# HyDelta

## WP 1C Pipes and indoor installations (components)

D1C.5 question 101 – Risks involved in the use of hydrogen instead of natural gas

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# Document summary

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**Dissemination level**

| Dissemination level | | |
|---|---|---|
| **PU** | Public | X |
| **R1** | Restricted to<br>• Partners including Expert Assessment Group<br>• Other participants of the project including Sounding Board<br>• External entity specified by the consortium | |
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## Summary

A study was recently carried out within the framework of the national HyDelta research programme into the risks related to existing gas installations at domestic gas consumers after the conversion from natural gas to 100% hydrogen.
The study is aimed at gaining more insight into whether additional measures should be taken to ensure the existing safety level of an indoor installation is maintained. Determining the effect of these measures on the risk is not part of this study.

Records of natural gas-related accidents during the period from 2010 to 2020 were also analysed. These records concerns (flash) fires, explosions and carbon monoxide poisoning. When switching to hydrogen, the risk of carbon monoxide poisoning is eliminated. The risk of fire or explosion, on the other hand, may increase.
Information from leak-tightness tests in the field was also analysed - three sources in total - of which the largest source came from 1.4 million gas connections. The analysis shows that 1 to 2% of existing pipe installations are leaking (0.1 - 1 $dm^3/h$), without this causing problems and without this being noticed by the residents.
Pilot projects involving households with a hydrogen installation show that additional technical and organisational safety measures have been or are being taken due to the experimental nature of the projects. In the current pilot projects in the Netherlands, cooking hobs that use hydrogen are excluded.

Using a risk assessment based on the Fine and Kinney model, different scenarios were mapped out in which an incident would lead to injury or death. Each scenario was given a risk index, both for natural gas and hydrogen.

The main conclusions relating to the additional risks involved with switching from natural gas to hydrogen are as follows:

- The probability of carbon monoxide poisoning is reduced from 19.6 affected persons per million gas connections per year (of which 0.37 are fatal)[1] to 0 incidents per year.
- The risk of injury from minor gas leaks remains extremely small.
- The risk of injury in the event of large gas leaks, other than CO poisoning, will increase. At present, the number of injuries is 1.16 per one million connections per year (of which 0.06 are fatal).

Some additional mitigating measures that can prevent major gas leaks and/or adverse consequences are installing an excess flow valve[2] and inspecting the gas pipe installation (visually, for strength and tightness) before switching to hydrogen.

Context of this report
For the use of hydrogen distribution in the energy transition, a safety level is assumed that should be at least equivalent to that of the existing natural gas distribution. This report gives a picture of which risks are greater or smaller with hydrogen, if the set of mitigating measures for natural gas is maintained. For the situations where a risk is greater, the set of mitigating measures for hydrogen will be adapted in order to maintain the level of safety. This report only provides a qualitative comparison of the risks for hydrogen in relation to natural gas, based on the set of mitigating measures such as natural gas: is it higher, lower or equal. In HyDelta work package 1a quantitative research is done into the extent to which risks change and which adapted mitigating measures are effective in those situations.

[1] The Dutch “Onderzoeksraad voor Veiligheid” is estimating these amounts higher.
[2] Excess flow valve or flow restrictor; automatic shut of valve which is closing when exceeding a set gas flow.

# Contents

# 1. Reason

## 1.1 General

This study has been carried out within the framework of the national HyDelta 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

When converting the natural gas network to a hydrogen network, the natural gas in the pipes will be replaced by hydrogen. This means that hydrogen will flow through the indoor pipelines[3] and the combustion appliances will burn hydrogen. If no suitable additional measures are taken in these sections, the safety risk for the user is likely to increase.

## 1.3 Research question 101

This report answers research question 101 from Work Package 1C: Piping and Indoor Installations[4].

The research question is as follows[5]:
Question number HyDelta 101: What are the risks with regard to existing gas installations (at the customer) **after** converting from natural gas to 100% hydrogen?

[3] Piping and installations after the gasmeter.
[4] Other questions in this Work Package are mentioned in Appendix I.
[5] The original question as described in the work package description is: Investigation of risks related to existing gas installations (at the customers) when converting from natural gas to 100% hydrogen. The text has been slightly modified for the sake of clarity.

## 2. Objective

The aim of this study is to determine the risks for the user of the indoor installation and for third parties, after the conversion from natural gas to hydrogen has taken place. These risks are offset against the risks of natural gas.

The aim is to gain more insight into where additional measures are needed when switching to hydrogen, so that the living situation (including mitigating measures) is at least as safe as when natural gas was used.

Note:
This does **not** concern the risks directly related to the **work** involved with converting natural gas to hydrogen.

# 3. Procedure

To be able to answer the research question, a desk study was carried out that has two paths:

The purpose of the first path is to collect the information and knowledge known from (inter-)national studies and pilot projects, compile all the data and translate it to the Dutch situation. An example is collating the results from Hy4Heat and H21 from the UK, Hoogeveen, Green Village, Stad aan 't Haringvliet, and the demo house on the Kiwa site in Apeldoorn, the Netherlands.

The other path is more specifically aimed at using the already acquired knowledge of the risks of natural gas indoor installations as they are observed in the Netherlands (based on standards and practical experience gained during inspections of the indoor installations by Kiwa Technology), and translating that knowledge to determine the risks of using the indoor installations for hydrogen. The translation of the risks from natural gas to hydrogen involved looking at the results of the research study into minor leaks as presented in “Initial inventory of hydrogen outflows in permissible minor leaks” [7] and the findings obtained by DNV GL and shown in “Behaviour of hydrogen in case of leaks in the gas distribution network[6]” [6], as well as other reports.

The implementation of this study was coordinated with an Expert and Assessment Group (EAG). This group consists of participants from the network operators, manufacturers, the installation sector and Kiwa Technology (see Appendix II). In consultation with all participants, the risks of (natural gas distributing) installations were assessed both before and after the natural gas is “replaced” by hydrogen. It can thus be ascertained whether the risk with hydrogen is lower, higher or equal to that of natural gas.

The following risks were considered for both natural gas and hydrogen:

- (flash) fire,
- explosion,
- carbon monoxide poisoning, and
- aggravation of a fire with another cause due to failure of the gas installation.

The risk of suffocation was not considered. In the case of natural gas installations, there are no known cases where a gas leak behind the gas meter has led to suffocation[7].

The study consists of the following sections:
Chapter 4 discusses the data from a large number of minor natural gas leaks in the field that did **not** lead to an accident. This is supplemented with the consideration of the chance that this would have led to an accident if hydrogen was used.
Chapter 5 discusses practical situations that did lead to an accident. It contains records of incidents, fires, explosions and carbon monoxide poisoning for the period from 2010 to 2020.
Chapter 6 uses a risk model to compare several different risk scenarios for natural gas and hydrogen. The Fine and Kinney model is used as the basis and has been adapted specifically for this purpose.
Chapter 7 describes various pilot projects, with a particular focus on the mitigation measures. Unfortunately, no projects were completed to the point that could tell us with certainty that they were effective. Chapter 8 identifies the possible mitigation measures. In chapter 9, the findings are summarised in a final conclusion.

[6] The research results regarding the behaviour of hydrogen can also be used for indoor installations.
[7] Based on collected accident figures from Kiwa Technology BV. More about these figures in section 5.1

# 4. Practical data on minor gas leaks

Three sources of practical data on natural gas leaks were investigated:

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 $dm^3/h$).

## 4.1 Source a: Gas leakage rates, measured during meter replacements

Gas distribution network operators have been replacing traditional gas meters with so-called smart meters on a large scale since 2015. During these meter replacements, technicians check beforehand if there are any impermissible leaks in the indoor pipework. The measurement data collected during these meter replacements are very useful in understanding how often leaks occur in existing indoor gas pipes. That is why this measurement data was requested from four different network operators. This has resulted in a leak tightness database for almost 1.4 million indoor installations with a G4 or G6 gas meter, the typical sizes of domestic gas meters. See Appendix IV. This appendix also presents an analysis of the data. The appendix begins by setting out the method according to VIAG G07. A brief description is provided in the following box:

Leak-tightness measurement method according to VIAG G07 [1].
The gas tightness check is performed based on the pressure drop in the indoor pipe for 3 minutes and comprises two measurements:

1st measurement
The pressure drop is measured in the indoor pipe, including the connection pipes of the gas appliances and the gas valves/shut-off valves in these appliances.

- If the pressure drop is more than 10 mbar, the pipe is rejected (no second measurement).
- If the pressure drop is less than 3 mbar, the pipe is approved (no second measurement).
- If the pressure drop is between 3 and 10 mbar, the 2nd measurement is performed:

2nd measurement
Only the pressure drop of the indoor piping is measured (without connecting pipes and gas valve units), by measuring with closed connection valves.

