasonably useful for domestic kitchens;
- Flammable concentrations of gas were observed in wall and floor cavities for all gas outflows in the meter box (located on the outside of the house), but no flammable concentrations were observed in the rooms of the house.

In Figure 10 A and B, two schematic examples of experiments carried out in urban houses at the Spadeadam test site are provided (see reference page 49 for a summary) [40]. In addition, Appendix A and B of the reference *[38]* shows the gas concentrations of all 73 experiments.

Figure 10A Schematic representation of the tests in urban houses in Spadeadam. The experiments were carried out using both natural gas and hydrogen. Figure 10A shows how the concentration of a gas leak builds up in a house when the gas leak is located in a box under a staircase. The red area contains the gas leak and therefore also the highest gas concentration.

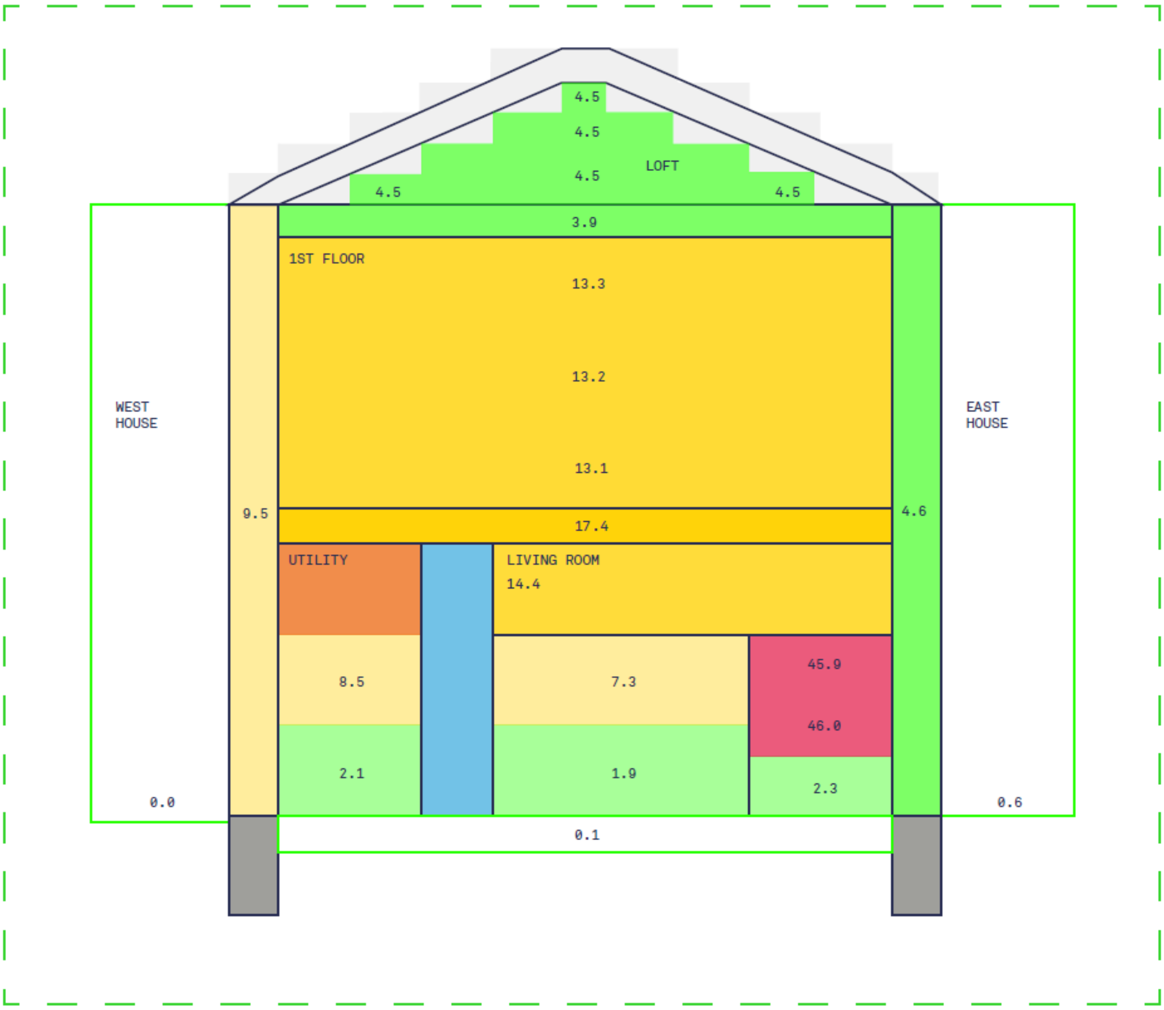
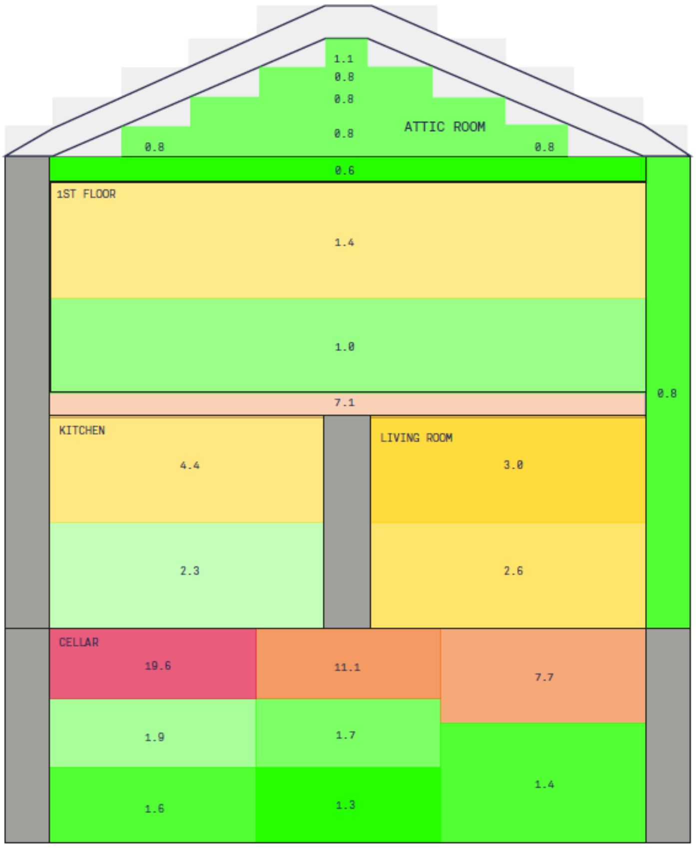


Figure 11B Schematic representation of the tests in urban houses in Spadeadam. The experiments were carried out using both natural gas and hydrogen. Figure 10A shows how the concentration of a gas leak builds up in a house when the gas leak is in the basement. The red area contains the gas leak and therefore also the highest gas concentration



The results obtained from these experiments ([38], page 3 ff) show:

- Layers with the high concentration of gas generally form at high levels in the room in a relatively homogeneous concentration. It generally extends from the top of kitchen cupboards to the ceiling.
- The highest leakages applied in phase 1 of the study (6.4 m^3/h through a 7.2 mm hole) with natural gas resulted in steady state concentrations in a layer with a high level in the kitchen that was above the upper flammability limit for natural gas. This limit was obtained soon after the start of the experiment. For hydrogen, the highest release rate (hole size of 7.2 mm, outflow rate of 18.6 m^3/hour) resulted in highly reactive concentrations (above 30 vol%) inside at a high level in the kitchen. 20 vol% hydrogen concentrations showed laminar burning rates and a factor of 2 higher than the worst case for natural gas. Concentrations of 30 vol% have a burning rate that is approximately a factor of 5 higher than the worst case for natural gas. This can have a considerable effect on the severity of an explosion, even if some ventilation is possible through windows or doors. For further details, see also reference page 15 [29]. Please note that the gas outflow indicated is very high. As a comparison, in a Dutch situation in a house with a G4 gas meter, it can be calculated that in case of a complete rupture of a cooker connection, the maximum natural gas outflow rate would be 10 m^3 per hour.
- Adding a 100 mm diameter vent above the kitchen door in the corridor in the situation with the highest leakage rate, resulted in the concentration in the kitchen layer reducing to about one third from ~30 vol% to ~20 vol%, with only small increases in gas concentrations observed in other areas of the house. This means that the concentration quickly dropped to a safer range of about 10-7 vol% gas.
- Adding 4 ventilation holes (100 mm) and 4 (100 mm) air vents in the side of the kitchen base cupboard with the highest release of hydrogen, resulted in the concentration measured in the cupboard dropping from a nominal 40 vol% to about 25-30 vol%. There was no significant effect on the concentrations in the bulk volume of the kitchen.

From this study, it is possible to compare dispersion due to leakages for hydrogen and natural gas in combination with different ventilation combinations:

- All ventilation combinations using vents to the outside or to a corridor showed lower concentrations at the height of the kitchen ceiling than in the non-ventilated houses;
- At the highest flow rate tested (78.6 m^3/hour), the venting (with both vent sizes) resulted in a reduction of the concentration at the kitchen ceiling from ~60 vol% to ~40 vol%, around the maximum burning rate for hydrogen mixtures. This highest flow rate tested was very high and does not normally occur in the kitchen for leaks that are possible there (e.g. complete rupture of pipe to gas cooker);
- A figure for the complete opening of a 100 mbar gas connection in the Dutch situation, for example in the meter room with a 32 mm diameter PE connecting pipe (10 metres long, SDR of 11, i.e. an inner diameter 26 mm), close to a gas receiving station, results in a natural gas leakage of roughly 110 m^3/h and for hydrogen a factor of 2 more, around 220 m^3/hr;
- The use of ceiling vents significantly reduced the measured concentrations in the ceiling (empty space above the kitchen).

For the calculation of the dispersion of the gases, please refer to the Hy4Heat Gas Dispersion Modelling Report [28], page 6 ff. The model calculates what the final concentration of the gas is, given a certain hole size of the leakage, in a certain room and depending on a ventilation level. The rooms included were a kitchen with a volume of 28.8 m^3 and a ground floor of the house with a volume of 76.8 m^3.

The tables below summarise the assumptions used in the models, which were based on information obtained from 471 houses of varying ages in the UK.

Typical ventilation data/air permeability data for the UK housing stock is given in Table 15 [25] (page 36 ff).

Table 15 Ventilation data/air permeability data of the UK housing stock and values applied in the model.

Air permeability description	Air permeability range (m3/(h.m2)) @ 50 Pa	Air permeability (m3/(h.m2)) modelled (kitchen)	Air permeability (m3/(h.m2)) modelled (ground floor)	Percentage of housing stock	Equivalent air changes per hour (ACH)
Low (Highly Sealed, e.g. no natural continuous ventilation)	2-4	2	1	4%	0.1-0.2
Medium (Moderately Sealed, e.g. with continuous ventilation)	5-10	5	5	37%	0.25-0.5
High (Leaky, e.g. older houses)	>10	15	15	59%	>0.5

Table 16 Assumptions for models: gas leakage locations and ventilation rate [25] (p. 73)

Gas leak locations	Kitchen		Storey (Downstairs of a terraced house)	
Space dimensions (width x length x height)	4m x 3m x 2.4m		8m x 4m x 2.4m	
Volume size (in approximation with potential leak locations)	~ 30 m^3		~ 75 m^3	
Air permeability description	Total leak & vent area	Air permeability rate estimated @50Pa	Total leak & vent area	Air permeability rate estimated @50Pa
Low (Highly sealed, e.g. no continuous ventilation)	~ 0.04 m^2	2 $m^3/(h.m^2)$	~ 0.04 m^2	1 $m^3/(h.m^2)$
Medium (Moderately sealed, e.g. continuous ventilation)	~ 0.08 m^2	5 $m^3/(h.m^2)$	~ 0.15 m^2	5 $m^3/(h.m^2)$
Leaky (e.g. older houses)	~ 0.20 m^2	15 $m^3/(h.m^2)$	~ 0.40 m^2	15 $m^3/(h.m^2)$

For the modelling of explosions and the underlying literature references used, please refer to the WP 7 detailed report: Hy4heat Consequence Modelling Report [29], page 39 ff.

