HyDelta 3

WP5a – QRA and Purging

D5a.1 – QRA of hydrogen in the built environment – effect of mitigating measures

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Technology and Safety

☐Activities (e.g. maintenance, purging etc.)
☐Assets
☐Digitalisation
☐End use
☐Gas network
☒QRA

Social aspects

☐Conversion (of the distribution network)
☐Education
☐Social

System and Economy

☐Business Development
☐Production and supply
☐Value chains

Gas Quality

☐Admixing
☐Gas Quality
☐Odorisation

Summary

To assess the risks of using hydrogen in distribution and transport networks compared to natural gas, it is essential to understand the differences in probability and consequence. Within the HyDelta program, the work package 'Hydrogen and Safety' has been established, with the primary objective of:

Mapping out risks related to the behaviour of hydrogen in case of leaks in homes and in the distribution network and defining control measures based on these risks.

For this purpose, a quantitative risk assessment (QRA) was conducted. This analysis compares the risks between the current natural gas distribution system and the potential future hydrogen distribution system and also compares them with other risks in our society. The total risk assessment includes risks arising from leaks in the distribution network and from leaks in homes. Given the approximation of reality, the model provides the individual risk resulting from a fire or explosion. The results of this analysis provide a quantitative basis to assess whether hydrogen distribution poses more risk to society and which measures are most effective in mitigating these risks.

Risks are small, but what does small mean?

The individual risks of hydrogen and natural gas in distribution networks are minimal and remain well below the acceptable $1x10^{-6}$ contour per year. However, public risk perception can vary depending on emotional, normative, and information-related factors. It is important that risk assessments are not only presented with figures but also through understandable methods or comparisons with other risks, to accurately inform and involve the public in decision-making without exaggerated or misleading information.

The calculated risks for using hydrogen in the case-study neighbourhood in the reference scenario without additional risk-reducing measures is ~$0.2x10^{-6}$/year. With the most effective risk reduction measure in this study, this risk is reduced to ~$0.05x10^{-6}$/year. The magnitude of these risks is on the same order as the number of lightning strike fatalities in recent years. Carbon monoxide poisoning fatalities are twice as high compared to the reference situation ($0.4x10^{-6}$/year). Annually, about 10 times as many people die in building fires ($2x10^{-6}$/year) or 25 times as many from accidental drowning ($5x10^{-6}$/year). Road traffic fatalities are about 250 times higher ($50x10^{-6}$/year). Compared to other causes of death, the risk of hydrogen (and natural gas) in the built environment is therefore very small[1].

Even though the risks are minimal, public perception can quickly change due to initial incidents. Therefore, it is important to proceed cautiously when introducing new technology, such as hydrogen in the built environment through pilot projects. Since new technology does not yet have established statistics on its failure, accidents can occur. However, by implementing a large number of extra safety measures at the introduction, the public might also perceive the new technology as inherently unsafe. It is therefore important to understand the magnitude of the risks and the contribution of different measures in reducing this risk.

A calculation of the risks for a case-study neighbourhood provides insight

To gain a better understanding of the relative effects of leaks behind the meter and from the distribution network, this study analysed a representative case-study neighbourhood. This neighbourhood consists of 57 homes connected to a 100 mbar main pipeline via service lines. The 100 mbar network is fed by a steel 8 bar pipeline running through the neighbourhood. The 100 mbar network is modelled in several segments with different materials and diameters. The homes are

[1] Another way to convey the risk of $2x10^{-7}$: the chance is about as likely as flipping a coin and getting heads 22 times in a row.

modelled based on their area and include detached houses as well as semi-detached houses. Additionally, the risk from leaks behind the meter for each home was determined. Based on failure frequencies in homes, it is confirmed that the individual risk for natural gas from behind-the-meter leaks closely matches the (limited) real-world data.

The analysis shows that the individual risk for hydrogen is greater than for natural gas due to more violent explosions, but smaller when the risk of carbon monoxide poisoning is included. Carbon monoxide poisoning is a common consequence of incomplete combustion of natural gas but does not occur with hydrogen due to the absence of carbon. When this risk is included in the comparison, a shift occurs from the reduced risk of CO poisoning to an increased risk of explosions. The total individual risk, given the chosen set of assumptions and without additional measures, is lower for hydrogen than for natural gas.

Different mitigating measures with different effects

The study calculated the effect of several mitigating measures. These measures can affect the likelihood of a leak, for instance, through regular inspection of pipes and equipment, or by limiting the consequences of a leakage. For regular inspection, a distinction is made between an annual check of the installation, with an assumed 20% reduction in the likelihood of spontaneous leakage, and an automatic daily inspection with an 80% reduction in the likelihood of spontaneous leakage. To limit the consequences of a leak, measures such as excess flow valves, sensors whether or not connected to an automatic shut-off valve, or increasing ventilation can be considered.

When modelling the measures, it is assumed that all measures are 100% effective. This means, for example, that excess flow valves always closes when the maximum flow is exceeded, and that every concentration above the threshold value is detected by the sensor at the location where it is mounted. However, when implementing the mentioned measures in practice, one must account for uncertainty in this effectiveness. Some measures lie within the domain of network operators, such as the excess flow valve, while many of the other measures will be installed in the home and are therefore the responsibility of the homeowner. This means that in addition to the estimated risk reduction, the measures each also have their own advantages and disadvantages. The table below lists these advantages and disadvantages for each measure.