- If the pressure drops by more than 1 mbar, the pipe is rejected.
- If the pressure drop does not exceed 1 mbar, the pipe is approved.

A total of 1.8% of all indoor pipeline installations were rejected due to gas leaks during the meter replacements, 0.8% of which after the 1st measurement and a further 1.0% after the 2nd measurement. The 1% of installations in the 2nd measurement is caused entirely by leaks in the indoor pipework. Of the 0.8% rejected installations in the 1st measurement, only a small part (estimated at 0.6 percentage points, see Appendix IV) enters the dwelling. The remaining part is discharged directly to the outside air through the gas appliance and the flue gas and/or air supply duct.

Remark: A number of these leaks will have been repaired afterwards. This means that after replacing the 1.4 million meters, the average leakage rate will have improved somewhat. The assumption in this study, however, is based on the situation before the meter replacement work.

To sum up:

- Approximately 0.6% of domestic installations (± 42,000 homes) show a leakage flow rate of 1 $dm^3$ per hour.
- Approximately 1% of domestic installations (± 70,000 homes) show a leakage flow rate of 0.1 $dm^3$ per hour.

Since these measurements were taken without the resident having reported a leak, it can be concluded that, in combination with some calculations and assumptions, a large proportion of existing domestic natural gas pipelines is leaking, without this resulting in an accident.

It is therefore warranted to state that a minor gas leak to the order of 1 $dm^3/h$ will not result in gas accidents.

## 4.2 Source b: Gas leaks in pipelines in the housing stock of housing corporations

Kiwa Technology has inspected residential dwellings for various clients over the years. The inspections concerned checking the gas pipes, sometimes as part of quality inspections of the maintenance carried out on gas appliances, and inspections in response to gas vapour reports from residents. Some of these inspections took place in areas where there was doubt about the state of the indoor installations. The results can therefore turn out worse than those from a random sample taken anywhere in the Netherlands.

A gas leak of 5 - 10 $dm^3/h$ was found on several occasions, or a situation where the pipe was not leaking yet but was about to do so.

On incidental occasions, residents smelled gas but the leak was almost always identified during the preventive inspection and measures were taken. The same applies to the repair work in response to discovering a hazardous situation, such as serious gas pipe corrosion and cracks in gas supply hoses. Despite encountering these potentially dangerous situations, no gas accident (fire, explosion) occurred.

## 4.3 Source c: Accidents caused by minor natural gas leaks

The natural gas accidents registered by Kiwa Technology during the period from 2010 to 2020 (more information is provided in chapter 5) were examined to determine whether any accidents are known to have occurred as a result of minor leaks. The outcome of this investigation revealed that not a single known fire or explosion had been caused by a minor gas leak (maximum 10 $dm^3/h$).

It can justifiably be stated that the probability of a natural gas leak of up to 10 $dm^3/h$ causing a gas-related accident is extremely small.

## 4.4 Risk comparison of minor natural gas leaks and minor hydrogen leaks

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 ignition 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 [8] (worst case) of 1/h with a natural gas outflow of 10 $dm^3/h$, the concentration will

[8] Ventilation rate of a room: number of air changes per hour.

ultimately be just 0.1% gas, only a fraction of the LFL. An explosion can only take place 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 the volume in a standard utility room. (Utility rooms and meter cupboards are designed for much higher ventilation rates.)

The lower flammability limit of hydrogen is 4%. The leakage flow rate will (due to laminar flow) be 1.2 to 1.6 times greater[9] than for natural gas. 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 [2], it is plausible that the probability of an incident resulting from a minor gas leak is not higher for hydrogen than for natural gas. This has therefore been taken as the guiding principle in completing the risk assessment.

This does not alter the fact that there are conceivable situations in which hydrogen actually represents a higher risk. It is impossible to say beforehand whether such situations will occur frequently in Dutch building practice. Further research into the ventilation rate of the current housing stock should provide more insight on the matter. This subject is addressed in WP1A.

## 4.5 Conclusion

In cases of minor natural gas leaks (up to 10 $dm^3/h$), the probability of a gas accident is extremely small. It is plausible that after converting the systems to hydrogen, the probability of an accident remains very small, although the gas release flow increases by a factor of 1.2 to 1.6.

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source [6]: factor 1,3 (related to natural gas)
source [7]: factor 1,6 (related to natural gas)
source [10]: factor 1,2 (related to methane).
In the work package HyDelta WP1C, research was done on question 124 to the ratios between leaks measured with different gases namely nitrogen (similar to air), natural gas and hydrogen at pressures of 30, 100 and 200 mbar. It concerns an investigation into small leaks in the connection pipe of the grid operator (ends in the meter cupboard). When writing this report, the report concerning question 124 was not finalized.

# 5. Practical data from natural gas accidents

## 5.1 Data collected

Kiwa Technology has been registering the gas accidents that occur in the Netherlands for several decades, both in the pipeline in front of the gas meter and behind the gas meter. Trend analyses are conducted annually based on the findings, and the results are reported to the Dutch network operators (see [3] for gas-related accidents in 2020). The aim of recording the data is to learn from incidents and to take measures to reduce the number of incidents.

Kiwa Technology collects this information through media reports, through existing contacts and through research assignments. Wherever possible, the specialists at Kiwa Technology investigate the cause of (serious) gas accidents on site. This is done in only a limited number of cases and only if there is a client.
Kiwa checks media reports with all parties concerned. The reason for this is because the circumstances are often not known at the time of publication and because it often emerges later that the cause is different from what was reported in the newspapers or online media.

Gas accidents behind the gas meter are classified in the categories carbon monoxide poisoning (CO poisoning), explosion (with or without fire) and fire. The number of registered incidents for each year in the period 2010 to 2020 is shown in Figure 1. Figure 2 shows the number of registered victims.

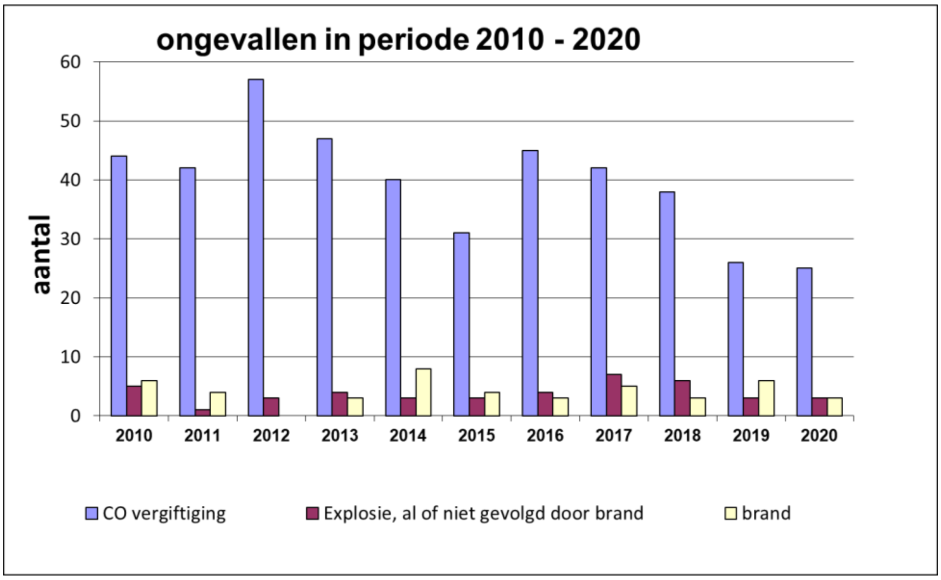


*Figure 1: Gas accidents behind the gas meter by nature of the gas incident: CO poisoning / explosion whether or not followed by fire, and fire. There were 597 incidents in total during this period (Excluding Intent / Theft / Vandalism)*