Also in the HyHouse 2015 project, reference page 26 ff [14], experiments were carried out in the UK on hydrogen dispersion in a house. During the outflow phase, hydrogen concentrations were measured at different locations in the house. The flow rates used varied from 0.16 litres/s to 5.26 litres/s (i.e. 0.6-18 m^3/h, or 2-64 kW). The experiments were carried out at three different air permeabilities by minimising the natural ventilation in stages. The maximum hydrogen concentrations measured are shown in the table below and were always measured in the room where the outflow also took place, including the meter box. Gas leaks were created and gas concentrations measured at various points in the house. For a detailed description of the test programme and the drawings/situations of the house used with dimensions and positions of the leak created, see page 26 ff. Starting on page 38, the maximum gas concentration values found at the various positions in the house are described. Table 18 provides a consolidated overview.

Table 17 The maximum hydrogen concentrations measured in the HyHouse project

	Air permeability home[10] (m3/hour/m2) *(dm3/s/m2)*	Maximum hydrogen concentration (vol.%)	
		House (excl. meter cupboard)	meter cupboard
Phase 1	9,85 (2,74)	6,5 – 7,0	18,2
Phase 2	6,64 *(1,84)*	10,0 – 10,5	19,3
Phase 3	3,46 *(0,96)*	12,0 – 12,5	22,1

[10] The Building Decree lists a number of classes of airtight construction. In order to comply with the Building Decree, the air permeability (Qv10 value) for class 1 may be a maximum of 1.0 dm3/s/m2. This class no longer occurs in new construction. Class 2 for energy-efficient construction is the standard for new buildings, where the air permeability must be between 0.4 and 0.6 dm3/s/m2. The house used in the HyHouse project is a house with quite a few draft holes, because only in Phase 3, after all the cracks and holes had been taped, did the air permeability correspond to that of class 1 of the Building Decree.

The important results of this study are as follows:

- At flow rates below 0.33 liter/s (= 1.19 m^3/h, or 3.6 kW) no hydrogen was measured in the house;
- For flow rates between 0.33 litres/s m^3/h and 0.66 litres/s (= 2.38 m^3/h, or 7.1kW) hydrogen was measured, but the LFL was not reached anywhere. These kinds of flow rates are characteristic of small leaks at a connection in a pipe;
- At a flow rate of 1.32 litres/s (=4.75 m^3/h, or 14.3 kW), the LFL was reached at the end of the outflow period (2.5 hours) and only in the immediate area where the leak was located. This implies that if a hydrogen outflow does not last too long (e.g. due to corrective action after a smell of gas is reported), the LFL will not be reached;
- The highest maximum concentrations were measured in the meter box and were a direct consequence of the limited contents of that cupboard;
- The outflows led to a stratified hydrogen layer on the ground floor. This shows that the outflows were most likely laminar in nature;
- The highest maximum hydrogen concentration was always measured in the room where the hydrogen was released and at the sensor placed the highest. Similar concentrations were measured in the other rooms on the same storey;
- The more airtight the house was, the higher the maximum hydrogen concentration was.

These results confirm that the formation of an explosive mixture at the most common small leaks and usual ventilation does not seem realistic.

The Gas Dispersion Data Analysis report [39] validated the above findings from Hy4Heat and Hyhouse and supplemented them with field studies on the dispersion of hydrogen and natural gas in domestic environments. The research results were found to be very much in line, which increases the value of the research results.

Gas consumption settings between 0.4 and 264 kW were tested in order to simulate typical leak scenarios ranging from a leaking connection to a broken gas pipe. More than 300 experiments were conducted. Gas concentrations at different heights in all indoor spaces were measured in order to enable the dispersion of the gas in air concentrations reached (% Gas In Air abbreviation used =GIA) and to make a correlation to expelled energy quantities possible (kWh). Gas injections in spaces, boxes/cupboards and basement environments were compared. These field studies resulted in the following most important findings

- For a given pipe hole size, 1.2 to 2.8 more volume of hydrogen leaks as compared to the volume of natural gas [40], reference page 8. Overall, however, the maximum concentrations measured for hydrogen and natural gas were similar in all the scenarios. In all tests and as expected, the highest GIA concentrations were measured closest to the point of gas release;

- Similar maximum concentrations were observed in the rooms where the gas was released as carried out during HyHouse and in the basements where the gas was released during the Hy4Heat programme at leakage rates below 50 kW. This suggests that the dispersion patterns are consistent for both hydrogen and natural gas. Gas leaks in kitchen cupboards resulted in very high concentrations of both hydrogen and natural gas in the cupboard space and the highest concentrations were at the top of the kitchen. Gas stratification in the room of release was evident in almost all of the tests where higher GIA concentrations were observed at the top of the room as compared to the rest of the room;
- This effect was strongest in tests where the gas leakage occurred at a height and is broadly concurs with the results from the calculations with existing dispersion models, although on windy days this can be distorted. Complex dispersion patterns were observed in the basement with the direction of gas release influencing the level of gas stratification;
- Again, it was found that ventilation in the house, particularly in the room where the leak occurs, had an obvious effect on the resulting GIA concentrations measured in the room when compared to tests where no (or little) ventilation was present. This effect was observed by opening or closing doors, or by adding additional ventilation such as wall vents;
- The addition of wall vents with an outlet to the outside was found to reduce the maximum GIA concentration in the room of the leak and also to reduce gas accumulation throughout the house. Ventilation added to cupboards (in case of gas leaks in cupboards) reduced the high gas concentrations, and in combination with room ventilation, lowered the maximum gas concentrations seen in the wider kitchen area;
- Gas leaks in the basement resulted in the highest gas accumulation in the entire house. This is likely due in part to reduced ventilation factors in a basement environment, but also to the volume of the house above the basement in which it is possible for the gas to disperse. Basement leaks were also the only tests where a notable concentration of gas (of both hydrogen and natural gas) was measured in all of the empty spaces of the house (e.g. cavity walls, etc.). This was measured at extremely high leakage rates (more than 200 kW, which is an amount that normally cannot occur in a normal house). It should be noted that in high ceiling cavities (from the ground floor to the first floor) concentrations were also observed during the larger leaks in kitchen cupboards, but this was greatly reduced when ceiling vents were installed. Based on the exploratory measurements, the decision was made not to further study leaks in basements (yet) and to exclude houses with basements from the pilot projects.

5.2 Risks of hydrogen dispersion and inflow into other spaces

- The experiments and CFD simulations show that in the event of a leak, hydrogen will first accumulate at the top of a room before mixing into a homogeneous mixture. In addition, the gas can also escape to adjacent spaces. In principle, gas escaping to adjacent spaces is beneficial, as a leak will be smelled sooner and the concentration in the space where the gas has escaped from will decrease. This assumes that the gas has been odourised. If the size of the leak is the same, natural gas will flow into the closed space at a smaller volume flow and thus build up lower concentrations. The faster dispersion of hydrogen cannot always compensate for this effect;
- The pattern of gas accumulation and the maximum concentration in the space of release depend on the height of the gas release. Large leaks (of more than 100 kW or ~30 m^3/h) are necessary to obtain high (20% or higher) hydrogen GIA concentrations. However, relatively small leaks in an enclosed small space such as a box/cupboard can lead to areas of very high concentrations locally;
- Ventilation placed at a high position makes a clear difference to the maximum GIA concentrations at the ceiling height of the room where the leak took place. For hydrogen leaks around 67 kW (20 m^3/h), concentrations in the kitchen were almost halved using external ventilation (a ventilation opening of 100 or 200 cm^2 placed near the ceiling);
- Ventilation of a cupboard containing a gas appliance such as a boiler reduces the possible hydrogen concentration and the risk of a sudden outflow of flammable gas. Current building regulations (e.g. Approved Document J (England)) already provide for ventilation to be added to boxes/compartments containing combustion appliances;
- Open and closed doors have an obvious effect on the pattern of gas dispersion in a house. For hydrogen injection rates around 67 kW (~20 m^3/h) or lower:
  - If the door of the room in which the gas was injected was open, the gas was dispersed throughout the house. But, in general, the concentration remained below 13% GIA. The exception to this was the area above the height of the door lintel in the room of release;
  - If the door of the room in which the gas was injected was closed, gas concentrations were also found throughout the house (excluding the room of release). These concentrations were generally less than 10% GIA.
- In certain circumstances, especially in the absence of ventilation in accordance with building regulations and closed doors of the room in which the gas leak occurs, this can result in high (20% or higher) GIA concentrations in the room of release.

It is thus clearly demonstrated that ventilation is an important factor in the dispersion pattern and is therefore an effective risk-reducing measure. The need for ventilation is stipulated in the current building regulations.

The following ventilation capacities are the most important ventilation requirements for a residential function (Buildings Decree 2012, Article 3.29 [41]):

- Living area: at least 0.9 dm^3/s per m^2 floor area with a minimum of 7 dm^3/s (lower limit for older houses (Existing Buildings Decree, Article 3.38: 0.7 dm^3/s)).
- Toilet area: 7 dm^3/s.
- Bathroom area: 14 dm^3/s

- Kitchen: 21 dm³/s.

Please note: this is no guarantee for continuous ventilation. It only indicates the capacity (what a ventilation installation is able to supply). However, according to the Dutch Buildings Decree, it must also be possible to switch off a ventilation installation.

In NEN 2768 (meter box standard) there is an obligation to ventilate meter boxes. However, there are situations known in the Netherlands in existing buildings where there are no ventilation openings in the doors of the meter box. If the gas supply is switched from natural gas to hydrogen, this is a point for attention during the pre-inspection of a house.

5.3 Conclusions regarding dispersion of hydrogen and natural gas

With regard to dispersion outdoors, the research results from H21 concerning dispersion of hydrogen in the soil as compared to natural gas are not reproducible and show too great a dispersion. No conclusions can be drawn from this. In general, it can be said that hydrogen does not disperse further into the soil than natural gas does. In addition, for hydrogen (in particular at higher pressures), inflow into an area (e.g. via an underground wall vent) seems to cause the greatest risk, but this is also a risk for natural gas. The degree of difference between the two is unclear.

Research during Hy4Heat, HyHouse and the Gas Dispersion Analysis Report into hydrogen dispersion in spaces gives a thorough picture of the risks. For the most common leak sizes and degree of ventilation, no explosive mixture of hydrogen is formed.
Both hydrogen and natural gas will first spread to the top of a room indoors. Hydrogen does this even more so because of its lower density. Adding ventilation high up in a room, opening windows/doors or ventilation in accordance with Article 3.29 of the Buildings Decree 2012 will lower the present hydrogen concentration considerably. Please note that the same Building Decree also states that it must be possible to switch off ventilation.
In the Netherlands, meter boxes also have to be provided with ventilation in accordance with NEN 2768. This is not always the case in practice, however. Hydrogen dispersion in a closed space can lead to an explosive concentration relatively quickly.