Mitigating Measure	**Risk reduction** (% compared to reference value)	**Advantages**	**Disadvantages**
Doubling ventilation in the house	54%	- Effective measure	- Poor controllability - Increases heat demand
Perform annual inspection	19%	- Limited impact on the home - Can be combined with boiler inspection	- Limited effect - Requires many inspections (personnel, high costs) - Adjusting regulations for access options
Installing Automatic Inspection	51%	- Effective measure - Limited impact on the home	- Susceptibility to interference and reliability must be demonstrated
Excess flow valve at the gas meter ($20m^3/hr$)	20%	- Limited impact on the home, not visible - Cheap solution - Also effect in the event of deliberate leaks	- Limited effect - Not yet a standard solution

Excess flow valve between main and service	22.5%	- Limited impact on the home, not visible - Also effect in the event of deliberate leaks and leaks in the service pipe to the meter.	- Limited extra effect compared to excess flow valve at the meter - More expensive, labour-intensive solution
Gas sensor with alarm in the home	31%	- Low-cost, widely accepted solution	- Limited effect - Resident responsible (replace batteries etc)
Gas sensor with automatic shut-off valve in the house	77%	- Highly effective	- Conceptually, not yet on the market. Susceptibility to interference and reliability must be demonstrated - Privacy issues (being able to close remotely)

Finally, it is noted that the purpose of this study was to provide a quantitative basis for the risks of hydrogen in the built environment and to explore the effect of mitigating measures. The goal is not to impose mitigating measures. Each of the additional measures will require extra costs. Therefore, the described advantages and disadvantages of the individual measures must be weighed for each situation. In addition, it is important to gain experience with hydrogen as an energy carrier for the built environment in pilot projects over the coming period and to further investigate the effectiveness of measures.

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1 Introduction

Hydrogen can be used as a clean alternative to natural gas, both for heating and hot water production for households, and for providing energy to businesses. To integrate hydrogen safely and efficiently into the existing infrastructure, it is crucial to thoroughly identify and manage the associated risks.

In the HyDelta program, the work package 'Hydrogen and Safety' has been defined with the main objective as follows:

> *Identify risks related to the behaviour of hydrogen in case of leaks in houses and in the distribution network, and define mitigating measures based on these risks.*

To estimate the risks of hydrogen in the Dutch distribution network, a quantitative risk analysis (QRA) has been conducted. This analysis compares the risk between the current natural gas distribution system and the future hydrogen distribution system. This analysis provides a solid foundation to assess whether hydrogen poses more risk to society and which measures are most effective in reducing these risks. The results of such analyses are essential to ensure the safety of hydrogen use in the built environment and to strengthen the public's confidence in this new technology.

The total risk in the analysis consists of the risk arising from both leaks in the distribution network and within the home itself. The results of such an analysis provide a quantitative basis for whether hydrogen distribution poses more risk to society, and if so, which measures have the most impact on reducing this risk. A commonly used measure for the risk of a hazardous activity is the 1×10^{-6} contour, which means that the chance of a fatal accident within a certain area around the activity is equal to 1×10^{-6}, or one in a million, per year. This is generally considered an acceptable or negligible risk according to some standards or guidelines.

The QRA model developed by DNV for a similar analysis in the United Kingdom forms the basis for this analysis. To identify the risks related to the behaviour of hydrogen in case of leaks in houses and in the preceding distribution network, and to define mitigating measures based on these risks, the schematic approach shown in Figure 1 is used. This approach recognizes two processes: a vertical process in which recommendations are made through a quantitative risk analysis to achieve an acceptable risk, and a horizontal process aimed at improving the risk model for the given situation.

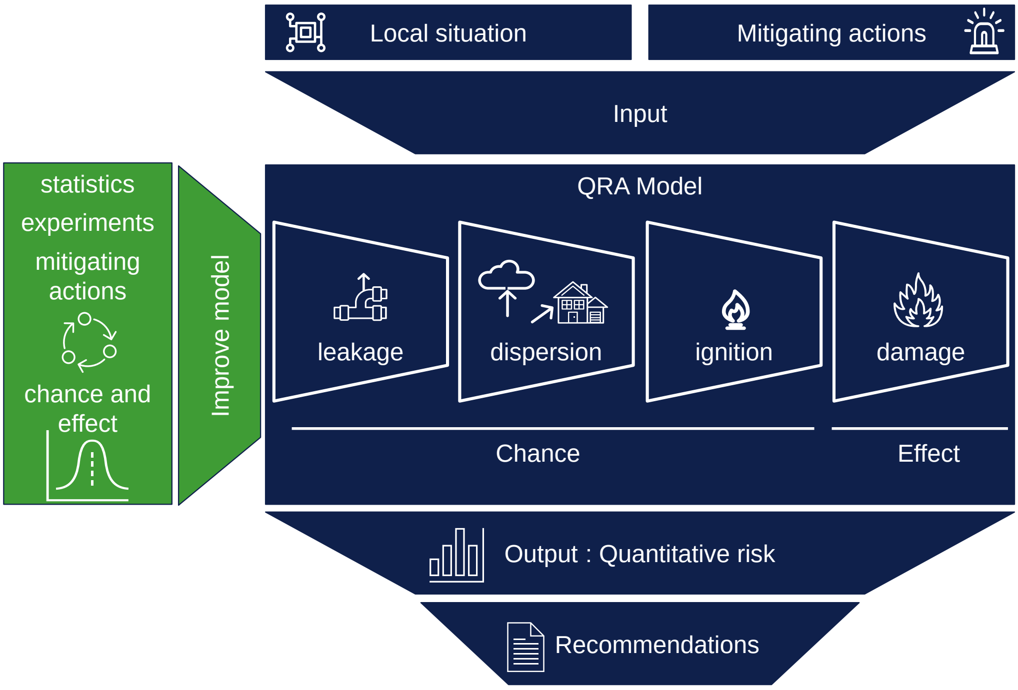


Figure 1 Model-based approach to quantitative risk analysis.