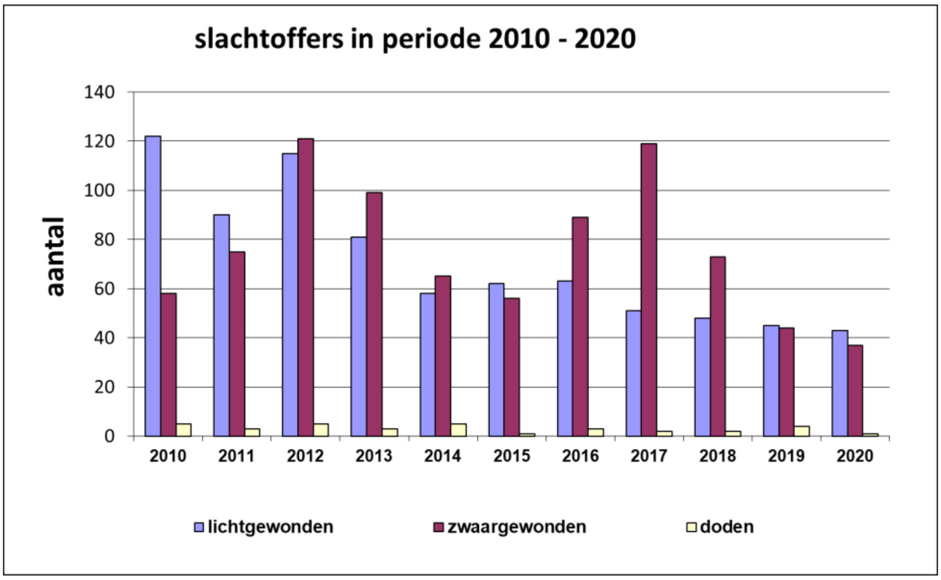


*Figure 2: Victims of gas accidents behind the gas meter during the period 2010 to 2020, as far as known from the data. The totals during this period are categorised as follows: 778 lightly injured, 836 seriously injured and 34 fatally injured (excluding intent/theft/vandalism)*

In addition to gas accidents, Kiwa also records cases where gas is deliberately released. These cases of intent are not included in the aforementioned accident records [3]; intentional damage or injury is not regarded as an accident, after all. This HyDelta report has opted to include cases of deliberate release of natural gas. See Table 1.

*Table 1. Overview of incidents (accidents and deliberate incidents) involving **natural gas** (period 2010 - 2020) translated into an average number per year. Probability per connection (≤G6), related to 7.2 million connections.*

| Type of incident behind the gas meter | Number of natural gas incidents | Probability Incident per connection x $10^{-6}$ | Number of fatalities | Number of people injured | Number of major damage claims #) | Probability of injury or fatality per gas connection x $10^{-6}$ | Probability of an incident involving hydrogen instead of natural gas (estimate) |
|---|---|---|---|---|---|---|---|
| Carbon monoxide poisoning | 39.5 | 5.5 | 2.64 | 138.2 | - | 0.37 (fatality) 19.2 (injury) | nil |
| Fire or explosion (excluding intentional cases*) | 14.5 | 2.0 | 0.45 | 7.8 | 14.5 | 0.06 (fatality) 1.1 (injury) | greater[10] |
| Intent* resulting in fire and/or explosion | 9.8 | 1.4 | 2.18 | 6.5 | 9.8 | | greater [10] |
| Intent* not resulting in fire or explosion) | 4.9 | 0.7 | - | - | - | | smaller[11] |
| **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.

Not all incidents that have occurred will be included in Table 1. This is because not every incident makes the news and Kiwa is often not informed.

When focusing on carbon monoxide accidents, the Dutch Safety Board [4] estimates that the number of victims is considerably higher than the figures provided by Kiwa. The reason for this disparity is that complaints and deaths aren't always related to carbon monoxide and therefore go unnoticed: *"Each year, an average of five to ten people die from carbon monoxide poisoning and carbon monoxide poisoning leads to approximately two hundred hospital admissions and several hundred treatments in an Accident & Emergency ward (A&E). The annual numbers vary greatly. There are indicators that the actual numbers are three to five times higher."*

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.

[10] Large natural gas leakages (intended and unintentional) into a building may occur before it comes to an ignition. This is partly because natural gas is "difficult to inflame" (narrow bandwidth of ignition limits, high minimum ignition energy). Hydrogen has a much larger bandwidth and lower minimum ignition energy. When switching to hydrogen this may increase the risk of fire or explosion. On the other hand, the effect of the inflammation of hydrogen may be less severe because it ignites earlier. The energy density of a hydrogen flame is also lower than that of natural gas. On balance, on the basis of the data, the sources consulted cannot say with certainty what effect is the deciding factor. For safety reasons, this table has opted for "larger".

[11] Of the intentional gas leakages, there is a greater chance of ignition or explosion than with natural gas. If the number of intentional gas outflows with hydrogen remains the same as with natural gas, is therefore the remaining number, that does NOT result in fire/explosion, smaller.

## 5.2 Analysis of gas incidents

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 gas

During the period in question, the number of recorded 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.

Hydrogen brings the risk of CO poisoning to zero as no carbon monoxide is released during combustion. 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 of the Dutch Safety Board, the actual numbers of carbon monoxide deaths and injuries are a multiple of these figures, which works even further in favour 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. 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. Had hydrogen been used in the pipelines, the number of fires and explosions would probably have increased.

# 6. Risk scenarios of natural gas versus hydrogen

## 6.1 The Fine and Kinney risk assessment model

For the use of hydrogen distribution in the energy transition, a safety level is assumed that should be at least equivalent to that of the existing natural gas distribution. In this research it is estimated which risks are greater or smaller with hydrogen, if the set of mitigating measures for natural gas is maintained. For the situations where a risk is greater, the set of mitigating measures for hydrogen will be adapted in order to maintain the level of safety. This examination only provides a qualitative comparison of the risks for hydrogen in relation to natural gas, based on the set of mitigating measures such as natural gas: is it higher, lower or equal. In HyDelta work package 1a quantitative research is done into the extent to which risks change and which adapted mitigating measures are effective in those situations.

It was decided to use the Fine en Kinney[12] method in determining the risks in households due to the method being commonly applied by network operators (for example by the VIAG working group) and because it is also used in the WP1C report, question 187. This is a qualitative assessment, as opposed to the quantitative risk assessment (QRA) used in WP1A. It does have a wider scope than only behind the meter.

The Fine and Kinney determines the **risk index** by assigning a value for the **probability** of the risk, the **frequency of exposure** to the risk, and the **severity** of the adverse event. Each of these aspects is assigned a numerical value. See Table 2. The risk index is calculated with the following formula:

**Risk index = probability x exposure frequency x severity**

To determine the severity, the potential consequence **that can reasonably occur** (worst-case scenario) is used as the basis for an adverse event.

The original method cannot be applied word-for-word to the risk of an existing installation in households, as Fine and Kinney assume risks in a company setting and not in homes, making it a model designed for working conditions. For the purpose of this report, the method has been adapted slightly, as explained below. The result is shown in Annex III.

In developing this table, the researchers first determined the probability, frequency and effects of natural gas. These represent the risk of the existing situation.

*RISK (SCENARIO): adverse event + severity*

When using the term risk in this method, we are referring to a risk scenario. A risk scenario consists of two aspects:

1. an adverse event, and
2. the severity of injury[13] resulting from this adverse event. The injury leads to a numerical value for the effect:

[12] This introduction to the risk assessment method uses the RI&E Gas technical risks (version 2, dated 02-12-2019) as updated by working group VIAG 2019. See for completeness, www.beiviag.nl under 'other documents'.

[13] The method does not include damage but only injury.

### SEVERITY

In Table 2 you can see that the effect of the risk is given a numerical value ranging from 1 (slight injury) to 40 (disaster).

*Table 2: Risk index according to Fine and Kinney*

***Probability of the risk P***

| Value | Description |
|---|---|
| 0.1 | Next to impossible / unthinkable (never heard of it) |
| 0.2 | Almost unimaginable (never heard of it within the industry and sector) |
| 0.5 | Highly unlikely, but conceivable (heard of in the industry, but not in the Netherlands) |
| 1 | Unlikely, but possible in borderline cases (has not occurred in the last 10 years) |
| 3 | Unusual, but possible (has occurred in the Netherlands in recent years) |
| 6 | Possible (has occurred a few times a year in the Netherlands) |
| 10 | To be expected (occurs often/frequently in the Netherlands) |

***Exposure frequency of the risk: E***

| Value | Description |
|---|---|
| 0.5 | Very rarely (once a year) |
| 1 | Rarely (a few times a year) |
| 2 | Sometimes (monthly) |
| 3 | Occasionally (weekly) |
| 6 | Frequently (daily) |
| 10 | Constantly |

***Severity of the risk: S***

| Value | Description |
|---|---|
| 1 | Slight effect: injury without absence (first aid) or inconvenience |
| 3 | Important: injury and absence from work |
| 7 | Severe: lasting injury (disability) |
| 15 | Very severe: one fatal casualty (acute or delayed) |
| 40 | Disaster: multiple fatal casualties (acute or delayed) |

***Risk Index: R=P*E*S***

| Class | Risk Index[14] |
|---|---|
| 5 | $R \leq 20$ |
| 4 | $20 < R \leq 70$ |
| 3 | $70 < R \leq 200$ |
| 2 | $200 < R \leq 400$ |
| 1 | $R > 400$ |

[14] The original table, for working conditions, also mentions an action for each class. These actions are in this situation not applicable as the scores are only used for comparison.