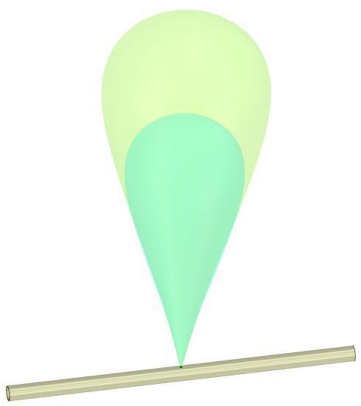
In conclusion, ventilation (as stipulated in the Buildings Decree and NEN 2768) considerably reduces the risks of hydrogen dispersion indoors. However, it is not a given that houses have been built in accordance with these regulations. Inspections during the conversion process are necessary.

6 Risk of ignition

This chapter deals with the actual risk of ignition that may occur following a leakage, dispersion and possible inflow into other areas. A summary of this chapter is included in the last section.

A gas cloud of natural gas and hydrogen have a different ignition area, as shown schematically in Figure 11.

*Figure 12 Drilled hole of **3mm** diameter in a pipe of **22 mm** diameter, pressure **20 mbar**. The dark green area shows the zone where the natural gas can ignite (up to a height of about 40 cm above an outlet), the light green area the area where hydrogen can be ignited (up to a height of about 60 cm above an outlet). This is up to 25% further.*



6.1 Study of ignition sources

The risk of ignition mainly depends on two factors: 1) the occurrence of a flammable mixture of gas and air and 2) the presence of an ignition source with sufficient ignition energy. These two factors are interdependent and are shown in Figure 13a and b [12] (Chapter 4). The ignition energy required for hydrogen is lower than for natural gas for almost every ratio with air. In addition, the ratios of gas and air at which a flammable mixture is possible are much broader for hydrogen than for natural gas. These are the called the lower and upper flammability limits in English (LFL and UFL). In Dutch these are called the explosion limits (LEL and UEL).

Figure 13a Dependence on ignition energy and gas/air concentrations for hydrogen and natural gas

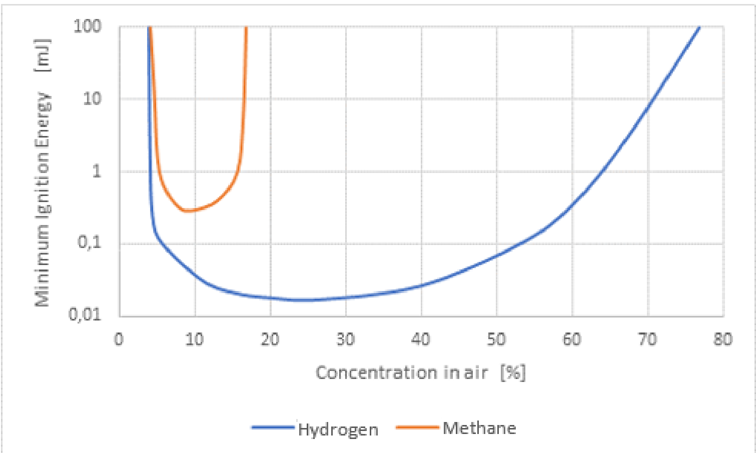
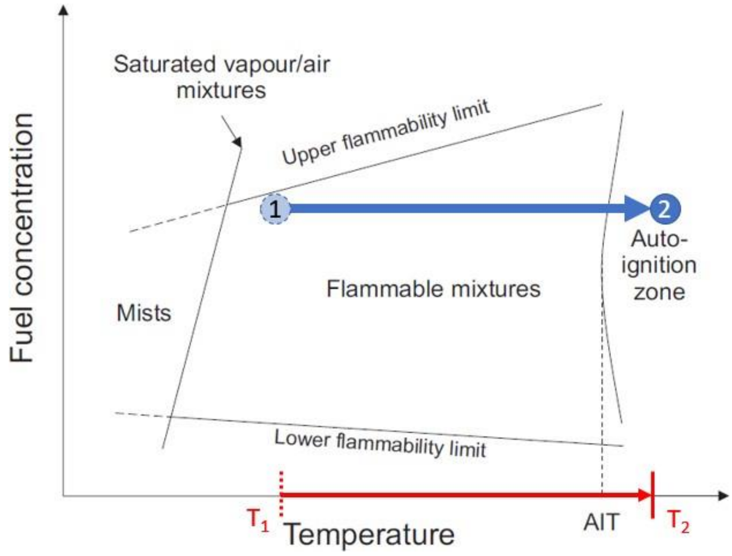


Figure 13b; Schematic representation of the generation of flammable gas mixtures as a function of concentration and temperature, (page 46).



In the H21 project, common ignition sources were tested in combination with a flammable hydrogen mixture [40], reference page 65. The results are summarised in the table below, Table 18. Not all ignition sources led to an actual ignition, as the ignition energy was too small to ignite a flammable mixture. The ignition sources can roughly be classified into:

- flames;
- hot surfaces;
- sparks (caused by mechanical friction or of electrical origin).

Spontaneous ignition was not included in the study.

The sub-sections of Section 5.3 in the literature review referred to above address the matter in more detail. The results for ignition tests are shown in the table below. The ignition sources apply both indoors and outdoors:

Table 18: Overview of the ignition sources tested in H21 both outdoors and indoors. (see page 2 from [42]. This has been tested with stoichiometric concentrations.

Test Item	**Result**
Mobile phone	No ignition with actual device or battery (3.82 V) Ignition was only achieved with a conservative inductance / capacitance circuit, using a 10 V supply after 560 cycles at ER1.0 (low ignition energy) (ER = Equivalence Ratio)
Cordless phone	No ignition with device, battery (3.3 V) or cradle
Thermostat	No ignition
Light switch	No ignition with LED bulb (7 W) Immediate ignition with halogen bulb (230 W) at ER0.2 (high ignition energy)
Door entry system	Ignition after 4 cycles with whole system, including push button inside the cloud (8V – doorbell) at ER0.2 (high ignition energy) No ignition with intercom system and mag lock only inside the flammable volume (12V)
Static discharge	Immediate ignition (0.3 mJ) at ER0.2 (high ignition energy)
Mechanical spark	Immediate ignition at ER0.2 (high ignition energy)
Vehicle starter motor	Ignition with new starter motor at ER0.2 (high ignition energy) but unable to repeat the result at any other concentration. Used starter motor resulted in no ignition at ER0.2 (high ignition energy) but immediate ignition at ER0.3.

Telecoms equipment	No ignition
Cable TV equipment	No ignition (10W)

Table 19 below shows more detailed test results from the Hy4Heat programme of various ignition sources for indoor use. Up to 5 (L1 to L5, see table for mixture ratio) hydrogen mixtures have been tested, depending on when ignition took place; for methane the L1 and L2 comparable mixtures have been used.

Table 19 Overview of ignition sources and probability of ignition of a flammable mixture from Hy4Heat, sources that may be present inside a house [25] (Section 5.3.3 and page 64).

Level	Nominal Conc.	Conc. Range	Equivalence Ratio H2	Equivalence Ratio CH4
L1	5.90%	5.6 % - 6.2 %	0.15 (0.14 - 0.16)	0.60 (0.56 - 0.63)
L2	8.90%	8.6 % - 9.2 %	0.23 (0.22 - 0.24)	0.93 (0.90 - 0.96)
L3	17.80%	17.5 % - 18.1 %	0.52 (0.51 - 0.53)	N/A
L4	26.60%	26.3 % - 26.9 %	0.86 (0.85 - 0.88)	N/A
L5	29.60%	29.3 % - 29.9 %	1.00 (0.99 - 1.02)	N/A

	Notes	Hydrogen		Methane	
Small extractor fan 1 (new unit)	Manrose 11640	-	No	-	n/a
Small extractor fan 2 (old unit)	Manrose XF100S	-	No	-	n/a
Medium sized extractor fan 3 (old unit)	Vent Axia 17104020E	-	No	-	n/a
LED light fitting (new)	Sylvania 6412X LED ceiling light 24 W	-	No	-	n/a
Bayonet light fitting (old)	LED Filament bulb	-	No	-	n/a
	60 W bulb	-	No	-	n/a
	LED Filament bulb (smashed)	-	No	-	n/a
	60 W bulb (smashed casing)	Immediate	L1	Immediate	L1
Fluorescent light fitting (old)	Old but working	-	No	-	n/a
	Old with faulty starter	-	No	-	n/a
Hair drier (old)	Babyliss S190A, 2 kW	Immediate	L1	-	No
Vacuum cleaner (old)	Art Miele	20 sec	L1	-	No
Microwave oven (new)	Tesco Microwave	-	No		n/a
Tumble drier (old)	Hotpoint Aquarius TVM570	9 min	L1	Equipment damaged so unable to test	
Fridge unit (door closed) (old)	LEC R-RD40F	-	No		n/a
Fridge unit (door open) (old)	LEC R-RD40F	-	No		n/a
Iron (new)	Tesco's £10 Iron	8 min	L4	Equipment damaged so unable to test	
Toaster (new)	Tesco's £7 toaster	Immediate	L1	-	No
Electric hob	Cooke & Lewis CLCER60A	5 sec	L1	10 sec	L2

In subsequent studies, Hy4Heat concentrated on the kitchen as that is where most ignition sources are located. The living room, with a possible decorative gas fireplace, was not considered further. Many ignition sources can only be ignited after human intervention, such as light switches, so the presence of a human being is required.

The most important results are as follows:

- Exhaust fans (mechanical extraction) and lighting fixtures did not cause ignition with either gas during normal operation. This is of particular importance as lamps and exhaust fans are almost the only potential sources of ignition likely to routinely occur near the ceiling of a kitchen.
- Of the range of white goods tested, the majority of items showed no significant difference between the gases. These types of white goods will almost always be at a worktop height in the case of kettles, microwaves and ovens. In the case of tumble dryers or washing machines, they are almost always installed on the floor. The risk of ignition at this height in the kitchen is even lower as gas leaks rise quickly and first form a concentration at the top of the room;
- When ignition occurred, the hydrogen ignitions were loud and fast as compared to the natural gas ignitions under similar conditions. The natural gas ignitions were brighter, quieter and of longer duration.

6.2 Translation to the Netherlands

There is no reason to assume that the research carried out as described in the previous section would have a different outcome in the Netherlands. These research results can be applied to the historical natural gas incidents in the Netherlands in order to make a comparison with hydrogen. In the period from 2017 to 2019, there were a total of 734 natural gas incidents. This gives an indication of the magnitude of incidents with hydrogen:

- 62 incidents where the gas was directly ignited:
    - 31 natural gas fires as a result of another fire (e.g. meter box fire).
    - 16 natural gas fires resulting from excavation work during which the natural gas pipe and electricity cable were damaged simultaneously. In the case of hydrogen, the hydrogen would ignite almost immediately with a limited volume.
    - 15 natural gas fires resulting from damage caused during work activities (welding, grinding, using a burner, etc.). In the case of hydrogen, an ignition source close to the source of the leak would lead to an ignition with hydrogen;
- 5 incidents in which the gas was ignited with a delay:
    - In 5 incidents, the gas was ignited after a delay. This means after dispersion, the gas then has time to spread through the soil with the risk of accumulating in a room;
    - The source of ignition was not determined in any of these natural gas incidents. In a few incidents, a switch to electrical equipment was a plausible ignition source. In the case of hydrogen, this source can also lead to ignition, as described in the previous paragraph;
    - The consequences of ignition of hydrogen or natural gas in an enclosed space depend on several factors, including the percentage of gas in the air. In the case of a stoichiometric mixture, ignition of either gas would result in the complete destruction of a house. In the case of hydrogen, the debris is likely to spread further. Destruction could vary from blowing out windows/frames to complete destruction of the property. See, reference page 32 ff [13]. In case of ignition of a non-stoichiometric hydrogen mixture (except for <10% GIA), the damage to a building is expected to be greater than with natural gas. See also the overviews provided in Hy4Heat - Gas Ignition & Explosion Assessment [5];
- 505 incidents in which no ignition took place:
    - 444 incidents in the open air, of which 76 incidents were caused by welding or drilling;
    - 61 incidents in a building due to leakage, of which in 15 incidents the leakage was caused by drilling or grinding. In 29 incidents, an odour of gas was detected although the cause of the leak was outside the building;
- 162 incidents in which no gas was released (not taken into consideration further).