Logically, before the model can be applied, it must be adapted to the given situation in the Dutch hydrogen distribution network.

The original model was developed for the situation in the United Kingdom (UK). Based on the model input, such as failure frequencies and characteristics of the network and buildings, the risk for natural gas (the number of expected casualties) was calculated. This risk for natural gas has been validated based on historical data. To demonstrate the applicability of such a model to the Dutch situation, an initial effort was made in the first phase of HyDelta to translate the model to the Dutch situation. The focus was primarily on the components that have a significant impact on risk and that clearly differ in the Netherlands compared to the UK situation [1]. In the second phase of HyDelta, the model was further translated, and the outcomes were validated against historical statistical data available for natural gas (failure data). For several situations, the risks for both natural gas and hydrogen were determined. Subsequently, the specific cause of increased risks was identified, and the impact of mitigating measures could be estimated using the model [2]. In the current phase of HyDelta, the effect of mitigating measures is further elaborated.

1.1 Preconditions of the model

The model developed in HyDelta considers the gas distribution system for pressures up to 8 bar(g), as operated by regional network operators. The regional and high-pressure transport network of Gasunie is outside the scope of this analysis. Specifically, the model focuses on the following points:

- Mains in the distribution network
- Services between the main pipeline and the meter connection in the house
- The indoor installation in the house from the meter cupboard to the boiler

The model is based on the composition of the Dutch distribution network, with various pressure regimes, material types, diameters, and lengths, as well as the failure data of recent years for the natural gas network.

1.2 In this report

In this report, an analysis is carried out using the quantitative risk analysis model for the effects of mitigation measures on the risks of hydrogen in the Dutch distribution system and thus builds on the report of HyDelta 2. [2]

In Chapter 2, a summary is provided of the operation of the model and the implementation of the mitigating measures therein. For the analysis of the effects of these measures, the case-study neighbourhood [2] is used as an example of a typical residential area with a representative hydrogen network (with common materials, pressures, and diameters). Chapter 3 provides a summary of the outcomes of the risk calculations as determined in the previous phase.

The effects of the mitigating measures on the risk in the district are described in Chapter 4. To discuss the results of the model, Chapter 5 describes the effect on other types of housing. Chapter 6 places the results in a broader perspective regarding risk perception compared to other risks. The findings of the report are summarized in the conclusion in Chapter 7.

2 QRA model

2.1 CONIFER

DNV has developed a standardized method called CONIFER for risk analysis of the gas distribution network. This model, originally for the gas network in the UK, has been adapted for hydrogen transportation systems as part of the H21 project [3, 4]. The model uses incident data, measurement data from experiments (Spadeadam), and validated model data, which have been developed further in modules within a software package. The model uses input parameters such as materials, gas pressures, diameters, gas types, leakage causes, physical phenomena, indoor installation setup, and housing compositions. The results are translated into individual and group risk levels, including the effects of explosions and fires. In HyDelta 1 and 2, the existing model from the UK was translated to the Dutch situation. Below is a brief summary of how the model works. A comprehensive version of the operation and assumptions used in the QRA model for the Dutch built environment can be found in [2].

The CONIFER software package is continually adjusted to add new functionalities and refine underlying models. These refinements can result in differences between the outcomes of different versions. The majority of the calculations in this report were performed in version 8.0.8.39. This version provides similar results to those in the report from HyDelta2 and offers the capacity to calculate most mitigating measures. For varying the capacity of the excess flow valve, a newer version of the package (v8.0.9.16) was partly used.

2.2 Leaks in the gas distribution network

The main input parameter for the model is the failure frequency of the mains and services. These are determined for the Dutch situation based on the statistics of failures as monitored in the NESTOR database. For the frequency of leaks in the indoor installation, in the absence of Dutch statistics, data from the UK is used[2]. Based on the failure frequency, leak sizes, and network structure, the frequency and probability of different leak sizes are established (see [2]). The outflow rate is determined by leak size, gas pressure, ground cover, and surface layer. The model simulates the behaviour of gas flow through different soil types and spaces. It distinguishes between outflow to the open air, which can lead to fire, and underground movement to enclosed spaces, which can result in explosions after ignition.

The model takes into account the effects of both fires and explosions. The effects of explosions are extensively described in HyDelta2. In addition, this report describes how fires resulting from leaks in the distribution network are included in the risk calculation. Fires can occur outdoors as a result of ignited escaping gas from a main or service. The thermal radiation is predicted in the vicinity of the fire, taking into account variations in distance from the release point and wind direction. Many leaks, including pipe breaks, result in an outflow rate that decreases over time. For this outflow, radiation predictions are made at different times to account for the decreasing size of the fire.

The vulnerability of people outdoors is calculated based on the thermal dose they receive. In this calculation, it is assumed that people move away from the fire at a speed of 2.5 m/s, and the calculation takes into account the decreasing thermal radiation as they move further away from the fire and as the size of the fire decreases over time. Depending on the amount of thermal radiation (thermal dose), the probability of fatal injury is calculated.

[2] During a (smart) meter replacement, a leak-tightness test is conducted as standard. More statistics may be available at the network operators but was not available at the time of model creation (in HyDelta2). Additionally, the data used aligns with the number of casualties from natural gas, thereby validating the model.