We have taken one of the situations from Appendix III as an example for further consideration:

> **Example 1**
> An adverse event can be: a gas leak due to unintentionally cutting or drilling into a pipe. In this adverse event, we look at two possible effects (one possible effect is generally sufficient in many other adverse events):
> Effect a: Unburned gas escapes from the pipe and ignites, causing a flash fire: one person is permanently disabled as a result. The numerical value for severity S = 7 (Table 2).
> Effect b: Unburned gas escapes, ignites and leads to a house explosion with the following consequence: one fatality. The numerical value for severity S = 15 (Table 2).

*PROBABILITY*

The chance of each of these risks (risk scenarios) occurring is then assessed to determine the numerical value for the probability (P):

- Someone cuts through or drills into a pipe AND a person becomes permanently disabled (effect a). Kiwa knows of at least one such accident with severe burns to the body in the past 10 years. The chance that it has occurred more often is real, considering the fact that similar incidents often don't make the news. We estimate the chance of this happening as "unusual, but possible (has in the Netherlands in recent years), so Probability P = 3 according to Table 2.
- Someone cuts through or drills into a pipe AND one person is fatally injured caused by a gas explosion (effect b). Kiwa is not aware of any real-life examples of this occurring. We estimate the chance of this happening as "Unlikely, but possible in borderline cases (has not occurred in the last 10 years)",
- so Probability P = 1 according to Table 2.

The probability of the pipe being sawn through or pierced, causing gas to flow out freely **without** igniting - and therefore without causing injury - has not been considered in the model.

*EXPOSURE FREQUENCY*

The exposure frequency indicates how many times and how often there are people present at the location where the risk event takes place. In most dwellings, there is often or constantly someone at home; numerical value 6 or 10 (Table 2).
The description "constantly" has been chosen in the elaboration of the risk assessment because, on average over the year, there is always at least one person present. And it goes without saying that if the leak is an immediate result of drilling or cutting, someone has to be present. That is why the exposure frequency E = 10 has been chosen in all risk scenarios in Appendix III.

*RISK INDEX*

The risk index for effect a (permanent disability) due to drilling or sawing in a natural gas pipeline in example 1 is obtained as follows:

Risk index (R) = Probability x Exposure frequency x Severity = P x E x S = 3 x 10 x 7 = 210 (see Figure III, under "Natural gas").

These values were subsequently redetermined for a situation where the gas is not natural gas but hydrogen (see the same figure under "Hydrogen"). This enables us to make a well-founded comparison of the risk index between hydrogen and natural gas. Because hydrogen ignites much more easily, the probability is now estimated to be one step higher, i.e. class 6.

| | | | Natural gas | | | | Hydrogen (in case of no extra measures) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **undesirable event** | **Mecha-nism** | **Severity of the risk** | **Probability of the risk P** | **Exposure frequency E** | **Severity of the risk S** | **Risk-index P x E x S** | **Probability of the risk P** | **Exposure frequency E** | **Severity of the risk S** | **Risk-index P x E x S** |
| leakage causes by sawing/drilling pipe resulting in injury | sawing/ drillig | Flame affects person | 3 | 10 | 7 | 210 | 6 | 10 | 7 | 420 |
| | | Explosion affects person | 1 | 10 | 15 | 150 | 3 | 10 | 15 | 450 |

*Figure 3: Example of determining the risk index for natural gas (yellow) and hydrogen (blue). The complete table is in Annex III.*

### *Note on risk scores*

The risk indices give a distorted picture when they are compared to the VIAG document (see footnote 12).

The risk index in Table 2 range from class 5 (low risk) to class 1 (high risk) in accordance with the VIAG document. The VIAG working group assigns an action to each class. As an example, the following action applies to 200 < R ≤ 400 (class 2): "Immediate improvement required (high risk)". In Figure 3 and Appendix III of this report, the risk scores seem rather high. These scores do give a distorted picture: they do not relate to an individual gas installation but to an average of all 7.2 million household gas connections in the Netherlands.

For one gas connection, the probability of a scenario is therefore 7.2 x $10^6$ times lower. Consequently, the risk index per connection is also 7.2 x $10^6$ times lower.

The risk index is therefore only used in this report to compare the risk of hydrogen with that of natural gas.

## 6.2 Guiding principles for determining the score

Appendix III contains the results of the risk assessment. The guiding principles for determining the risk index were tightened following the EAG discussion on 16 July 2021, and the tables were restricted as finally included in Appendix III. The following principles were used in drawing up these tables:

a. In the first instance, the risk score was determined on the basis of probability (P), exposure frequency (E) and severity of the effect (S) in the current situation, i.e. with natural gas. This is the reference score.
   The risk score was then determined for the scenario that the pipeline installation remains unchanged but is switched to hydrogen, with the same mitigating measures as applied with natural gas (such as adding an odorant). In this scenario, however, all combustion appliances are replaced by hydrogen-compatible appliances, with CE marking and according to the same safety level. By comparing this risk score with that of natural gas, one can see whether the risk involved increases or decreases or remains the same.
b. This means that cooking appliances that use natural gas will also be replaced by suitable hydrogen appliances, although current Dutch pilot projects assume cooking entirely on

electricity.[15] As such, the comparison of natural gas and hydrogen is not distorted by the installation of different equipment and gas pipelines. (The use of electric appliances can still be used as a mitigating measure). Other types of gas appliances, such as gas heaters or gas-fired hearths, will also be replaced by compatible hydrogen appliances.

c. The focus was primarily on the general risk of gas leakage, whether or not followed by a flash fire or explosion, and leading to injury. Material damage is not considered in the method. Another aspect that is considered is carbon monoxide poisoning, which only presents a risk with natural gas.
d. The main pipeline up to the gas meter has been professionally installed in accordance with the applicable regulations.
e. The indoor installation (behind the gas meter) may have been installed:
    e1. In accordance with the regulations
    e2. Not in accordance with the regulations
f. When determining the risk index, the table shows the difference between e1 and e2 and for certain adverse events by indicating whether or not they comply with the regulations.
g. The measures already in place to limit the risks (installation compliance with regulations) have been taken into account to calculate the risk index, unless stated otherwise.
h. The risk probability has been applied to 7.2 million household installations over a period of 1 year.
i. In addition to the figures for natural gas, the change in the risk index is described when hydrogen is distributed.
j. When looking at the risk of aggravation of fires that have another cause, the risk index is not based on the fire as a whole, but only on the degree of aggravation of an already existing fire.
k. The maximum service life of a fixed gas pipe installation is 50 years (NEN 8078); the service life of appliances and flue systems is 15 years[16].
l. The risks of the work carried out by professional installers have not been included. Reference is made to the Health and Safety Catalogue for Network Companies [*In Dutch: Arbocatalogus Netwerkbedrijven]* , relevant standards and company-specific regulations/procedures and risk assessments.

**Example 2**
We have chosen the same adverse event as before: a gas leak due to unintentionally cutting or drilling into a pipe. How do the numerical values change for the scenario with effect a (permanent disability) from Example 1?

The probability of accidentally cutting a hydrogen pipeline is equal to that of natural gas, but the probability of this leading to a flash fire that hits a person is not.
On the one hand, the probability of hydrogen igniting is higher because it has a lower minimum ignition energy and the ignition limits cover a wider range.

[15] When replacing natural gas-fired cooking equipment with electric cooking equipment the risk of large gas leakages decrease. This applies to both cases of intent and accidents.
[16] The starting point is the same for natural gas and hydrogen. In practice, nothing is done with the 50 years / 15 years lifetime. Replacement takes place on the basis of practical data such as visual inspection and leak tightness test: for example, a pipe shows too much corrosion in the crawl space and additionally research has shown that there is little wall thickness left. Or in the case of a device: the device shows too many malfunctions because, for example, the heat exchanger is leaking. Then it may be economically better to replace the device.