6.3 Conclusion on the risk of ignition

Based on the studies described above and the information available (reference page 26 [13]), conclusions can be drawn about the risks of ignition for hydrogen:

- Hydrogen can be ignited from up to 25% further away than natural gas;
- Also, the range of gas/air ratios at which ignition is possible is much greater with hydrogen than with natural gas;
- In addition, the minimum ignition energy of hydrogen in air is lower than that of natural gas by a factor of 16 (both gases are stoichiometrically mixed). With a stoichiometric mixture of hydrogen (29% hydrogen in air), ignition sources with a weak static discharge are sufficient to ignite the mixture in principle. For hydrogen mixtures with lower concentrations (8-10% hydrogen in air), hydrogen has a lower chance of igniting than natural gas;
- Sparks caused by electrical equipment or switches are sufficient to ignite both natural gas and hydrogen even at low concentrations. Existing equipment that does not ignite natural gas will also not ignite hydrogen in principle.
- In practice, it appears that hydrogen does not ignite in a number of cases where it may be expected given the circumstances. Additional research to explain this behaviour is needed

7 Consequences of ignition: fires or explosions

This chapter deals with the consequences of a fire and/or explosion. A summary of this chapter is included in the last section.

If a flammable mixture is ignited with a sufficient amount of energy, the mixture will burn. This then releases flue gases and heat that can cause pressure to build up in enclosed spaces. In addition to simple combustion, this can also lead to an explosion. Depending on the speed of the pressure build-up and the temperature, additional detonation can take place. The latter is not a phenomenon that is likely to occur in practice. Under the same conditions, a hydrogen explosion can cause greater consequential damage than natural gas due to the higher burning rate. At low gas concentrations (<10 vol%) the consequential damage with hydrogen is lower; starting from 15 vol% it is more severe. In the case of an explosion with a stoichiometric (30 vol%) hydrogen mixture, pressure build-up can cause an overpressure of over 100 mbar and, in non-ventilated spaces, up to 7 bar. This can lead to walls collapsing or houses being destroyed. If there is no explosion but there is a fire, this fire can lead to direct damage in the case of both natural gas and hydrogen. In the case of hydrogen, the heat radiation for the environment is smaller, which may also mean that the potential consequential damage of the fire would also be smaller.

7.1 Behaviour of gas ignitions

Hy4Heat Work Package 7 [43] takes a closer look at the behaviour of gas ignitions. The report gives a qualitative overview of experimental data and other literature concerning deflagrations of flammable mixtures of hydrogen and natural gas. Almost all structures had the means (see: a kind of catalyst to start the ignition such as explosive ignition risks) to achieve the deflagration. These are conditions that would never occur in houses under normal conditions.

For a detailed analysis of the consequences of ignition under various (extreme) conditions, please refer to the WP 7 sub-report: “Gas Ignition and Explosion Data Analysis” [43]. This includes references to literature as well as actual experiments carried out. The results are presented in “ISO damage charts”. The data have been further developed into several different concentration bands, expressed in the percentage of gas in air (GIA). In summary, the following is concluded about the consequential damage in case of a natural gas or hydrogen ignition:

1. 0 – 10 vol% - Hydrogen can be less severe than natural gas
2. 10 – 15 vol% - Comparable damage between hydrogen and natural gas
3. 15 – 20 vol% - Hydrogen may be more severe than natural gas
4. 20 – 25 vol% - Hydrogen is likely much more severe than natural gas
5. >25 vol% - Hydrogen is likely much more severe than natural gas

The data presented (see also reference Chapter 5 [27]) were obtained from experiments with ignitions of flammable gas mixtures in different types of housing, constructed from different materials, with different levels of ventilation and with different levels of obstruction. None of these configurations perfectly represents a house. Some tests were carried out in enclosures that were completely different from a realistic domestic situation in order to ensure that the gas would ignite. Therefore, these data cannot be used to describe the consequences of ignition in a house.

One important difference between actual houses and test boxes with one ventilation opening is the ability of a house to ventilate in a progressive manner. The flame front can move in several directions, allowing other weak structures in the room to open, such as a second door or window, or a small wall that collapses due to the overpressure. The building will not collapse until the rising pressure causes a structural component to collapse.

Deflagrations in houses, e.g. a room, will always encounter a pressure relief surface (such as window or door) that reduces the pressure build-up.

Therefore, while many of the listed results are realistic for enclosed spaces, they cannot be considered representative for houses. ISO container tests have also been carried out, primarily aimed at the consequences of a deflagration at an industrial plant and with typical obstructions for that environment. In addition, tests with a bottle basket and pipe rack have been conducted. These were deemed to not be representative as it is unlikely that such a large volume of a property would be occupied by highly ordered repetitive obstructions. The shock tube insert used in the tests by Kiwa was geometrically designed to maximise the occurrence of deflagration in the tests and it is unlikely that this obstruction would be found in a property.

From these studies, the following is applicable to urban areas:

- The overpressure can reach up to 7 bar in non-ventilated situations;
- In a ventilated environment, a gas explosion takes place over several 100 ms. In practice, this usually gives burnt and unburnt gases time to ventilate through an opening in an outer wall, thus reducing the maximum pressure of the blast wave and reducing the risk of detonation. This is called the maximum ventilation pressure;
- In a house, there are several (possibly successive) sources of pressure release, for example windows, doors and ceilings. Small gas leaks (where the concentration in the room is >10 vol%) resulting in small local deflagrations would cause proportional local damage, e.g. only damage to one window or a window plus a door;
- If external parts of the building do not fail first, an explosion in one room may propagate through an interconnected room;
- The presence of obstructions (objects) in the combustion zone may cause turbulence of flammable gas mixtures. This could cause increased peak overpressure for both hydrogen and natural gas;
- At concentrations of approximately 10 vol% natural gas and 15-20 vol% hydrogen, the consequences of ignition are more or less comparable. Towards the higher end of this concentration band, hydrogen ignition starts to become more severe than natural gas;
- Above 20 vol% (up to about 40 vol%), the consequences of a hydrogen ignition become progressively more severe as compared to natural gas.

7.2 Conclusion

An ignition of hydrogen may lead to an explosion with deflagration (combustion) or detonation (spontaneous ignition due to very fast pressure build-up in combination with certain ambient and gas temperatures). Higher concentrations of hydrogen in combination with a closed room without ventilation create conditions where detonation are theoretically possible. In HyHouse, this only happened under very forced conditions, which no longer reflect reality. It seems unlikely that detonation could occur in urban areas.

At low gas concentrations (<10 vol% hydrogen in air) the consequential damage of hydrogen is less than with natural gas; starting from about 15% the consequential damage is then worse. In the case of a stoichiometric hydrogen mixture (around 30 vol%), the consequential damage could be very severe. With this mixture, an overpressure could occur upon ignition that can quickly rise above 100mbar. In a non-ventilated room, this pressure can even rise to 7 bar. Please note that walls collapse at an overpressure of 140 mbar, and houses are largely destroyed at 420 mbar [42].

Hydrogen fires (which are less visible) lead to direct damage, just like with natural gas fires. Hydrogen fires have an equal or lower heat radiation than natural gas at a comparable energy outflow, as a result of which the potential consequential damage to the surrounding area may be smaller.

8 General conclusion: Estimated total risk results from QRA models

In conclusion, this chapter describes the overall risks applicable to hydrogen in urban areas, both in distribution and downstream of the gas meter (i.e. Indoors). Subsequently, the resulting potential loss of life from the QRA models has been translated to the Netherlands. A summary of this chapter is included in the last section.

8.1 Risks from distribution network properties, indoor installations and residential construction

In the Netherlands, most gas incidents in distribution networks are caused by damage caused by excavations. The number of fatalities is very low, which means that the influence on the potential loss of life indicator (annual probability of fatality) remains very small in the distribution network even for hydrogen. Indoors, most fatalities in gas incidents are caused by carbon monoxide: hydrogen lowers the PLL here. This is because hydrogen combustion does not release any carbon monoxide. In the Netherlands, there have been discussions for several years about requiring certification of natural gas boilers, which should contribute to reducing carbon monoxide poisoning, as there would be fewer malfunctioning natural gas boilers.

In the Netherlands, network operators are carrying out replacement programmes to replace the pipe materials of cast iron and asbestos cement with plastic. This will reduce the likelihood of leaks, because the chance of hydrogen leaking is low with plastic pipe materials. In addition, leakages are being located and repaired through gas leak detection searches.

In the Netherlands, gas meters are placed in one room with the electricity meter. In the UK, this is not done with natural gas due to the danger of ignition. In the Netherlands, meter boxes are constructed in such a way as to prevent sparks from occurring. Please note that this does not include tampering by insufficiently qualified individuals. Combining gas and electricity meters in one room does not in itself increase the risk.

The Netherlands has a relatively large number of well-insulated houses. This means that hydrogen concentrations are more likely to accumulate. However, in line with the Buildings Decree and applicable NEN standards, there is sufficient ventilation present, as a result of which insulation in the Netherlands would not lead to an increase in the PLL.

8.2 Risks from nature and extent of leakage

The number of leaks does not increase as a result of hydrogen distribution as opposed to natural gas distribution. In the event of a leak, the volume does increase (+30% volume outflow for a leak of 1 litre per hour, up to 190% for large leaks). Most leaks occur in the “old” pipe materials, cast iron and asbestos cement, irrespective of the type of gas. Parts of the distribution network that are leak-tight for natural gas are also leak-tight for hydrogen and vice versa. Most leaks in the distribution network occur in connecting pipes and gas meter set-ups. Causes include damage cause by excavations, but also ageing (corrosion). In the vast majority of cases, rapid detection takes place owing to the alarming odour (odorant) of natural gas. Downstream of the meter (i.e. indoors), pipes and fittings that do not leak for natural gas do not leak for hydrogen either. Most leaks that occur are caused by installation errors. For the above, the PLL for hydrogen distribution (provided it is odourised) does not exceed that for natural gas.

8.3 Risks of dispersion and inflow into other areas

In the distribution network, dispersion of hydrogen in the open air (e.g. due to damage caused by excavation) does not lead to an increased PLL. The influence of underground dispersion is unclear. It is possible that the PLL would increase here due to underground dispersion leading to accumulation in crawl spaces or basements through a vent in the facade. Downstream of the meter (i.e. indoors), with the most common leak sizes and degree of ventilation, no dispersion occurs that would lead to an explosive mixture of hydrogen. Hydrogen accumulates even faster than natural gas, first at the top of a room. In principle, this has the effect of increasing the PLL. However, providing some ventilation can prevent an explosive gas/air mixture from developing. In a closed space (such as a meter box without the mandatory ventilation as required by NEN2768) hydrogen dispersion leads to an explosive concentration faster than natural gas. It is not a given that ventilation will actually be applied in (older) houses and meter boxes. Here, using hydrogen instead of natural gas therefore slightly increases the risk, and extra inspections and a possible adjustment of the ventilation would be necessary when converting from natural gas to hydrogen.