For residents in houses within the predicted ignition distance, it is assumed that 90% can leave the house at the moment of ignition. These people receive a thermal dose while trying to escape, and their probability of becoming a fatality is calculated in the same way as for people who were initially outdoors. For the remaining 10% of residents, it is assumed that they cannot leave the house, leading to fatal casualties.

2.3 Leaks behind the meter

For leaks in the indoor installation, a simplified scheme is used. The failure probability of the meter installation, the indoor piping, and the end-user equipment is determined based on historical data from the UK. The amount of gas entering the house, and the probability of a flammable mixture are determined by the leak size and the ventilation rate of the space. The probability of ignition is estimated based on the presence of ignition sources and the duration of the presence of people. The formation of flammable mixtures in the pipe due to (prolonged) gas stagnation is not included in the model.

2.4 Implementation of mitigation measures

In this study, several mitigation measures are considered:

- Ventilation in the home
- Increased inspection of the indoor installation
- Excess flow valves
- Gas detection through sensors.

The implementation of these measures in the model is discussed below.

2.4.1 Ventilation

In HyDelta 2, the ventilation rate in a space was identified as a significant factor in determining the risk of an explosion. Increasing the ventilation rate can eliminate the possibility that a particular leak leads to a flammable gas-air mixture, or at least limit the concentration that can be reached. Furthermore, the time required to reach a concentration of flammable gas in the air increases as the ventilation rate increases. Enhancing the ventilation rate in buildings, especially in areas where gas meters or gas appliances are located, is a potential risk mitigation measure.

The CONIFER model offers the possibility to increase or decrease the reference ventilation rate by a factor. The reference value corresponds to a ventilation rate of 0.8 per hour and is validated based on measurements of the test houses in the H21 project at DNV in Spadeadam (UK). No crawl space has been included in the modelling of the houses.

2.4.2 Increased inspection

At present, gas pipes and equipment in homes are generally not inspected after initial installation. There are opportunities to detect or prevent some leaks, such as during meter readings or while maintaining boilers or meters. However, meter readings are increasingly automated, and not every boiler is regularly maintained. Moreover, pipes and other equipment are rarely inspected until there is a malfunction.

During the transition from natural gas to hydrogen, it is expected that every connection will be inspected to ensure that they meet specified standards. The pipework will be checked, a gas-tightness and leak test will be performed, and parts will be replaced if necessary.

In some cases, these measures can detect problems and prevent potential leaks before they occur. One could argue that some of these effects are temporary, as only leaks that would occur in the next few years would be prevented, and failure rates would gradually increase as the equipment starts to deteriorate. However, some of these effects would be permanent if problematic pipes or appliances are replaced.

Failure statistics in the UK show that most spontaneous leaks in homes can be partially prevented by regular inspections. This does not mean that all defects or potential problems would be detected in practice. In the model we assume that 20% of spontaneous leaks[3] could be prevented with an annual inspection of the gas meter installation and internal pipes after the conversion to hydrogen. High-frequency inspection, for example, through daily automatic pressure drop measurements over the internal pipework, could prevent a larger portion of spontaneous leaks. To estimate the effect of this measure, it is assumed that the frequency of spontaneous leaks in the internal pipework and meter setup would be reduced by 80%. Note that the assumed reductions in the frequency of spontaneous leaks are estimates.

Additionally, it is likely that during the transition from natural gas to hydrogen, end-user appliances will be replaced, with additional safety features such as flame protection being installed. These types of features are expected to be standard in hydrogen appliances, but they are not present in all natural gas appliances currently in use (although they are often in new natural gas appliances). This study assumes that 50% of spontaneous appliance failures can be prevented by design improvements and additional safety features. Leaks caused by third parties (interference) are not affected by these inspections. The reduced failure rates with better inspection are shown in the table and figure below.

Table 1 Failure probabilities per connection per year, behind the meter (source: H21).

Failure probability per connection per year	**Interference**	**Spontaneous**	**Spontaneous at annual inspection**	**Spontaneous on daily inspection**
Gas meter	2.040×10^{-3}	5.720×10^{-3}	4.576×10^{-3} (-20%)	1.144×10^{-3} (-80%)
Internal piping	1.460×10^{-3}	4.810×10^{-3}	3.848×10^{-3} (-20%)	0.962×10^{-3} (-80%)
Gas appliance	0.916×10^{-3}	3.370×10^{-3}	1.685×10^{-3} (-50%)	1.685×10^{-3} (-50%)

[3] Spontaneous damage refers to damage without direct human interaction. This could include, for example, the failure of couplings or corrosion. Third-party damage or external interference is caused by human interaction, such as excavation damage where a pipe is accidentally hit.