On the other hand, the effect of hydrogen igniting is possibly less intense due to its earlier ignition moment. Also, the energy density of a hydrogen flame is lower than that of natural gas.
To be on the safe side, we estimate that the adverse effects are the most serious by stating that the probability of permanent disability after cutting through a gas pipe is one class higher for hydrogen than for natural gas.
Seeing as the risk index for natural gas is 3, the risk index for hydrogen is set to 6.
The exposure value E remains the same at 10
The severity value S remains the same at 7

The risk index for effect a (permanent disability) due to drilling or sawing in a natural gas pipeline in Example 1 is obtained as follows:

R = P x E x S = 6 x 10 x 7 = 420

## 6.3 Substantiation of the scores

The estimations of the probability, exposure frequency and severity are based on available literature (see reference list), the database of accidents managed by Kiwa Technology, and on the decades of experience of the three authors in the field of safety and accidents involving gas installations behind the gas meter. Due to a lack of hard evidence in most cases, they often remain estimates. This definitely applies to the use of hydrogen, for which there is no practical data available at this time. An estimate is made in the present study based on the differences in characteristics between natural gas and hydrogen and based on technical research.

The following choices have been made:

For each scenario, we opted for the following exposure frequency: E = 10 (constantly present), for the reasons explained earlier in section 6.1.

When drafting each of the scenarios, we separated all the possible installation components and subsequently investigated for each component what could reasonably go wrong (adverse event), what the possible causes were and what the consequential injuries could be within reason. This generally resulted in one scenario. In specific cases, two scenarios were developed for a single adverse event (as in example 1).

The **probability** and **severity** of a scenario for natural gas is mainly based on data from the Kiwa accident database and on the authors' own field experience.

The probability and the effect of the same scenario for hydrogen gas is more difficult to determine, as no experience data is available at this point in time. Those estimates have therefore been derived from the probability and severity of natural gas, taking into account the specific characteristics of hydrogen.

The same probability P has been chosen for both gases for scenarios with minor gas leaks, considering the fact that both gases have a very small probability of a gas accident (see section 4.5).

Where bigger leaks occur, the probability P for a specific scenario is always chosen one step higher for hydrogen than for natural gas, as shown in Table 1. For example, P = 0.2 for natural gas becomes P = 0.5 for hydrogen. The reasoning is as follows: For scenarios that involve a major gas leak, the same probability has been chosen as for the release of a large amount of gas, regardless of what type of gas it concerns. The probability of this leading to a particular injury depends on the circumstances:

Factors that can increase the chance of making a particular injury with hydrogen more serious:

- In most situations, the probability of hydrogen being ignited is higher than with natural gas. This is because of the lower ignition limit of hydrogen (4.0% versus 5.9%), because the bandwidth between the lower and upper ignition limit is considerably larger, and because the minimum ignition energy of hydrogen is lower.
- The explosion pressure increases at higher concentrations.

Factors that can reduce the risk of injury:

- Because hydrogen ignites relatively easily, it is harder to produce a large volume of unburned gas.
- Hydrogen dissipates more rapidly because its density is much lower than that of natural gas.

As we cannot predict this probability in a general sense and to be on the safe side, we have opted to classify the risk for hydrogen at one step higher than natural gas in the event of major leaks.

For scenarios involving carbon monoxide poisoning, the key figures are mainly based on the data in the gas accident database. In the case of hydrogen gas, the risk index is obviously 0.

**Example relating to the first line of Appendix III**
**Scenario**
Pipe leak due to unintentional behaviour; hard impact resulting in fire or explosion. The pipe cracks or ruptures. A large quantity of gas flows out, which ignites after some time. The gas-air mixture ignites and an explosion takes place; one resident becomes disabled.

**Natural gas**
*Probability*
This scenario is conceivable. There is no known case over the past decades in which this has led to death. The score is therefore P = 0,5.

*Exposure frequency*
There is (as with every case) one person present, so E = 10.

*Severity*
One person permanently disabled, so E = 7.

*Risk score*
P x E x S = 0.5 x 10 x 7 = 35.

**Hydrogen without additional measures**
*Probability*
One step higher than for natural gas, so P = 1

*Exposure frequency*
There is (as with every case) one person present, so E = 10.

*Severity*
One person permanently disabled, so E = 7.

*Risk score*
P x E x S = 1 x 10 x 7 = 70

## 6.4 Analysis/discussion of risk table results

The risk table in Appendix III shows the following:

- The risk figure for **all** cases of carbon monoxide poisoning changes from risk 450 to 0 after a conversion to hydrogen.
- The risk figure for **all** cases of major leaks increases somewhat from the range 15-1500 to 30-3000 after a conversion to hydrogen.
- The risk figure for all cases of minor leaks remains relatively small: range 5-100 for hydrogen and natural gas.

# 7. Pilot projects: homes with hydrogen

In order to understand which risks are identified, a number of different pilot projects are discussed in this study, together with their mitigating measures. The original reason to include pilot projects in the study (project plan in 2018) was to learn from the gained experience. However, at the time of writing this report, none of these projects have been completed to a level that allows us to assess if they are actually effective. We have opted to still mention the projects, despite their unfinished status. A side note on the mitigating measures in these projects is that very severe measures have been taken due to the still very limited practical experience. It is expected that the severity will be relieved somewhat in the years to come.[17]
In the following sections, a distinction is made between unoccupied and occupied pilot projects.

## 7.1 Unoccupied pilot projects

### 7.1.1 Apeldoorn, Hydrogen Home Alliander/Kiwa

The project concerns a new small house with an attic, including a gas control station and distribution pipes to this house for training and demonstration purposes.

Mitigating measures:

- Automatic safety shut-off valve in the gas supply outside the dwelling. This is closed on activation by:
  - Gas detection in the dwelling (also acoustic signal),
  - Fixed emergency stops inside the home,
  - Portable emergency stops for work carried out on the distribution pipes,
  - Portable emergency stops for teachers.
- Odorisation
- Excess flow valve in connecting pipe
- Periodic inspections

### 7.1.2 Uithoorn

This project was carried out in 14 vacant residential properties. The aim of the project was to gain experience in converting from natural gas to hydrogen with the fewest possible modifications to the existing installation and/or home.

Mitigating measures:

- Gas detection with carbon monoxide detectors that also detect hydrogen.
- Gas detection equipment worn 'on the person' (natural gas and hydrogen)
- Specific components that there were doubts about beforehand were taken from elsewhere in the gas network and tested in the laboratory.
- Leak tightness inspections performed on connections, domestic pressure regulators, gas meters and pipes. Tests were performed with natural gas, nitrogen and helium, whereby the helium step did not show any added value with this test.
- On-site interruption of the gas supply (4 emergency buttons) and remote dial-in facility.
- Pipe sections were closed at times when there was no supervision.
- Ventilation as primary requirement during the conversion.

[17] With the introduction of PE-X for natural gas indoor pipelines, it also went that way in the late 90's. Initially, here a thermal valve and per device a constant flow limiter prescribed. Later these extra measures dilapidated.

#### 7.1.3 Spadeadam, UK

This project concerns Phase 1 of a research study into three purpose-built terraced houses with different floor types as test objects for investigating the flow behaviour of hydrogen. Mitigation measures have not yet been investigated; this will follow in Phase 2 of the study  (see page 89 of [5]).

### 7.2 Occupied pilot projects

#### 7.2.1 Rozenburg

This project was carried out at an apartment building. The mechanical room has both a natural gas boiler and a hydrogen boiler.

Mitigating measures:

- No gas pipes in the building, but an external communal mechanical room.
- Sensors are hung in the mechanical room that cut off the production supply when activated.
- The pipes are inspected/checked for leaks regularly and sensors measure the pressure.

#### 7.2.2 Stad aan ’t Haringvliet (in preparation)

The aim of this project is to connect a large section of the city (600 residential units) to locally generated hydrogen.
Only limited information is available on the mitigation measures.

#### 7.2.3 Hoogeveen, Lochem and Wagenborgen (projects in preparation)

There are plans for pilot projects to supply several occupied dwellings in these three towns with hydrogen. The three projects will also be carried out by different parties. These parties are currently (September 2021) coordinating the mitigating measures to take in order to avoid the impression that there are “safe” and “less safe” hydrogen homes.  HyDelta Work Package 1A is also involved in these projects.

Measures currently under discussion are the following (although other measures can be added):

- construction in the spirit of the natural gas regulations (NEN 1078, NPR 3378).
- periodic inspection of potential leakage sources
- installation of hydrogen sensor with acoustic and optical alarm and follow-up (removal of source).
- instructions for users, surroundings and emergency services
- pre-inspection of indoor pipelines
- modified equipment if necessary
- no cooking hobs on hydrogen
- ensure that the meter cupboard is properly ventilated
- automatic pressure drop test with acoustic, optical alarm and follow-up (removal of source) – and the detection and repair of leaks in the event of a pressure drop during a pressure drop and leak test
- staff equipped with gas and hydrogen detection equipment
- odorisation of the gas
- additional measures in connection with nitrogen (for flushing purposes)

### 7.2.4 The Green Village/TU Delft, Project H2@home (project in preparation).

This concerns an occupied dwelling in a public area, heated with a hydrogen-fired central heating boiler[18]. Information about the project is yet to be made publicly available. H2@home will communication on the project in due course.