8.4 Risk of ignition

Hydrogen can be ignited from up to 25% further away than natural gas. In addition, the range (lower and upper explosion limit) of the gas/air mixture is much greater with hydrogen than with natural gas. Moreover, for stoichiometric mixtures, the minimum required ignition energy of hydrogen in air is 16 times smaller than the minimum required ignition energy of natural gas in air. If an explosive mixture eventually forms indoors, this makes the PLL of hydrogen higher than that of natural gas. This is not further exacerbated by the presence of equipment. Research results (see Chapter 6, Table 19) show that equipment present that does not cause natural gas ignition, will also not cause an ignition with hydrogen in principle. Table 19 does show some exceptions to this when they are placed lower in a room. Dispersion studies show that hydrogen first forms a combustible mixture at the top of a room, where providing some ventilation directly reduces the chance of a combustible mixture. The formation of a combustible mixture at a low physical height in a room is therefore even smaller

8.5 Consequences of ignition: fires or explosions

A hydrogen explosion may, under the same conditions, cause greater consequential damage than a natural gas explosion due to the higher burning rate. Results of experiments [43] show that natural gas concentrations of 10%vol and hydrogen concentrations of 15-20%vol have similar effects upon ignition. From a hydrogen mixture of 20%vol, the impact of an explosion of hydrogen is much heavier as compared to natural gas. If there is no explosion but there is a fire, this fire would cause direct damage in the case of both natural gas and hydrogen. With hydrogen, the heat radiation for the environment is lower, which means that the potential consequential damage of the fire may also be smaller.

8.6 Total risk assessment from the QRA and application to the Netherlands

8.6.1 Distribution network (up to and including the gas meter)

8.6.1.1 UK specific

In the UK, the QRA model has been used to translate the safety risk of the Northern Gas Network (reference year 2020) for the distribution of natural gas into the UK-wide distribution network. This network has also been used as the basis for calculating the safety risk when 100% hydrogen is used. In addition, adjustments were made to this model (taking into account previously mentioned replacement programmes) to assess the predicted network in 2032 for the distribution of 100% hydrogen.

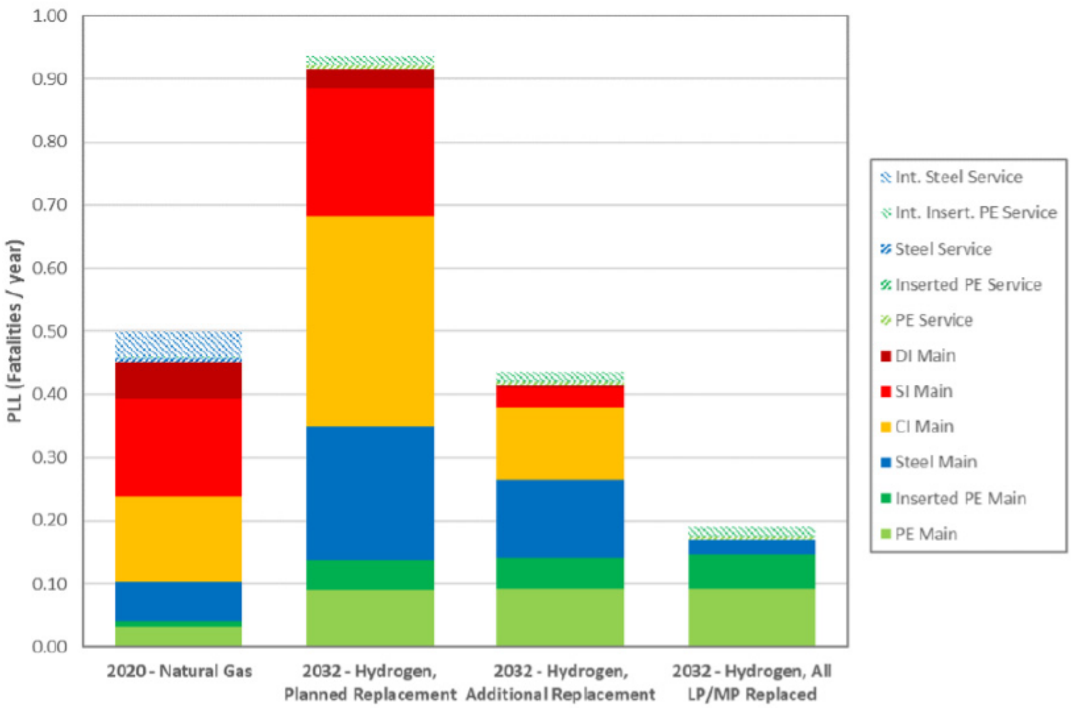
Based on the number of domestic gas meters for the Northern Gas Network (NGN network) versus the Great Britain network (GB network), the potential loss of life (PLL) values for the NGN network were scaled up by a factor of 9 to 11.05 to provide the total risk for the GB network; see reference [16]; this publication is not publicly available. However, this extrapolation of the calculated risks for natural gas and the resulting PLL value is a factor of four higher than the actual value obtained from the natural gas field data. When the same materials, pressures, lengths and number of household customers, data for the large-scale replacement, are connected to hydrogen, a very high, unrealistic value for the PLL comes out.

The resulting social risk, measured as potential loss of life (PLL), is shown in Figure 14 for the current network '2020 - Natural gas', and the network in 2032 transporting 100% hydro '2032 - Hydrogen Planned Replacement'. Figure 13 shows two possible options (mitigation measures) when using hydrogen in existing systems:

- Option 1 - 2032 - Hydrogen, additional replacement, third column in Figure 13 –, [3] (see Section 6.6.3.1) the completion of all currently planned replacement activities in the UK, plus the following: Low-pressure networks made of metal with diameters between 8 and 18 inches will be reduced to 10% of their size by 2020. A further 20% of the metal gas network in all other categories will be replaced, excluding intermediate pressure networks;
- Option 2 - 2032 - Hydrogen, all low-pressure/medium-pressure networks will be replaced, fourth column in Figure 14 - the completion of all planned replacement activities, plus replacement of all remaining metal networks in the LP and MP pressure classes, see [3] (Section 6.6.3.1).

The PLL for the distribution (i.e. this includes only the distribution network and not the transport network, gas meter set-up or indoor installation) of hydrogen in 2032 will be 1.88 times higher than the PLL for natural gas in 2020, based on the probability of an explosion/fire with fatal consequences. Some 83% of the hydrogen risk is related to the metal networks that are expected to remain in the system based on the current replacement plans. The risk mitigation measures studied show that it is possible to reduce the PLL related to the entire hydrogen distribution network to the same or even lower overall risk level than the current natural gas network using credible and practical risk mitigation measures, see columns 3 and 4 in this figure. For an overview of these results, see the following Figure 14.

Figure 14 Estimated potential loss of life (PLL) for the gas distribution system (excluding indoor installation, downstream of the gas meter) in the UK. Four situations have been provided. The first column describes the situation in 2020 – Natural Gas, the current situation. The second column describes the network in 2032 that transports 100% hydrogen with the planned replacement of the old cast iron pipes to be completed by 2032 - Hydrogen Planned Replacement. The third column describes the situation if a significant part of the steel pipe network is also replaced. The fourth column describes the situation if the steel connecting pipes in the low-pressure network are also replaced. Abbreviations used in the legend: Main= distribution pipe; Service line = service pipe or connecting pipe; DI = ductile iron; SI = spun iron; CI = cast iron; Steel = steel.



Other possible mitigation measures in the UK, including the calculated reduction in PLL, could include:

- Moving internal meters - Removing all internal meters and moving them to the outside of the house would provide a PLL reduction of less than 0.01 deaths per year, or 1.6% of the total social risk of the base case. However, this represents a 72.6% reduction in the risk associated with the gas meters;
- Reducing the pressure of the gas network - Reducing the pressure at which a part of the low-pressure network operates would result in a PLL reduction of less than 0.02 deaths per year for the hydrogen network, or 3.9% of the base value. Reducing the operating pressure of the medium-pressure network would result in a PLL reduction of approximately 0.04 deaths per year, or 10.3% of the base value;
- Installing excess flow valves (EFV = gas stoppers) - It appears that 97.8% of the PLL for hydrogen in the distribution network alone by 2032 will be caused by leakages from the distribution network, which would not be affected by excess flow valves (EFV) installed in the gas meter. In other words, gas stoppers have a relatively small effect on the total PLL during distribution, resulting in a reduction of approximately 0.6%. Note that this analysis in H21 does not include any benefit from reducing leakages behind the gas meter, behind the ECV. The risk reduction in houses may be more significant.

Despite the relatively small effect on the total PLL of the distribution network, the decision was made in the UK to apply this additional EFV as an extra safety measure for implementing large-scale pilot projects. This recommendation was made based on the research conducted, as there is still limited insight into the risk of gas accumulation in enclosed spaces (basements) under houses or how quickly this can lead to an explosive mixture. This is because there have only been limited measurements carried out into gas accumulation in basements or crawl spaces under houses, where the gas originates from leaks in the street (see Hy4Heat). It is unclear at what rate an explosive mixture would be created in a basement in the event of a leak, but given the rapid accumulation in other areas, it is estimated that an explosive mixture will also be created quickly in crawl spaces or basements in the event of a leak outside. Here, the EFV is an additional safety measure to prevent leakage from accumulating in pilot projects in urban areas where basement may be present. In addition, the risk of gas leaks that may occur in houses downstream of the ECV (emergency control valve) has not yet been included in the H21 QRA model (CONIFER), which was another reason that this additional safety measure was chosen. See also the justification in Section 8.2. In the UK, a model is being developed that links together the risks both upstream and downstream of the gas meter.

8.6.1.2 Comparison of the UK and the Netherlands

The main difference between the UK and the Netherlands is that the Netherlands has been using plastics in the distribution system for much longer: starting with uPVC (unmodified PVC) at the end of the sixties, then impact-resistant PVC and HDPE in the seventies. In addition, the Netherlands started replacing the old cast iron pipes that were already in use in the town gas era much earlier. This means that approximately 80% of the Dutch distribution network consists of plastic pipe systems. Therefore the QRA model from the UK cannot simply be replicated on this point. In another sub-report of Work Package 1A HyDelta, the QRA model above described with the estimated PLL will be filled in with specific Dutch data about the current distribution network. The first results will be published in the follow-up study HyDelta 2 [1] and can then be compared carefully with the results presented in this paragraph. It is recommended for the Netherlands to set a target deadline for the replacement of old cast iron distribution pipes and their components in the Netherlands, as well as asbestos cement pipes that are present in the distribution network.

Another difference is that in the Netherlands there is a 100 mbar gas connecting pipe in the house up to the gas meter. The emergency control valve is located in this part of the connecting pipe. The pressure present is higher than in UK connecting pipes where the applied pressure is 70 mbar.

A final difference is the positioning of gas meters. In the Netherlands, it is quite common to place gas and electricity meters in one space (the meter box), while in the UK this is highly unusual. In fact, about 50% of the gas meters in the UK are placed outside.

8.6.2 Downstream of the gas meter

8.6.2.1 UK specific

The basic natural gas data were modelled using historical data, and these data were then transformed into basic risk data for hydrogen. In the UK, the kitchen was chosen as this is where the risk is estimated to be the highest in 50% of the gas meter set-up situations, and due to the presence of gas appliances with appliance taps, the different lengths of pipe and the presence of potential ignition sources.