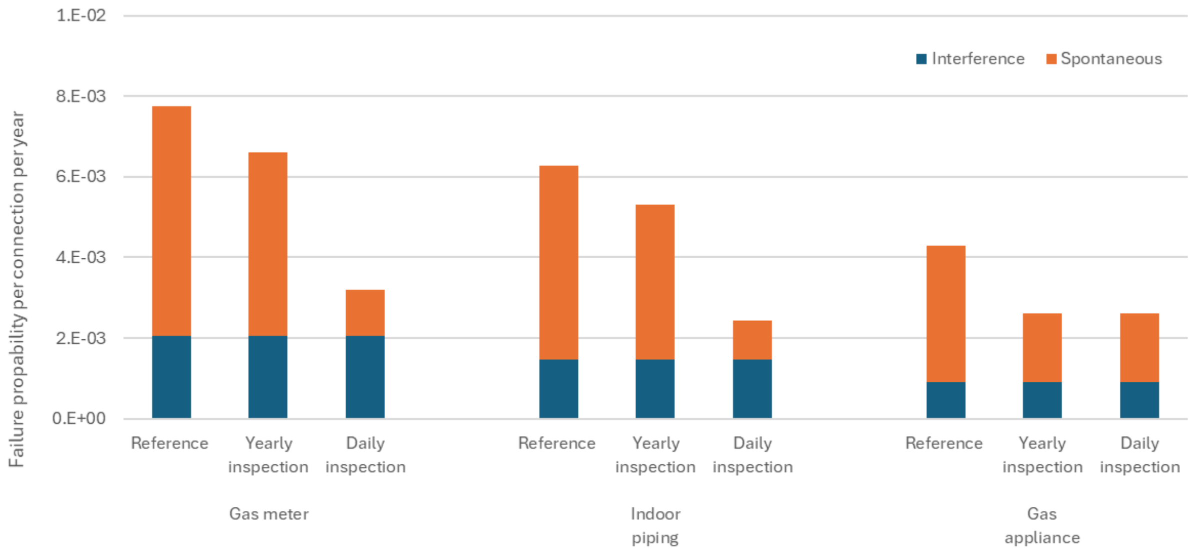


Figure 2 Failure probabilities per connection per year, behind the meter (based on UK data) and assumed reduction as a result of increased inspection (HyDelta assumptions).

2.4.3 Excess flow valve

An excess flow valve (EFV) is a component installed on a gas pipeline that stops the gas flow above a set rate. This valve is used to shut off the free flow of gas in case of a leak or accident. Several studies in the UK recommend a maximum flow rate for hydrogen of 20 m³/hour. This roughly corresponds to the maximum consumption of all gas appliances in a house, and a higher flow rate is often caused by a leak. The values recommended by this research are implemented in the QRA model for excess flow valves[4]. Two possible locations for the EFV are considered: just before the meter in the meter cupboard and at the connection of the service pipe to the main. In the first situation, the EFV will only intervene in leaks in the indoor installation, while in the second situation, leaks in the service are also taken into account.

In the model, the use of end-user equipment can influence the closing of the excess flow valve. If the EFV is set for flow rates above 20 m³/hour, it is possible that leaks with flow rates below 20 m³/hour will cause the EFV to close if other appliances are using gas at the same time. For example, a household boiler that runs on hydrogen consumes an estimated 7 to 10 m³/hour. Therefore, a leak releasing more than 13 m³/hour would result in a total flow of more than 20 m³/hour through the meter if a boiler with a hydrogen consumption of 7 m³/hour is in operation at that time. This would result in the EFV closing.

It is assumed that 25% of leaks between 12 m³/hour and 20 m³/hour will cause the EFV to close. This is based on a boiler using gas with a capacity of 8 m³/hour, with central heating in a house in use for 6 months of the year, and the boiler operating half the time. This period is 25% of the total time. The use of the boiler for hot water supply is neglected in this assumption because the time during which the boiler is on for this purpose is relatively short.

2.4.4 Gas detection by sensors

Gas detection installed in homes has the potential to increase the likelihood that a gas escape is detected, without relying on a person to smell the gas, and also to shorten the time needed to take mitigating measures. In the reference situation, it is assumed that the gas is odorized.

[4] A newer version of the model gives an option to set the capacity of the gas stopper yourself (see 2.1)

In CONIFER, the probability that a leak is detected is calculated for intervals of 15 minutes in the period of 24 hours after the start of the leak. The probability that a leak is detected depends on the number of people in the building and the time of day. Residents are most likely to detect a leak between 9 am and 9 pm, when they are likely to be awake and active, and least likely between midnight and 6 am, when they are likely to be asleep. Thus, a leak that begins at midnight is unlikely to be detected before 6 am, increasing the likelihood that flammable concentrations will form before the release is detected.

When a resident detects gas, they can report it by calling the emergency number. In the CONIFER model, 90% of people report detected gas within an hour, 5% of people report detected gas after more than an hour, and 5% never report detected gas. When a resident reports a leak, they are advised to ventilate the property and shut off the gas valve. Based on survey data from H21, 44% of people take both actions, 16% only shut off the gas valve, 12% only ventilate the property, and the remaining 28% take neither action. The emergency service arrives after the leak is reported. The probability of its arrival in each 15-minute period is derived from NGN (UK) data based on many thousands of reports[5]. The emergency service will ensure that the gas supply is shut off and the property is ventilated if the resident has not already performed these actions.

A simple option is to install a gas detector with an alarm that goes off if gas is detected. This would work similarly to smoke detectors or carbon monoxide detectors that are already common in homes. Two cases are considered:

- In the first case, it is assumed that an alarm increases the probability of gas detection to 100% when there is at least one person in the house, but that it has no further effect. In some cases, the resident hears the alarm but still waits before reporting the presence of gas, or does not report it at all, as described above.
- It is possible that an alarm triggered by a gas detector reduces the time before a resident calls the emergency number. For example, the resident would not need to ask if other occupants also smell gas. To investigate this, in the second case it is further assumed that 90% of residents call the emergency number within 30 minutes, instead of 1 hour in the baseline scenario.

When the technicians arrive at the property, it is assumed that they shut off the gas supply and ventilate the property. This does not account for the possibility that the property is unoccupied when the technicians arrive, and that they are unable to enter. In this situation, it is also assumed that an alarm goes off inside the house and the resident responds as described above.

Finally, gas detectors could potentially be configured to shut off the gas supply without human intervention when they detect gas. Shutting off the gas supply due to a false alarm can cause inconvenience to the occupants of the property. Therefore, it is assumed that this only happens if the concentration is higher than half of the LFL. These calculations also assume that an alarm goes off in the house. This option would also result in the supply being shut off if the leak originates from the distribution network rather than the indoor installation, without then repairing the leak. However, in the model, the indoor installation is modelled separately from the outdoor installation. Thus, the effects of this measure in the model only apply to leaks in the house.