### 7.2.5 UK Hy4Heat Community Trial (project in preparation)

After completing an extensive research programme on behalf of the government, the following mitigating measures have been identified for the practical trial [2]. For household connections up to 20 $m^3/h$, these measures include:

- two excess flow valves in series, of which one is inside the gas meter
- a new $H_2$-approved central heating appliance
- a new $H_2$-approved central gas meter
- installation of the gas meter outside the building (if this isn't possible, a customised risk assessment)
- prescribed dimensions of non-closable ventilation in rooms with gas pipes and appliances
- pre-inspection and tightness testing of gas pipes
- replacement of cast iron parts
- same odorant as natural gas
- gas detection if occupants have no sense of smell
- prior assessment of each gas supply point and reporting of findings
- an agreement with the owner or manager at each location regarding the safety of the installation
- competent and trained technicians should carry out the installation.
- all data during this community trial should be collected in order to make further improvements to the system if possible.

[18] the project is being carried out with a subsidy from the Ministry of Economic Affairs, Regulation of National ENERGY Subsidies, Top Sector Energy Subsidy implemented by the Netherlands Enterprise Agency.

# 8. Mitigating measures

The following mitigating measures are useful in the transition from natural gas to hydrogen. A distinction has been made between recommended and optional measures. The link between risk scenario on the one hand and mitigating measure on the other has not been made, as this falls outside the scope of work package 1C (WP1C). This chapter therefore contains a first estimate of what the considerations can be in pilot projects. For further substantiation, elaboration and testing of the effectiveness and necessity of the measures, please refer to the results of WP1A.

## 8.1 Natural gas (current mitigating measures for indoor installation)

The following mitigating measures are already common to stop the release of unburned gas from the indoor installation:

- Odorisation of gas
- Installation (sometimes) of excess flow valves in new connecting pipes by the network operator
- Construction with materials that are certified
- Strength inspection of the pipeline after construction (pressure surge)
- Leak tightness testing of the pipeline after construction
- Ventilation of the meter cupboard
- Installation and maintenance by authorised and qualified fitters (on a voluntary basis)
- Protect plastic and multilayer pipes with protective sleeves

## 8.2 recommended additional mitigating measures

The measures below are specifically intended for the conversion to hydrogen. The assumption is that the mitigating measures that are generally applied to natural gas (section 8.1) will also be applied to hydrogen. Buildings and gas installations will obviously have to comply with the relevant regulations. This is the case for natural gas, but also applies to the application of hydrogen. The specific additional measures are as follows:

- Installation of excess flow valves in all connecting pipes and/or in the home.
- Inspect the strength of the pipeline before switching to hydrogen
- Tightness test of the pipeline before switching to hydrogen
- Visual inspection of the gas pipe to determine its condition and suitability for use with hydrogen. Replace unsuitable or substandard pipes or pipe sections.
- Obligation to have construction and maintenance carried out by recognised and competent installers.
- Protect plastic and multilayer pipes with protective sleeves
- Check the presence of ventilation facilities in the meter cupboard in accordance with the Buildings Decree.
- Inspect the gas tightness of wall penetrations.
- Communication including instructions to occupants/owners/neighbourhood/emergency services on the hydrogen system in the home
- Obligation to periodically inspect the gas pipe installation (e.g. once every 10 years)
- When converting, only use appliances that are specifically certified for hydrogen.
- When converting, check whether appliances not certified for hydrogen are disconnected and whether the indoor installation has been properly shortened and capped.
- Make residents aware of their own responsibility with regard to the meter cupboard, such as not storing goods inside to ensure proper ventilation and the risk of damage to components.

## 8.3 Optional measures

The following optional measures can be considered in pilot projects.

- Installing flushing points near the gas meter and a gas appliance for flushing the line with nitrogen or vacuuming the pipe (the latter requires further research).
- Gas detection (sensors) linked to a central valve (in the meter cupboard): acoustic and optical alarm.
- Additional excess flow valve in the gas meter and/or at each gas appliance
- For cooking hobs: shield the flame or add colouring agent to the gas,
- Cookers only electrical (ban on gas cookers).

After gaining practical experience in the pilot projects and after testing the effectiveness of the proposed measures in a follow-up study, the mitigating measures may be reduced and rolled out on a large scale.

# 9. Conclusions and recommendations

## 9.1 Conclusions

The current annual number of carbon monoxide poisonings is 19.6 persons per million natural gas connections, of which 0.37 are fatal. These figures are based on data collected by Kiwa from its own investigations and from the media. The Dutch Safety Board estimates that the actual numbers are significantly higher. When converting pipes and indoor systems to hydrogen, this probability becomes zero.

The chance of incidents caused by minor leaks is extremely small with natural gas. This depends for a large part on where the gas is released. It is plausible that the probability of incidents with minor leakages is also very small with hydrogen. This does not alter the fact that there are conceivable situations in which hydrogen represents a higher risk. It is impossible to say beforehand whether such situations will occur frequently in Dutch building practice.

In the event of a major leak, the probability of an incident (both accidental and deliberate) is higher for hydrogen than for natural gas, with all other conditions being equal. Mitigating measures that are effective against major gas leaks should also be applied when using hydrogen. For further substantiation, elaboration and assessment of the effectiveness and necessity of these measures, please refer to the results of HyDelta work package 1A (WP1A).

## 9.2 Recommendations

If necessary, do an additional study on the effectiveness of the mitigating measures.

Carry out further research into the risks of minor gas leaks (in the order of magnitude of up to 10 $dm^3$ of natural gas per hour/16 $dm^3$ of hydrogen per hour) in small, poorly ventilated spaces (cupboards and coves up to approximately 250 $dm^3$ ), related to situations that commonly occur in the Netherlands.

# References


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[3] ir.H.J.M.Rijpkema, "Registratie van gasinstallatieongevallen achter de meter; jaaroverzicht 2020," Kiwa Technology, Apeldoorn, 2021.

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[9] Nikhil_Hardy.e.a., "Hy4Heat WP7 Safety Assessment: Gas Ignition and Explosion Data Analysis," Kiwa Gastec UK, Cheltenham UK, Mei 2021.

[10] N.Ryan.e.a., "Hy4Heat WP7 Safety Assessment: Experimental Testing - Domestic Pipework Leakage," H4Heat, 2021.

# I List of questions HyDelta WP1C

The following questions are addressed in this work package.

- Question number HyDelta 187: Research into the safe commissioning and decommissioning of pipeline sections in hydrogen distribution during the conversion to a hydrogen network and the associated costs.
- Question number HyDelta 124: Research into the performance of strength and density tests.
- Question number HyDelta 135: What is the effect of the existing gas network on the quality of hydrogen in distribution and transport? (Such as dust and dirt and THT)
- Question number HyDelta 185: Home pressure regulator: What are the risks if it is not modified?
- Question number HyDelta 101: Investigation of risks related to existing gas installations (at the customers) when converting from natural gas to 100% hydrogen.
- Question number HyDelta 61: How is it ensured that the developments of all components suitable for 100% hydrogen are integrated - in the distribution network (incl. connections), in the indoor installation and in the gas consumption appliances in homes and businesses - so that the entire chain is compatible?
- Question number HyDelta 55: What will a conversion to a hydrogen network look like?