The following historical data for natural gas in the UK has been used:

Table 20: Incident data behind the gas meter for natural gas in the UK over the last 5 years [25]

Year	Fires and/or explosion incidents	Incidents with injuries
2016/17	18	9
2017/18	13	8
2018/19	6	5
2019/20	9	5

In order to predict the risk level for natural gas, the data from Table 20 have been combined with the consequences. Table 21 shows the resulting risk level for natural gas based on the number of predicted incidents (fire and/or explosion with casualties) per year, broken down into type of incident. In total, this amounts to about 9 incidents per year.

Table 21: Possible events/scenarios for natural gas incorporating the data from Table 22 [25]

Type of event	**Predicted number of events per year (GB population)**	**Predicted number of individuals injured per event**	**Predicted number of individuals injured (per year GB)**
Kitchen explosion (5-7.5 vol%)	3.5	0.35	1.2
Kitchen explosion (7.5-14 vol%)	2.2	2	4.4
Kitchen explosion (14-15 vol%)[3]	0	0.35	0
Whole downstairs explosion (5-6.5 vol%, or 11-15 vol%)	1.5	0.9	1.4
Whole downstairs explosion (7-11 vol%)	1.8	5.5	10.1
Total	**9**	**n/a**	**17**

As a comparison, the same exercise is carried out in Table 22, but for hydrogen. The risk levels for hydrogen, as shown in Table 22, are estimated to be higher because of the more far-reaching consequences (damage) of an explosion. For further explanation, see also reference [25] Chapter 9 from page 85.

Table 22: Estimated risk of casualties per event for 100% hydrogen [25]

Type of event	**Predicted number of events per year (GB population)**	**Predicted number of individuals injured per event**	**Predicted number of individuals injured (per year GB)**
Kitchen explosion (5-14 vol%)	20.0	0.35	7.0
Kitchen explosion (14-23 vol%)	2.8	2.3	6.5
Kitchen explosion (>23 vol%)	2.8	7.4	20.4
Whole downstairs explosion (5-13 vol%)	11.4	0.9	10.2
Whole downstairs explosion (13-21 vol%)	0.4	5.5	2.4
Whole downstairs explosion (>21 vol%)	2.0	9.4	18.8
Total	**39**	**n/a**	**65**

The results from both tables predict a high number of incidents. In any case, this is higher than found in reality for natural gas. This is due to assumptions in the input parameters from the computer models used. These models have been calculated without including additional safety measures. These are however possible, as is also described in reference [25] from page 88 ff. The risk level in hydrogen applications is reduced when various risk-reducing measures are applied. This has been taken into account in the models: Installation of excess flow valves (EFV): 1 in the connecting pipe and 1 at the entry to the building (possibly built into smart gas meters). When the model takes into account the application of two excess flow valves applied in the hydrogen basic risk description, this leads to an estimated risk of casualties as shown in table 23. The "Predicted number of individuals injured (per year GB)" drops from 65 to 16, therefore corresponding to the calculated values when applying natural gas which amounted to 17 per year (from Table 22). As a result of the additional measures, the safety level of the hydrogen network is at the level of the current natural gas network. A detailed analysis of incidents that have occurred, the causes and possible mitigating measures can be found in Appendix A of [25].

Table 23: Estimated risk of casualties with hydrogen per year, depending on the event/scenario [25] (page 88 ff).

Type of event	**Predicted number of events per year (GB population)**	**Predicted number of individuals injured per event**	**Predicted number of individuals injured (per year GB)**
Kitchen explosion (5-14 vol%)	18.5	0.35	6.5
Kitchen explosion (14-23 vol%)	0.4	2.3	1.0
Kitchen explosion (>23 vol%)	0.05	7.4	0.3
Whole downstairs explosion (5-13 vol%)	6.5	0.9	5.8
Whole downstairs explosion (13-21 vol%)	0.4	5.5	2.4
Whole downstairs explosion (>21 vol%)	0.03	9.4	0.3
Total	**26**	**n/a**	**16**

8.6.2.2 Comparison of the UK and the Netherlands

The tables above are not available for the Netherlands, as there is no mandatory reporting of incidents downstream of the meter in the Netherlands. However, it is possible to make reasoned conclusions about the PLL. The PLL in the Netherlands downstream of the meter is expected to be lower, because in addition to the traditional materials of copper and steel, multi-layer plastic installation pipes have also been used since the end of the previous century.

It is quite likely that the application of 2 EFVs will also lead to a reduction in the PLL in the Netherlands, to a similar extent as the reduction seen in the UK.

In addition, in the Netherlands it is currently being assumed that hydrogen will only be used in combination with a central heating appliance for heating and hot water, and that the gas installation pipes in the house will consist of a single line to this appliance. With fewer appliances installed (because of electric cooking), fewer appliance taps and therefore fewer pipe lengths for hydrogen as compared to natural gas, it is expected that the risk of incidents in houses will be further reduced.

8.6.3 Conclusion of risk assessment downstream and upstream of the gas meter

Based on the above risk assessments, the following can be concluded: When hydrogen is used instead of natural gas in distribution networks in combination with urban areas (i.e. distribution network, gas meter set-ups and indoor installations), the total risk with hydrogen appears to be slightly higher as compared to natural gas. This is explained in more detail in Sections 8.1 to 8.5. With targeted measures, this risk level can be reduced to the level known for current natural gas networks, see Sections 8.6.1 and 8.6.2 onwards.

It is important to add that in the Netherlands, people are killed every year as a result of carbon monoxide poisoning. In the case of hydrogen combustion, no carbon monoxide is released which would mean no casualties here.

9 Translation into mitigating measures in the UK

This section describes potential control measures, including follow-up research required due to remaining uncertainties surrounding the safety of applying hydrogen in urban areas of the UK. For the Netherlands, a reference is made to the report [1]. The measures here follow a logical sequence: prevention of the occurrence of leaks, detection of leaks, prevention of dispersion and inflow, prevention of ignition and minimisation of consequential damage.

The control measures are aimed at making the risks of hydrogen equal to those of using natural gas, so that the planned pilot projects are safe for the occupants of houses. For the sake of clarity: the pilot projects in the UK do not aim to test additional safety measures. A set of mitigating measures for the roll-out of pilot projects have come about from the QRA models and experiments conducted in the UK. For more details see Appendices A,B and C of [25]

From the WP7 Hy4Heat studies conducted, a general set of measures has emerged that will help ensure that the pilot projects are carried out without increased PLL:

- Ensure that suitable competent staff, procedures and measuring equipment are available for the pilot with regard to: installation, testing, commissioning, inspection and maintenance of the downstream installation and equipment
- Ensure these individuals know how to respond to any hydrogen leakage and emergency situations that may arise
- Install hydrogen detection alarms ‘if the occupants cannot smell the odour’
- For larger ‘light’ properties (up to 100 kW, i.e. >20 m^3/hour), install a conventional interlock system (automatic isolation valve) that cuts off the supply to these premises in the event of a leak.
- Develop arrangements in advance for monitoring health and safety performance during the pilot project, both to ensure safety during the pilot and to fine-tune future safety assessments.

9.1 Mitigating measures for the prevention of leakage

Based on the history and nature of leaks in the distribution and use of natural gas, it is likely that the number of leaks in hydrogen will be the same. The sample taken in H21 confirms this – assets that are gas-tight for natural gas are also gas-tight for hydrogen and vice versa. The PLL for hydrogen distribution can be reduced by taking the following control measures with regard to leaks:

- Hydrogen will not affect the existing natural gas network, there will not be more leaks due to the use of hydrogen as opposed to using natural gas. Diffusion and permeation for H2 is higher than for natural gas, but the volumes remain very small. If the right materials are used, it is possible to keep the policy on maintenance and leak detection unchanged. In the case of hydrogen, the risk from leaks appears to be greater due to the larger volume. That means that more search for leaks could be conducted more frequently in order to reduce the number of leaks and the duration of leaks. Restoring pipes with a higher leakage frequency would also reduce the PLL.
- There are fewer leaks with plastic assets, and replacing pipe materials made of cast iron and asbestos cement will reduce the PLL. In practice, replacement programmes are already underway for cast iron distribution pipes.
- Most leaks in natural gas distribution networks occur in connecting pipes, the meter connections and the internal pipes, usually as a result of work activities. By far the largest proportion of these leaks are detected through odour. Odorization enables gas leaks to be discovered more quickly and action to be taken sooner. This does not reduce the PLL, but timely detection of a leak can prevent further consequences.
- Fittings used in indoor installations that are suitable for natural gas have also been found to be suitable for hydrogen. Here there is no increased PLL and full preventive replacement is not necessary. However, since most leaks occur around the gas meter set-up and indoor installations, preventive checks and possible replacement upon conversion are logical conclusions. In the Netherlands, plastic inner pipe systems have been applied (pipes and fittings). It is recommended that these sometimes entirely plastic systems be tested for hydrogen permeation. Before conversion, each house should be assessed for suitability based on the following characteristics: condition of the indoor installation, GMS (gas meter set-up), presence of room ventilation, gas appliances and the place/space where they are located. Pipes that are no longer used should be capped immediately at the branching of the main pipe. Pipes located behind the GMS should be visually inspected and a tightness test should be carried out. If necessary, repair or replacement work should be carried out if they do not meet the current gas standards as usual for natural gas. In addition, and also after any repair work, a tightness test should be carried out on the installation behind the ECV (emergency control valve).
- Only new hydrogen combustion devices should be used that have been certified by a notified body.

9.2 Mitigating measures for the prevention of dispersion and inflow into other areas

If a leak does occur in the distribution area or downstream of the gas meter set-up, mitigating measures can be taken to prevent and minimise dispersion and inflow into other areas. One important factor here is human behaviour: how does a person respond to the smell/outflow of gas:

- Respond, ventilate (open windows and doors) and close the main gas pipe

- How fast is the person, what is his/her response time?
- No difference is expected in response time for the different gases.

Additional mitigating measures have been proposed in the UK which are also applicable in the Netherlands and will reduce the elevated PLL:

- Lowering the pressure in the low-pressure network decreases the dispersion of gas in case of a leak.
- Excess flow valves stop the gas supply, and therefore the potential dispersion of gas in the event of a leak to an undesirable concentration that can ignite. Most gas leaks remain below the maximum permissible leakage rate, the most significant gas leaks can be effectively nullified by excess flow valves. Supporting research is needed as to whether it is actually necessary to do this upstream and downstream of the meter. In the UK both are applied for the roll-out of large-scale pilot projects (1 EFV upstream of the meter and 1 in the meter). This is done as an additional measure to reduce the indoor PLL risk; also because the QRA models have not yet been finalised. In addition, the risk of such a situation has not yet been included in the existing QRA models. Follow-up research is necessary if the decision has been made to opt for one EFV: what is then the most effective position for this EFV? It is recommended to follow the UK approach for now, reference [25] from page 88.
- By applying new hydrogen smart gas meters with an integrated excess flow valve functionality, the flow rate is limited to a maximum of 20 m^3/h; this reduces the amount of gas that can be dispersed. This is still being further coordinated with the gas meter manufacturers in the UK [44]. The value of 20 m^3/h depends on the setting of the maximum hourly consumption of the gas appliance present. If several appliances are present, this value may be adjusted to 40 m^3/h.
- Relatively small leaks in an enclosed space can lead to a high concentration of gas locally; the mitigating measure is ventilation. Ventilation is an effective risk-reducing measure for the dispersion pattern of hydrogen. Ventilation added to (meter) boxes lowers the concentration inside the box considerably. Houses are already required to comply with current UK building regulations regarding ventilation and installation of appliances. In addition, rooms with gas appliances or large (diameter > 32 mm) or long (> 8 metres) pipes must have ventilation openings with an equivalent area of 10. 000 mm^2 as close as possible to ceiling level and not more than 500 mm below ceiling level.
- During large-scale pilot projects, the installation of gas pipes and appliances in basements should be avoided, as the risks of gas accumulation in basements or crawl spaces are still too uncertain. The risks of gas pipes and appliances in basements have not yet been properly studied. During large-scale pilot projects, attention needs to be devoted to this by implementing control measures (ventilation, sensors, etc.) It is clear that this requires additional CFD and supporting field research. In the limited research conducted so far, gas injections in basements have resulted in the highest gas accumulation in the entire house, probably due to the reduced ventilation factor in combination with the volume of the house above the basement where the gas is able to spread. Whether this is indeed the cause, and what the effective preventive and corrective measures are, remains to be seen.
- The studies carried out in the UK recommend that gas meters should be installed outside of houses. In the Netherlands, this presents a range of practical challenges due to the current typical placement in houses. For this reason, this does not appear to be a feasible recommendation for the Dutch situation.