2.5 Validation of the model for natural gas

In HyDelta 2, the model was validated for natural gas without additional mitigating measures. The statistics for the occurrence of leaks were used, and the results for both natural gas leaks in indoor

[5] The assumptions from the UK have been programmed into the model and cannot be easily adjusted. In the Netherlands, the emergency number of the network operator is usually called. They determine whether the fire department needs to be alerted. The procedure is similar to the situation in the UK. Therefore, we assume that we can use the same settings as the UK in the model.

installations and in the distribution network were calculated and compared with historical data in the Netherlands.

The model for leaks in indoor installations indicates that the probability of an explosion per year is approximately once per two million gas connections (1.8 x 10^{-6}). Based on the concentration of the gas during an explosion and the corresponding force of the explosion, the probability of injury or death is determined. These probabilities are shown in Figure 3. The model calculates that roughly half of the explosions will lead to at least injuries, and about 8% have the force to cause fatalities. When the presence of persons in the house is included, this results in an average individual risk of over 0.02 x 10^{-6} per year.

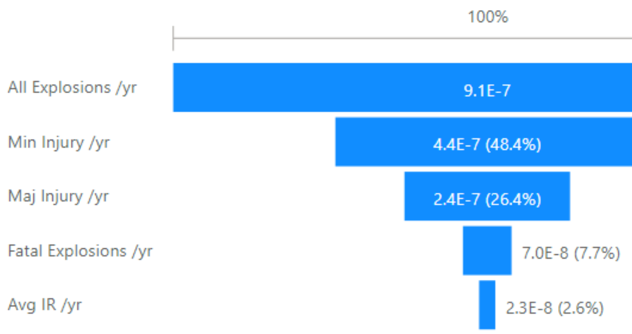


Figure 3 Individual risk for natural gas explosions as a result of a leak in the indoor installation.

The calculated individual risk corresponds well with the historical accident data for natural gas as described in HyDelta 1 [1]:

Table 2 Overview of incidents involving natural gas in the Netherlands after the meter (period 2010-2020) translated to average number per year. Probability per connection (≤G6), involved on 7.2 million connections. There can be several victims per incident [1]

Type of incident after the gas meter	Number of natural gas incidents	Probability Incident per connection x 10^{-6}	Number of fatalities	Number of injured *)	Number of major damages #)	Chance of casualty per gas connection x 10^{-6}
Carbon monoxide poisoning	39,5	5,5	2,64	138,2	-	0.37 (lethal) 19.2 (injured)
Fire and/or explosion (excluding intentional cases*)	14,5	2,0	0,45	7,8	14,5	0.06 (lethal) 1.1 (injured)
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 letting a lot of natural gas escape, etc.*
#) Major material damage: more than €10,000.
**) Injured: persons who are treated after an incident and/or transported to hospital for further treatment*

The probability of a fatal victim in the Netherlands due to an explosion or fire per house is 0.06 x 10^{-6}/year, excluding cases where intentional acts are involved. Additionally, the probability of injuries is 1.1 x 10^{-6}/year. The model respectively gives 0.02 x 10^{-6} for fatal victims and 0.4 x 10^{-6}/year for injuries, thus providing the same order of magnitude as the historical data.

The ratio between injured and fatal victims is nearly identical in both the historical data and the model outcomes (historical: 1.1/0.06 = 18; model: 0.44/0.023 = 19).

These risks exclude the risk of carbon monoxide poisoning, which is higher with natural gas than the risks shown here. The probability of a victim due to carbon monoxide poisoning is equal to 0.4 x 10^{-6} per natural gas connection. For the validation of the distribution network model, the total number of victims resulting from leaks in the distribution network across the Netherlands is considered. In HyDelta 2, an approach was made based on the composition of the distribution network in the Netherlands, in terms of materials, pressures, diameters, all with corresponding lengths and connected households. The total number of victims, Potential Loss of Life (PLL), is 0.64 per year. This is considered the same order of magnitude as the practical data (~0.3 based on a very limited number of incidents).

3 Summary results case-study neighbourhood

This chapter presents and discusses the impact of hydrogen in the network of a typical Dutch residential neighbourhood. By using this case-study neighbourhood as input in the QRA model, a comparison in individual risk can be made between natural gas and hydrogen for a detailed and realistic distribution network with houses. This serves as a supplement to the risk results for the general Dutch situation. The impact on individual risk of pipeline failure can thus be investigated at a local level. For example, it is interesting to examine the influence of houses on each other, such as closely spaced or semi-detached houses, as well as the difference in risk between houses near high-pressure or (multiple) low-pressure pipelines.

3.1 Case-study district in the QRA model

The composition of the case-study neighbourhood is very important for the relevance of the results. Therefore, defining the district was carried out in consultation with the network operators. The neighbourhood had to look like a typical part of a village or small town. Furthermore, differences in the structure and topology of the distribution network are interesting, such as the materials, pressures and diameters used. Some variation in the type of houses and the distances to the distribution network increases the value of the results.

Based on an existing neighbourhood, a model was created of a neighbourhood with 57 houses. In this neighbourhood, various segments of the main pipelines were installed, each with a specific type of material, diameter, and pressure. The topology of the distribution network is shown in Figure 4.

Figure 4 Overview of houses and distribution network topology of the case-study district.