# II List of participants Expert- and Assessment Group (EAG) question 101

*Table 3. Composition Expert- and Assessment Group (EAG)*

| Name | Employer |
|---|---|
| D. Nieuwenhuizen | Stedin |
| H. Smit | Enexis |
| W. Koppenol | Enexis |
| W.R. Nispeling | Alliander |
| R. den Hartog | Westland Infra |
| J. Jonkman | RENDO |
| R. Scholten | RENDO |
| C.H. Hermsen | Hermsen Installatiegroep |
| F. van Gijtenbeek | Henco |
| D. Vroman | Henco |
| F. Vos | Techniek NL |
| R. van den Tempel | Remeha |
| V.M.A. Barendrecht | HSF |
| S. Lueb | Kiwa Technology |
| H.J.M. Rijpkema | Kiwa Technology |
| H. Salomons | Kiwa Technology |

The draft-rapport is also send to the projectleader of WP1A (A. van den Noort)

# III Risk table (3 pages)

| | | | | | Natural gas | | | | | Hydrogen (in case of **no** extra measures) | | | | Hydrogen (**after** extra measures) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Piping material** | **Connection** | **Undesirable event** | **Mechanism** | **Severity of the risk** | **Probability of the risk P** | **Exposure frequency E** | **Severity of the risk S** | **Risk index P x E x S** | **Remarks** | **Probability of the risk P** | **Exposure frequency E** | **Severity of the risk S** | **Risk index P x E x S** | **Risk index P x E x S** |
| All | not appliacable | Leakage of pipe due to unintentional behavior; impacts resulting in fire or explosion. | Breakage, tear | Fire or explosion affects person | 0,5 | 10 | 7 | 35 | Explosion often only leads to material damage. This probalitiy of the risk is especially high if installation is not installed according to regulations | 1 | 10 | 7 | 70 | |
| All | not appliacable | Leakage due to sawing/piercing pipe with injury | Sawing/drilling | Flame affects person | 3 | 10 | 7 | 210 | | 6 | 10 | 7 | 420 | |
| | | | | Explosion affects person | 1 | 10 | 15 | 150 | | 3 | 10 | 15 | 450 | |
| PE, PEX, multi-layer | not appliacable | Leakage of inner pipe (after the gas meter) due to sparks from E-installation in the meter cupboard | Melting | Fire affects person | 3 | 10 | 15 | 450 | Often limited to damage only on the basis of gas and electricity accident figures. | 6 | 10 | 15 | 900 | Applying additional measures (see H8) will lower the risk scores. For a further substantiation, elaboration and assessment of effectiveness and necessity of measures, reference is made to the reports as issued by WP1A. |
| PE, PEX, multi-layer, copper | not appliacable | In the event of an already existing fire elsewhere in the house, the extra risk of leakage of pipe | Melting | Brighter or faster fire*) | 10 | 10 | 3 | 300 | | 20 | 10 | 3 | 600 | |
| mainly copper and steel | not appliacable | Leakage due to corrosion in case of installation in accordance with regulations | Corrosion | Explosion affects person | 0,2 | 10 | 15 | 30 | | 0,5 | 10 | 15 | 75 | |
| mainly copper and steel | not appliacable | Leakage due to corrosion in case of installation **not** in accordance with regulations | Corrosion | Explosion affects person | 3 | 10 | 15 | 450 | | 6 | 10 | 15 | 900 | |
| mainly copper and steel | not appliacable | Leakage at exit locations due to various unintentional behaviors (as a hanging rack or at floor toilet, kitchen and shower) | Corrosion, fatigue | Fire affects person | 6 | 10 | 3 | 180 | | 10 | 10 | 3 | 300 | |
| All | not appliacable | Leakage due to intent/theft/vandalism resulting in fire or explosion | Sawing, breakage, unmounting, etc.. | Explosion affects person | 10 | 10 | 15 | 1500 | see further explanation regarding accident figures | 20 | 10 | 15 | 3000 | |

*) Due to a fire that has arisen elsewhere in the house, the gas pipeline installations can eventually fail. Also fires from outside the house: shed / car next to house / garbage container etc. can lead to house fires. Background information: In 2019 there were an average of 440 house fires per month, in 2020 there were 550 per month.
Source: www.ifv.nl and : www.pricewise.nl/blog/aantal-brandmeldingen-in-2020-gestegen/

| | | | | | Natural gas | | | | | Hydrogen (in case of **no** extra measures) | | | | Hydrogen (**after** extra measures) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Piping material** | **Connection** | **Undesirable event** | **Mechanism** | **Severity of the risk** | **Probability of the risk P** | **Exposure frequency E** | **Severity of the risk S** | **Risk-index P x E x S** | **Remarks** | **Probability of the risk P** | **Exposure frequency E** | **Severity of the risk S** | **Risk-index P x E x S** | **Risk index P x E x S** |
| Steel | Thread (max2")<br>Press connection<br>Metal coupling<br>Welding connection | Leakage of the connection | Various mechanisms; connection leaks gas but connection remains fixed, limited leakage | Flame affects person | 0,5 | 10 | 1 | 5 | It is a limited leakage as it is usually detected in time by the smell | 0,5 | 10 | 1 | 5 | |
| | | | Connection comes loose or breaks, major leakage. | Fire or explosion affects person | 0,2 | 10 | 15 | 30 | | 0,4 | 10 | 15 | 60 | |
| Copper | Compression coupling<br>Solder fitting<br>Pressfitting | Leakage of the connection | Various mechanisms; connection leaks gas but connection remains fixed, limited leakage | Fire affects person | 0,5 | 10 | 1 | 5 | It is a limited leakage as it is usually detected in time by the smell | 0,5 | 10 | 1 | 5 | |
| | | | Connection comes loose or breaks, major leakage. | Explosion affects person | 0,2 | 10 | 15 | 30 | | 0,5 | 10 | 15 | 75 | |
| Polyethylene (PE) | Welding connections<br>Connection with couplings | Leakage of the connection | Various mechanisms; connection leaks gas but connection remains fixed, limited leakage | Fire affects person | 0,5 | 10 | 1 | 5 | | 0,5 | 10 | 1 | 5 | Applying additional measures (see H8) will lower the risk scores. For a further substantiation, elaboration and assessment of effectiveness and necessity of measures, reference is made to the reports as issued by WP1A. |
| | | | Connection comes loose or breaks, major leakage. | Explosion affects person | 10 | 10 | 3 | 300 | | 20 | 10 | 3 | 600 | |
| Multilayer and PEX | Press<br>shear sleeve connections | Leakage of the connection | Various mechanisms; connection leaks gas but connection remains fixed, limited leakage | Fire affects person | 0,5 | 10 | 1 | 5 | It is a limited leakage as it is usually detected in time by the smell | 0,5 | 10 | 1 | 5 | |
| | | | Connection comes loose or breaks, major leakage. | Explosion affects person | 0,2 | 10 | 15 | 30 | | 0,5 | 10 | 15 | 75 | |
| ribbed stainless steel / gasmeter / pressure regulator | Flare connection<br>(anaconda gasmeter) | Leakage of the connection | Various mechanisms; connection leaks gas but connection remains fixed, limited leakage | Fire affects person | 10 | 10 | 1 | 100 | | 10 | 10 | 1 | 100 | |
| | | | Connection comes loose or breaks, major leakage. | Explosion affects person | 0,1 | 10 | 15 | 15 | | 0,2 | 10 | 15 | 30 | |

*) Based on database "Nestor" (Kiwa data); more than 300 reports regarding gas air / gas leakage. These can be leaks on the anaconda, but also in other positions in the meter cupboard.
Nestor is the national method for registering malfunctions and interruptions that all grid operators work with.

| | | | | Natural gas | | | | Hydrogen (in case of **no** extra measures) | | | | Hydrogen (**after** extra measures) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Appliance** | **Type** | **Undesirable event** | **Severity of the risk** | **Probability of the risk P** | **Exposure frequency E** | **Severity of the risk S** | **Risk-index P x E x S** | **Probability of the risk P** | **Exposure frequency E** | **Severity of the risk S** | **Risk-index P x E x S** | **Risk index P x E x S** |
| space and domestic hot water heating | central heating boiler (combi and solo) / tap water heater (geyser) / local heater (façade stove, gas fireplace) / storage tap water appliance (direct fired gas boiler) | limited gas leakage in the appliance due to leaking gas valves | Fire or explosion affects person | 0,5 | 10 | 7 | 35 | 1 | 10 | 7 | 70 | Applying additional measures (see H8) will lower the risk scores. For a further substantiation, elaboration and assessment of effectiveness and necessity of measures, reference is made to the reports as issued by WP1A. |
| | | limited gas leakage in the appliance in combustion air chamber | Fire or explosion affects person | 0,5 | 10 | 7 | 35 | 1 | 10 | 7 | 70 | |
| | | large gas leakage in the appliance resulting in fire or explosion | Fire or explosion affects person | 0,5 | 10 | 7 | 35 | 1 | 10 | 7 | 70 | |
| | | overheating resulting in steam explosion | Fire or explosion affects person | 1 | 10 | 7 | 70 | 1 | 10 | 7 | 70 | |
| | | excessive CO emissions and large flue gas leakage / release of CO with open appliance | Person deadly poisoned | 3 | 10 | 15 | 450 | 0 | 0 | 0 | 0 | |
| | | unstabel combustion | Fire or explosion affects person | 6 | 10 | 1 | 60 | 6 | 10 | 1 | 60 | |
| | | device not suitable for the correct fuel resulting in incorrect combustion | Fire or explosion affects person | 3 | 10 | 7 | 210 | 6 | 10 | 7 | 420 | |
| | | | | | | | | | | | | |
| cooking appliance | cooker/hob/ oven | Limited gasleakage | Person injured | 3 | 10 | 1 | 30 | 3 | 10 | 1 | 30 | Applying additional measures (see H8) will lower the risk scores. For a further substantiation, elaboration and assessment of effectiveness and necessity of measures, reference is made to the reports as issued by WP1A. |
| | | Large gas leakage resulting in explosion | Person injured | 1 | 10 | 7 | 70 | 2 | 10 | 7 | 140 | |
| | | Failure to close gas from the stove resulting in explosion | Person injured | 0,2 | 10 | 1 | 2 | 0,4 | 10 | 1 | 4 | |
| | | Cured gas hose with limited gas leakage | Person injured | 6 | 10 | 1 | 60 | 6 | 10 | 1 | 60 | |
| | | Cured gas hose with large gas leakage resulting in explosion | Person injured | 3 | 10 | 7 | 210 | 6 | 10 | 7 | 420 | |
| | | Melted gasvalve causing limited gas leakages | Person injured | 3 | 10 | 1 | 30 | 3 | 10 | 1 | 30 | |
| | | Insufficient combustion air supply resulting in incomplete combustion and excessive CO emissions | Person injured | 1 | 10 | 1 | 10 | 0 | 0 | 0 | 0 | |