9.3 Mitigating measures for the prevention of ignition

If hydrogen disperses due to a gas leak, this could lead to ignition. The ignition energy required for hydrogen is lower than for natural gas for virtually every ratio with air, meaning that less ignition energy is needed. In addition, the proportions of gas and air within which a combustible mixture is possible are much broader for hydrogen than for natural gas. Research shows that preventive measures can be taken to reduce the risk of ignition and increased PLL by ensuring that flammable mixtures are not possible. For a sensitivity analysis of the risks of ignition, please refer to Appendix D (page 127 ff) of [25].

- The vast majority of gas leaks are detected through odour, leading to a smell of gas being report. Adding an odorant to hydrogen is therefore an effective way of preventing ignition, as a combustible mixture can be prevented in time before it can form.
- The conclusion can be drawn from the tests with ignition sources that there is little difference in the ignition behaviour of natural gas and hydrogen in principle. It is important to note that hydrogen tends to concentrate first at the top of a room, which means that equipment located at a low physical level in the room will ignite later. If a hydrogen concentration ignites, this is fast and loud in comparison to natural gas.
- No potential ignition sources should be placed near the gas installation. The meter set-ups are already designed to be non-sparking, but it is possible for private individuals to add their own ignition sources. One potential solution would be to raise awareness by providing explanations and possibly marking meter boxes.

9.4 Mitigating measures for minimising the consequences of ignition

The previous sections have outlined mitigating measures that can be used to reduce the probability of leaks, decrease the probability of a flammable mixture dispersing, and reduce the probability of it igniting. During combustion, flue gases and heat are released that can cause pressure to build up in an enclosed space. The concentration of the fuel determines the degree of pressure accumulation in combination with the environment. If the combustion gas cannot escape, the pressure will build up. The most effective measures are aimed at preventing ignition, as described above. If ignition does take place, measures can be taken to reduce the consequences of ignition:

- A room must have a means of venting an explosion, even if turbulent gas is ignited in an adjacent room.
- In practice, progressive ventilation takes place when ignition occurs (a door opens or a window is forced out). As a result, in practice, overpressure will only occur in limited cases inside a house.
- The overpressure can also be reduced in closed rooms such as meter boxes by applying ventilation openings.

9.5 Required follow-up research based on existing uncertainties

From the research that has been conducted and considered here, a series of necessary follow-up studies have emerged concerning the nature and extent, dispersion, risk and consequences of ignition, both upstream and downstream of the meter. This research is partly aimed at validating earlier research, but also at ensuring the correct application and/or extension of the aforementioned control measures.

The recommendations below are not intended to be exhaustive, but have been compiled from the studies included in this work package.

Description	Category	Possible approach
Gather experiential data on the nature and extent of hydrogen leaks including detection, and create statistics to indicate further control measures.	1. Nature and extent	b To obtain a clear picture of the distribution of the size and frequency of hydrogen leaks, an inventory needs to be created (e.g. by removing sections of pipe and examining them in a measuring laboratory) and statistics need to be compiled. During pilot projects and in subsequent major conversion projects, network operators could take on the task of maintaining a database of materials encountered and associated leaks. In the initial period, the frequency of measurements should be higher in order to be able to answer the question of whether hydrogen leakage in smaller leaks occurs in larger quantities. Based on these statistics, future policy regarding maintenance and applicability of materials can be further refined.
Study how hydrogen disperses underground and how it accumulates in crawl spaces	2. Dispersion	Field testing of underground hydrogen leakage with different leak sizes, pressures and soil compositions. Work has started on this; see Knowledge Centre Report [12], reference summarised on pages 2 and 3. In addition, field tests on gas leaks have been conducted from the exterior to the interior of a building, with the following conditions: - how far the leak is from the facade of the building - the depth of gas pipe in the street (lower than the building's foundation?) - unsealed openings in the facade (below ground level), - dispersion in the soil, whereby type of soil and gas permeability of the complete package (soil, foundation, paving, joint) also play a role - Distance of the gas connection within the facade to the GMS (in the building) varies from 0.5 metres to 4-6 metres. In residential constructions, the meter box can also be located in the middle of the building with the gas connection running into the crawl space/basement of the building. Much of the information obtained from studies in the H21 project is not public, but has been included in this report. It is useful to hold sessions with experts from the Netherlands and from H21 to discuss specific questions related to the Dutch situation in order to determine which experiments would be useful in the Dutch situation, regardless of whether or not they are carried out at the

		Spadaedum test site. This also applies to categories 3 and 4 in this table
Study the influence of ventilation on accumulation for different meter boxes and enclosed spaces. In the Netherlands, building codes already apply concerning the air exchange rate; this helps to prevent natural gas accumulation.	2. Dispersion	Field tests with hydrogen provide validated insight into the influence of ventilation in accordance with applicable building regulations. These field trials can be supported with CFD modelling for specific Dutch situations.
Study the most effective placement of gas stoppers	2. Dispersion	Conduct field tests using gas stoppers, as this appears to be a very effective control measure against the dispersion of hydrogen. Study the most effective location for insertion upstream and/or downstream of the gas meter.
Validate the risks of ignition in gas distribution and indoors at various concentrations	3. Ignition	Repeat ignition tests focusing on the Dutch situation with different leak sizes, pressures and ignition sources in distribution networks. These ignition sources can be either equipment (tools) or actions (excavation work) More field research should also be conducted into the ignition sources and the ignition probability for hydrogen mixtures at different concentrations indoors. Examples include burning cigarettes, sparks from equipment (in the meter box: electricity meter, routers, etc.),
Study measures to avoid concentrations higher than 10 vol%	3. Ignition	Explosions (usually deflagration) of hydrogen occur at concentrations above 10 vol%. Most measures should ensure that these concentrations are prevented from occurring. These include 'earth leakage-like' switches for the gas network (gas stoppers, regardless of linkage to LFL sensors) or increased ventilation of the rooms. Another way would be to ignite the hydrogen well before it can form explosive mixtures, for example with a pilot light or catalytic.
Study whether deflagration in one compartment can lead to a local transition from deflagration to detonation (= DDT); and whether this can result in bulk detonation of the gas in the entire compartment	4. Consequence	Local detonation appears to be able to cause bulk detonation by DDT, however, there seems to be limited value in conducting specific research into this. After all, it is the consequential damage that counts, and distinguishing between detonation and deflagration is less important. Follow-up research can focus on the consequential damage of certain degrees of detonation.
Study the consequential damage of fires and explosions; the consequential damage and explosion force seems to be overestimated by models	4. Consequence	Conduct field tests upstream and downstream of the meter: gas stations, domestic environments and enclosed spaces.
Study the risk of flashback in case of leakages	4. Consequence	Conduct field tests on the risk of flashback in the event of leaks and incorporate this into safety work instructions
Study the influence of modern houses on progressive ventilation	4. Consequence	Single-glazed windows in old houses can be the weak link, but in better insulated houses the windows are often more solid (double-glazed). This could increase the pressure build-up in a house, thereby increasing the consequences of an explosion. This effect,

		which applies to both natural gas and hydrogen, could be studied further.
Translate the QRA model from the UK to the Dutch situation and create the corresponding risk profiles and control measures	5. Regulations	QRA modelling of the entire indoor installation, gas appliances and distribution networks (including meter set-ups) is necessary in order to determine the total risks and associated measures accordingly. One of the items to be included is the effect of separating gas and electricity meters.

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11 Appendices

11.1 Work Package 7: Annex: To Site Specific Safety Case for Hydrogen Community Demonstration (IGEM)

Hy4Heat demonstrating hydrogen for heat

Department for Business, Energy & Industrial Strategy

WORK PACKAGE 7

Annex:

To Site Specific Safety Case for Hydrogen Community Demonstration

Annex to Site Specific Safety Case for Hydrogen Community Demonstration – downstream of the ECV

Site Specific Safety Case to be submitted by GDNO

5th May 2021, Final Version 1

PART I

Purpose

This annex has been prepared to support Site Specific Safety Cases (S3C) for hydrogen gas community demonstrations, based on work undertaken by the Hy4Heat programme.

It covers a collection of recommended risk reduction measures for application downstream of the Emergency Control Valve (ECV) and inside the consumers' home or premises associated with such community trials. The measures are proposed for use in initial community demonstrations in order to ensure that the risk should be no greater than those currently experienced by consumers, passing members of the public, and those working on domestic natural gas installations and networks.

The safety risk assessment evidence can be found in the following reports which are published on the hy4heat.info website

- Hy4Heat Safety Assessment Precis
- Hy4Heat Safety Assessment Conclusions Report incorporating Quantitative Risk Assessment
- Gas Escape Magnitude and Frequency Assessment
- Gas Dispersion Experimental Data Analysis & Modelling Assessment
- Consequence of Gas Ignition Data Analysis & Modelling Assessment
- Experimental Testing Reports

The duty holder's Site-Specific Safety Case for the neighbourhood demonstration shall detail any additional risk reduction measures or modifications to these recommendations (with supporting evidence) that may relate to the circumstances of that particular location.

Regulations

The Gas Safety (Management) Regulations (GSMR) shall be used as the overarching guide for hydrogen community trials and provide a suitable framework for dutyholders to develop their Site-Specific Safety Case. However, GSMR does not apply to 100% hydrogen gas networks and cannot be used by HSE to regulate the operators of the community trials. The trials are subject to the Health and Safety at Work Act 1974, the Pipelines Safety Regulations 1996 and the Management of Health and Safety at Work Regulations 1999. As such, the dutyholders are required, as part of their safety management system, to design, produce and follow appropriate site specific and operational risk assessments, so that people are protected against the specific hazards that they have identified. Additionally, the following regulations shall also be used as guides:

- Gas Appliances Regulations – Certification of gas appliances
- Gas Safety (Installation & Use) Regulations - HSE and Gas Safe

Content

The content of this Annex follows the particulars to be included in a safety case of a person conveying gas, as set out in the HSE document 'A Guide to the Gas Safety (Management) Regulations 1996, Schedule 1'. This Annex provides input on those particulars which are relevant to the domestic and 'light' commercial gas systems downstream of the emergency control valve (ECV). For reference purposes it is noted that current deaths from natural gas incidents are less than one per year and injuries are about 20 per year in the UK (GSMR downstream data).