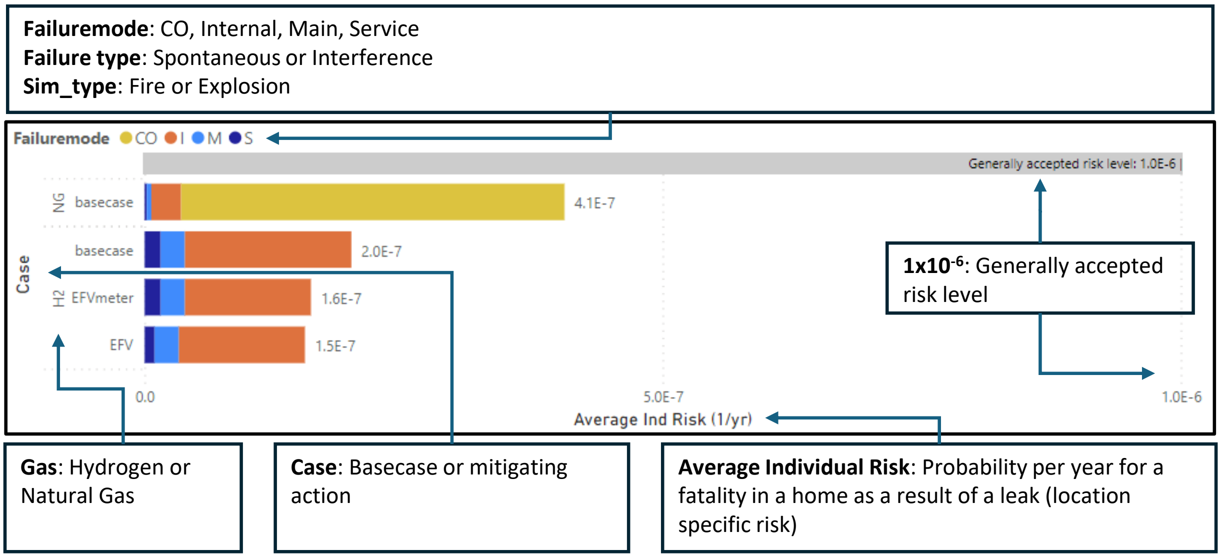
In the case-study, there are detached homes of various sizes and distances from each other and the distribution network. Additionally, there are several semi-detached houses, identifiable by the double service in Figure 4. The distribution network is modelled according to the following section distribution:

- 8 bar main, Steel, 115 mm
- 100 mbar main, PE, 160 mm

- 100 mbar main, PVC-A, 160 mm
- 100 mbar main, PVC-A, 110 mm (a, b & c)
- Services made of PE, 32 or 25 mm

Furthermore, the failure probabilities introduced for the section of the distribution network are specific to the combination of diameter, pressure, and materials used, as given in [2]. The configuration and failure probabilities of the internal installation are also taken as used in [2]. The individual risk for each house is determined for both hydrogen and natural gas.

In this report, the results of the model are presented in the following way. It has been decided to show the individual risks on a scale of 0 to 1x10^{-6} per year in all figures. The cause of failure, the effect or the mitigating measure shown can vary from figure to figure.



3.2 Risk hydrogen from a leak in the distribution network

The risks of hydrogen for each individual house from a leak in the distribution network are presented in Figure 5. For each part of the main pipelines from the overview in Figure 4, as well as for the service pipelines, the risk per house has been calculated. The results are combined for the main pipelines per pressure class. A colour scale is used to indicate the difference in risk between the houses.

Figure 5 Total risk due to a hydrogen leak from the distribution network.

The total risk per house in the district due to a hydrogen leak from the distribution network is shown in Figure 5. Houses that are close to each other and close to (multiple) mains show a higher risk. The highest risk is therefore posed by semi-detached houses. This risk effect is greater than that of a house near the 8 bar main.

The average effect across the houses in the district is shown below, with a breakdown between the contribution of the mains and the services.

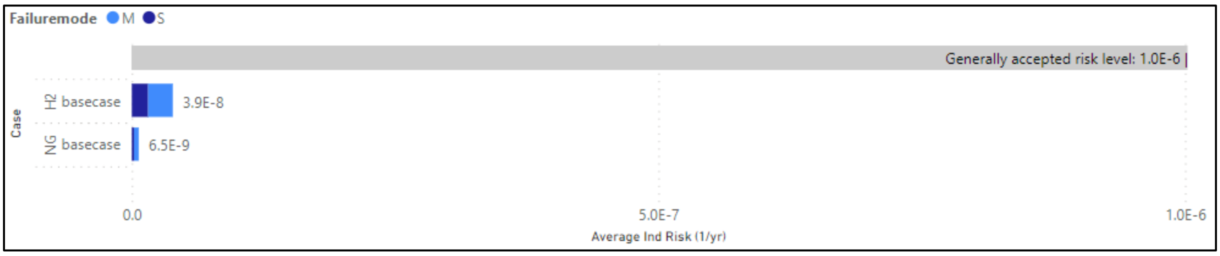


Figure 6 Average individual risk per house for hydrogen (H2) and natural gas (NG) from the distribution network with a subdivision into mains and services.

In the figure below, the risk from leaks in the distribution network is broken down by the contribution of explosions and fires. The risk of fires is of the same order of magnitude for both gases (~2 x 10^{-9}/year), but due to the greater contribution of explosions for hydrogen compared to natural gas, the relative contribution for hydrogen is lower than for natural gas (6% versus 39%).