# IV Measured leaks from indoor pipes when changing meters

Gas distribution network operators have been replacing traditional gas meters with so-called smart meters on a large scale since 2015. The fitters who replace the meters must first check whether the indoor pipe is sufficiently gas tight. A procedure for this test can be found in VIAG G07 safety work procedure [1].

The measurement data collected during these meter replacements are very useful in understanding how often leaks occur in existing indoor gas pipes. That is why this measurement data was requested from four different network operators, which is explained further on in the report.

## Leak tightness measurement method

The gas tightness check is performed based on the pressure drop in the indoor piping for 3 minutes[19] and is made up of two measurements:

**1st measurement**
This measurement comprises the indoor pipelines with opened connection valves of the gas appliances. This means that the tightness of the indoor pipe is checked, including the connection pipes of the gas appliances and the gas valves in these appliances.

- If the pressure drops by more than 10 mbar, the pipe is rejected.
- If the pressure drop is less than 3 mbar, the pipe is approved.
- If the pressure drop is between 3 and 10 mbar, the **2nd measurement** is performed:

**2nd measurement**
During this measurement, the connection valves of the gas appliances are closed. Only the tightness of the indoor pipe is checked, without connecting pipes and gas valve units.

- If the pressure drops by more than 1 mbar, the pipe is rejected.
- If the pressure drop does not exceed 1 mbar, the pipe is approved.

## Measurement data

A summary of the measurement data collected from four network operators can be found in Table 4.

[19] The measurement can also be carried out with air. The measurement time is then 4.5 minutes. This amounts to the same as 3 minutes with gas.

*Table 4: Number of rejected indoor installations per meter replacement*

| Gas meter/ network operator | Number of meter replacements | No. of rejections at 1st measurement | No. of rejections at 2nd measurement | Total number of rejections |
|---|---|---|---|---|
| **G4** | **1.326.488** | **9.960** | **13.293** | **23.513** |
| Enexis | 61.812 | 592 | 491 | 1.083 |
| Liander | 246.989 | 976 | 940 | 1.916 |
| Stedin | 1.001.764 | 8.392 | 11.862 | 20.254 |
| Westland Infra | 15923 | unknown | unknown | 260 |
| **G6** | **55.013** | **441** | **629** | **1.070** |
| Enexis | 4.888 | 66 | 47 | 113 |
| Liander | 11.584 | 60 | 58 | 118 |
| Stedin | 38.541 | 315 | 524 | 839 |
| **G10** | **4.750** | **48** | **51** | **99** |
| Enexis | 133 | 1 | 3 | 4 |
| Liander | 1.216 | 15 | 12 | 27 |
| Stedin | 3.401 | 32 | 36 | 68 |
| **G16** | **7.324** | **86** | **82** | **168** |
| Enexis | 618 | 4 | 6 | 10 |
| Liander | 1.755 | 24 | 22 | 46 |
| Stedin | 4.951 | 58 | 54 | 112 |
| **G25** | **2.178** | **13** | **12** | **25** |
| Enexis | 149 | 1 | 1 | 2 |
| Liander | 657 | 4 | 1 | 5 |
| Stedin | 1.372 | 8 | 10 | 18 |
| **GRAND TOTAL** | **1.395.753** | **10.548** | **14.067** | **24.875** |

As gas meters larger than G6 do not generally occur in dwellings, Table 4 has been compressed for G4 and G6 meter replacements. See Table 5. In total, the table covers almost 1.4 million meter replacements, and as many leak tightness inspections.

*Table 5: Rejection of leakage during meter replacements of approximately 1.4 million gas meters*

| Gas meter | Number of meter replacements | No. of rejections at 1st measurement | No. of rejections at 2nd measurement | Number of rejections Total | % of rejections at 1st measurement | % of rejections at 2nd measurement | % total of rejections |
|---|---|---|---|---|---|---|---|
| G4 | 1326488 | 9960 | 13293 | 23513 | 0.8% | 1.0% | 1.8% |
| G6 | 55013 | 441 | 629 | 1070 | 0.8% | 1.1% | 1.9% |
| **GRAND TOTAL** | **1381501** | **10401** | **13922** | **24583** | 0.8% | 1.0% | 1.8% |

Table 5 shows that 10,401 indoor pipes were rejected during the first measurements, and another 13,922 indoor pipes were rejected during the second measurements. As percentages, this comes to 0.8% and 1.0% of the pipes, respectively.

## Analysis

The analysis below attempts to give a clearer picture of the leak size that the measured drop in pressure can cause:

The measured pressure drop is obviously caused by a leak of a specific size. One can determine the leak size if the volume of the pipe is known. The measurement data in this study, however, does not offer any information on the pipe volume. In general, this in the order of 5 $dm^3$. This corresponds to 16 metres of copper piping with a diameter of 22 mm, which is enough to cover the distance from a gas meter at ground level to a domestic central heating boiler in the attic. For a pressure drop of 10 mbar in 3 minutes, the leakage rate is 1 $dm^3$ per hour (see Table 6 under "V=5 $dm^3$"). The same table also shows the leakage rate for a very small pipe volume (0.5 $dm^3$) and a very large pipe volume (50 $dm^3$) for a house.

*Table 6: Leakage rate in $dm^3$/hour as a function of pressure drop for rejection criteria*

| **Measurement** | **Tested pipe section** | **Gas pressure drop rejection criterion (3 minutes*)** | **Leak size depending on content V** | | |
|---|---|---|---|---|---|
| | | | Leakage rate if V=0.5 $dm^3$ | Leakage rate if V=5 $dm^3$ | Leakage rate if V=50 $dm^3$ |
| 1st measurement | indoor pipe, connection pipes and gas valve units | >10 mbar | >0.1 $dm^3$/h | >1 $dm^3$/h | >10 $dm^3$/h |
| 2nd measurement | only indoor pipe | >1 mbar | >0.01 $dm^3$/h | >0.1 $dm^3$/h | >1 $dm^3$/h |
| * The measurements can also be carried out with air. The measurement time is then 4.5 minutes, which is equivalent to 3 minutes with natural gas. | | | | | |

Some of the leaks from the first measurement will be caused by internally and externally leaking gas valve units. This gas isn't released into the home but flows out through the flue. We estimate that this is a quarter of the leaks measured (based on experience of the authors themselves). The remaining leaks (three quarters of the measured leaks) are released into the home. These are leaks in the indoor piping, connection pipes, pipe fittings and/or gas cooker hoses.

It follows from this measurement data that approximately 0.8% of all homes in the Netherlands have an indoor pipe system with a leakage rate of approximately 1 $dm^3$ per hour (some larger, others smaller), of which it is estimated that approximately three-quarters (0.6%) leak into the home.

In the second measurement, a further 1.0% were rejected. These are leaks in the indoor pipework only, excluding the connecting pipes and gas valves of gas appliances. In combination with Table 5, this means that a further 1% of all homes in the Netherlands have a leakage rate of approximately 0.1 $dm^3$ per hour.

## Conclusion

The measurement data shows that a large proportion of existing domestic gas pipes are leaking, without

- residents noticing it (assuming they take action when they smell gas); or
- this leads to an accident.

Order of magnitude of these numbers:

- Approximately 0.6% of domestic installations (± 43,000 homes) show a leakage flow rate of 1 $dm^3$ per hour.
- Approximately 1% of domestic installations (± 72,000 homes) show a leakage flow rate of 0.1 $dm^3$ per hour.

It follows from this that there is only a very small probability of a natural gas accident occurring due to a minor gas leak.