PART II

Particulars to be incorporated into Site Specific Safety Case (S3C) for a hydrogen community trial

General

Description of operation

The Hy4Heat analysis to date has focussed on standard common U.K. building types. A community trial relying on the evidence gathered in this assessment should be confined to the gas properties/operating conditions, pipeline configuration and building layout/typology which the evidence supports, namely:

- Properties that are masonry-built terraced, semi-detached or detached homes of normal types *(whilst the QRA has been conducted for a 'two up, two down' terraced house, the principles can be assumed to be extendable to encompass the additional properties listed)*
- Properties that are compliant *(or made to be compliant)* with current Building Regulations (versions specified below) regarding ventilation and installation of appliances. Minimum levels of permanent ventilation required are detailed later in this document
- Commercial properties, where buildings are similar to domestic, providing the total gas usage (i.e. total usage of all appliances including those used as part of the business) does not exceed 100kW
- Properties that are up to two storeys; but may include for example a basement/cellar and/or a loft conversion
- Properties fed by service pipes with maximum operating pressures of 75mbarg

The Hy4Heat assessment did not include the following building types and so these should not be included in community trials until further risk assessment work has been undertaken:

- Industrial facilities
- Commercial properties with gas usage significantly greater than domestic environment, i.e. installed gas usage greater than 100kW (e.g. sports facility with a swimming pool)
- Houses in multiple occupation, for example blocks of flats or other buildings in multiple occupation
- Any large or prefabricated buildings
- Buildings that do not have continuous natural ventilation in excess of the level specified later in this document
- Buildings that use mechanical (or forced) systems for background ventilation

Regulations and Standards for components and installations

Conversion and installation of all system components shall be in accordance with:

- Gas Safety (Installation & Use) Regulations

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- IGEM Hydrogen Reference Standard (IGEM/H/1) or equivalent hydrogen specific amendments to existing IGEM natural gas standards
- Installed hydrogen appliances must be new appliances (domestic or commercial), certified by a Notified Body in accordance with Gas Appliances (Enforcement), Miscellaneous Amendments Regulations with the use of PAS 4444
- Installed hydrogen smart gas meters must be new meters, certified by a Notified Body (for metrology and safety) and be SMETS2 compliant
- Excess flow valves shall be new and approved to a suitable published standard
- Building Regulations Approved Doc J Combustion appliances and fuel storage systems – *or equivalent regional documentation*
- Building Regulations Approved Doc F Ventilation (2021 draft) – *or equivalent regional documentation*

As and when the following is completed, conversion and installation practices should be brought into accordance with:

- BSI PAS Installation Standard – pipework and ventilation
- Other relevant IGEM standards
- Appropriate standard for mechanical hydrogen excess flow value
- Appropriate standard for hydrogen gas meter with reference to isolation in the event of excess flow

<u>Safety Management</u>

Safety assessment

The key findings from the safety assessment undertaken for Hy4Heat are as follows:

- Although there are differences between natural gas and hydrogen; through correct implementation of a holistic collection of risk reduction measures, the risk of using hydrogen can be made comparable to natural gas
- The consequences of the largest domestic hydrogen leak and subsequent explosion scenario are predicted to be more severe than those of the largest domestic natural gas explosion by the consequences model
- With the key risk reduction measures of fitting two Excess Flow Valves and ensuring adequate ventilation to properties supplied with hydrogen, as considered in the Quantitative Risk Assessment, the predicted likelihood of a largest domestic hydrogen explosion is lower than the predicted likelihood of a largest domestic natural gas explosion

- It is the combination of consequences and likelihood of explosions with the key risk reduction measures that has been evaluated in the Quantitative Risk Assessment and resulted in the conclusion that the risk of deaths and serious injuries can be made comparable

Health and Safety Arrangements

The following risk reduction measures should be put in place for a community trial:

- The following regulations and standards shall be complied with:
    a. Gas Safety (Installation & Use) Regulations
    b. IGEM Hydrogen Reference Standard (IGEM/H/1) or equivalent hydrogen specific amendments to existing IGEM natural gas standards
    c. As and when it is completed, the BSI PAS Installation Standard – pipework and ventilation, and other relevant IGEM standards
    d. All hydrogen appliances must be new (domestic or commercial), certified by a Notified Body in accordance with Gas Appliances (Enforcement), Miscellaneous Amendments Regulations with the use of PAS 4444 including Flame Failure Devices (FFDs) fitted on all appliances
    e. Installed hydrogen smart gas meters must be new, certified by a Notified Body (for metrology and safety), and be SMETS2 compliant
- Excess Flow Valve (EFV) to limit the flow rate to $20m^3/hr$ in the service pipe. This is either to be installed as a retrofit or as part of new installation. The installation of this mechanical excess flow valve should conform to the functionality of the standard ASTM F2138 - 12(2017) (Standard Specification for Excess Flow Valves for Natural Gas Service) or similar publicly acknowledged industry standard. It shall be located in either of the following locations:
    a. In the service pipe itself, or
    b. Immediately after the Emergency Control Valve (ECV)
- Hydrogen gas meter containing an integrated Excess Flow Valve (EFV) to limit the flow rate to $<20m^3/hr$ or set at a lower value that is related and proportionate to the maximum usage of appliances installed within the individual property. Minimum values for the setting of this should be agreed with appliance manufacturers
- Meter connections shall comply with the "Specification for gas meter unions and adaptors" upgraded from the Natural Gas specification (BS 746:2014) for use with hydrogen
- Hydrogen gas meter location: Hydrogen gas meters should be installed outside of the property* and comply with current best practice and BS6400-1:2016. **Where it is inappropriate to install the meter outside the property, then the GDNO shall conduct a full risk assessment for the individual property and ensure that any installation is within two metres of the service pipe entry*

kiwa ARUP

- Ventilation:

  a. Whole property: Rooms with gas appliances or substantial pipework installed should have non-closable vents with equivalent area of 10,000 mm2, located as close to the ceiling level as possible and no more than 500 mm below ceiling level.

     Such vents can most readily be assessed in conjunction with the requirements for the ventilation of new properties 2021 draft of Building Regulations Approved Document F (England or Wales) (or regional equivalent), but with the additional requirement of proximity to the ceiling.

     However, it should be noted that these regulations were not introduced with the intention of controlling the build-up of flammable gas.

     Particular care should be taken regarding:

     - Compliance with undercutting of internal doors in accordance with 2021 draft of Building Regulations Approved Document F (England or Wales) (or regional equivalent),
     - Vents that can be fully closed, either automatically or manually shall not be used. The use of stops to ensure provision of at least 10,000 mm^2 could be considered.
     - Mechanically ventilated buildings are excluded from the trial

  b. Hydrogen appliances in rooms: Compliance with appropriate product ventilation standards (domestic or commercial) is also required and/or manufacturers installation instructions

  c. Hydrogen appliances in cupboards and other appliance compartments (e.g. boilers): All appliances in cupboards shall be vented in accordance with Building Regulation ADJ (England or Wales) or equivalent regional documentation; and exemptions shall not be permitted. Manufacturers' guidance should take precedence if larger vents are required. Building Regulation ADJ Para 1.18 should be followed regarding co-compliance with both ADJ and ADF. In this context, equivalent regional legislation is Scottish Building Regulations guidance document 'Building Standards Division – Domestic Ventilation' and 'Building standards technical handbook: domestic buildings'

  d. Pipework in ducts: All ventilation of pipework in ducts shall be confirmed as complying with BS 6891 Specification for the installation and maintenance of low-pressure gas installation pipework of up to 35mm (R114) on premises

- Internal pipework (downstream of ECV):

  a. Shall be visually inspected where this can be done without disturbance to the fabric of the property and remedial work undertaken where it does not comply with current natural gas standards

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b. A tightness test shall be undertaken to current natural gas standards prior to conversion and subsequently prior to commissioning by a second person. The tightness test shall be assessed in accordance with IGEM/H/1 or other installation standards (e.g. BSI). Where this is not the case, then the pipework shall be replaced to meet current natural gas standards

c. Any cast iron components found during the inspection shall be removed or replaced

- For larger 'light' commercial properties up to 100kW, i.e. where demand is in excess of $20m^3$/hr (expected to be exclusively non-domestic), then a conventional interlock (AIV – automatic isolation valve) system shall be installed in accordance with IGEM UP/2 7.9.8 and associated Appendix 11. This shall cut off the supply to the building in the event of a leak being detected. An excess flow valve shall also be installed to limit peak flow to $<30m^3/h$
- Hydrogen detection alarms should be installed where residents are unable to smell the gas odorant or request such a device
- Same odorant with the same effectiveness must be added to hydrogen as is currently used for natural gas (Odorant NB)
- Each property (meter point) considered within the community trial shall be assessed for its suitability to accept hydrogen according to this guidance. The reasons should be recorded, including properties that have been assessed but deemed unsuitable for the initial community trial
- Householder agreement shall be in place and shall agree to ensure appropriate safety management of appliances and other infrastructure, including maintaining the system and appropriate reporting of incidents throughout the trial period. This should also include any information about the use of hydrogen that is considered relevant

The precise means of implementing these measures shall be site specific.

Competence and training

Existing competent Gas Safe engineers must be upskilled for facilitation of the community trial, including installation, testing, commissioning, inspection and maintenance having undertaken an appropriate training course (and subsequent accredited assessment) for working with hydrogen gas.

Existing competent First Call Operatives with appropriate training in hydrogen gas should be used for responding to any reported incidents.

Monitoring of health and safety performance

During the community trial, data shall be collected to further inform and improve the hydrogen safety management system and procedures.

This should include data and information on:

- The practicalities of conversion especially the location of gas meters and the accurate assessment of building ventilation
- Ease of repair of existing hydrogen pipework carcass and the ability of fitters to render such systems gas tight
- The occurrence and reporting of hydrogen leaks
- Any arising incidents, or near misses, even if below the RIDDOR threshold

This information should then feedback into the safety assessment to enable further refinement, modification and amendments of the assessment to ensure the robustness of the QRA, Site Specific Safety Case and dutyholder safety management systems. This will ensure that the hydrogen gas system still meets the objective of risks being no greater than the existing natural gas system.

Other considerations for <u>initial</u> community trial

- Basements/Cellars – The installation of gas pipework and appliances in cellars should not be permitted as part of an initial community trial
- Appliances – All appliances (domestic and commercial) shall be specifically confirmed by their Original Equipment Manufacturer (OEM) that the appliance has been approved by a UKCA to participate in a hydrogen neighbourhood demonstration. Feedback shall be provided to the OEM on the performance of their equipment
- Gas service pipe upstream of ECV – all service pipes shall comply with the Pipelines Safety Regulations 1996 and current natural gas installation standards and shall be of appropriate and approved material. (In the context of this Hy4Heat assessment, upstream of the ECV, this means that the service pipe shall be a plastic pipe where it is underground. The dutyholder shall be responsible for assessing the site-specific case)
- A detailed method statement shall be prepared for each stage of the installation and commissioning of either a new hydrogen network or repurposing of an existing natural gas network

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11.2 Composition of the Expert and Assessment Group (EAG) WP1A

Table 1. Composition of the Expert and Assessment Group (EAG) WP1A

Name	Employer
P. te Morsche	Alliander
E. Rikken	Alliander
P. Verstegen	Alliander
R. van Hooijdonk	Enexis
W. de Rooy	Enexis
M. Spoelstra	IFV
R. den Hartogh	Westland Infra
S. Buruma	Coteq
J. Jonkman	RENDO
R. Scholten	RENDO
R. van den Brink	Stedin
B. Meijer	n-tra
M. van Agteren	Gastransport
A. van den Noort	DNV
H-J. Fonk	DNV
H. Vlap	DNV
R. v. Aerde	Kiwa Technology
S. Delnooz	Kiwa Technology
P. Postma	Kiwa Technology
K. Pulles	Kiwa Technology
H.J.M. Rijpkema	Kiwa Technology
H. Salomons	Kiwa Technology