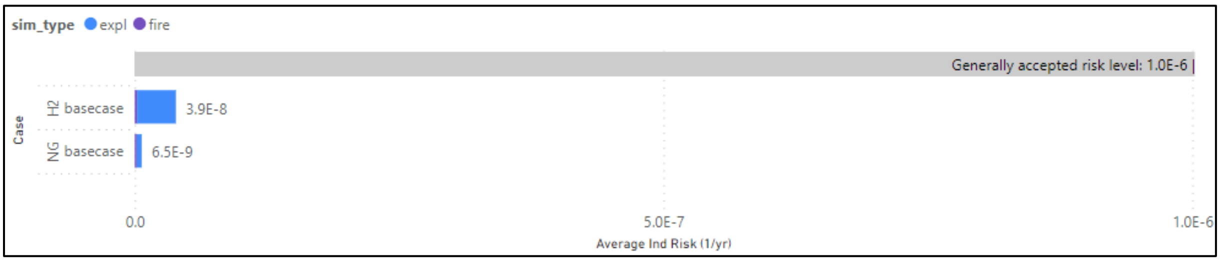


Figure 7 Average individual risk per house from the distribution network with a subdivision by contribution of explosions and fires.

3.3 Risk hydrogen from a leak in the indoor installation

In the indoor installation, from the meter to the boiler, leaks can also occur. The indoor installation is divided into three sections: the meter installation, the indoor pipes, and the boiler.

Below, in Figure 8, the risk per house in the case-study is shown due to a leak from the entire indoor installation. For clarity, the colour scale indicating the risk is different compared to the figures from the previous section.

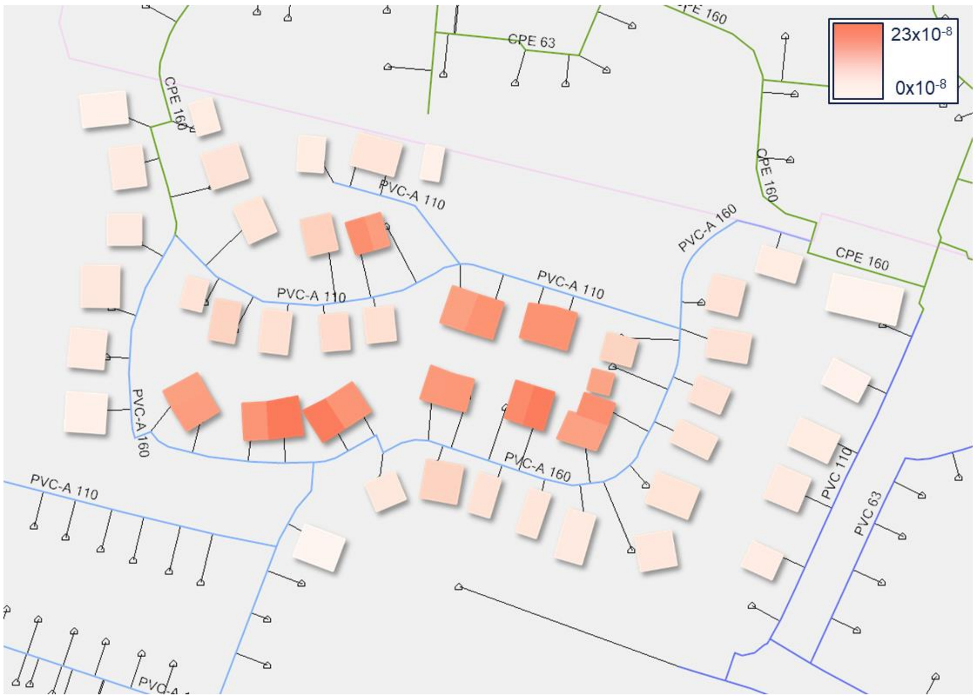


Figure 8 Risk in houses due to a leak in the indoor installation.

The outcomes of the model for a leak in the indoor installation show a clear trend for the houses in the case-study. Besides the risk in a house due to a leak causing an explosion in its own indoor installation, there is an influence from nearby houses. Especially semi-detached houses have an increased risk, as well as detached houses close to other houses, due to the higher overpressure caused by an explosion compared to natural gas. The risk from a leak in the indoor installation is significantly greater compared to the risk from a leak from the distribution network, for which a different colour scale was chosen.

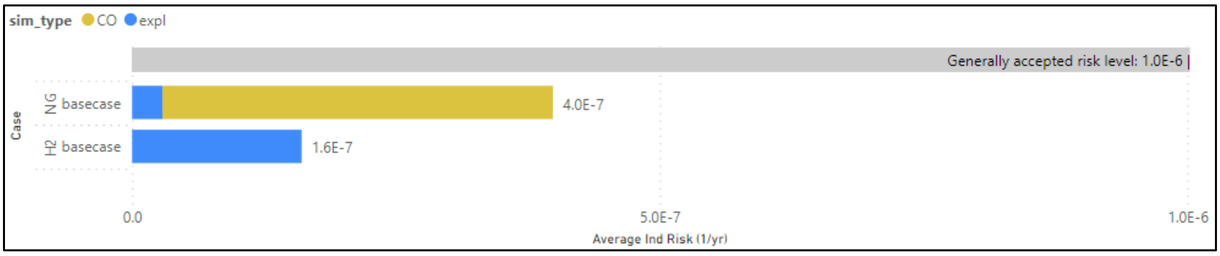


Figure 9 Average individual risk per house from a leak in the indoor installation, broken down by contribution of explosions and CO poisoning.

3.4 Total risk in the case-study neighbourhood

The combination of the risk caused by both a leak in the distribution network and in the indoor installation gives the total individual risk per home in the case-study district. Figure 10 shows the total risk for hydrogen.

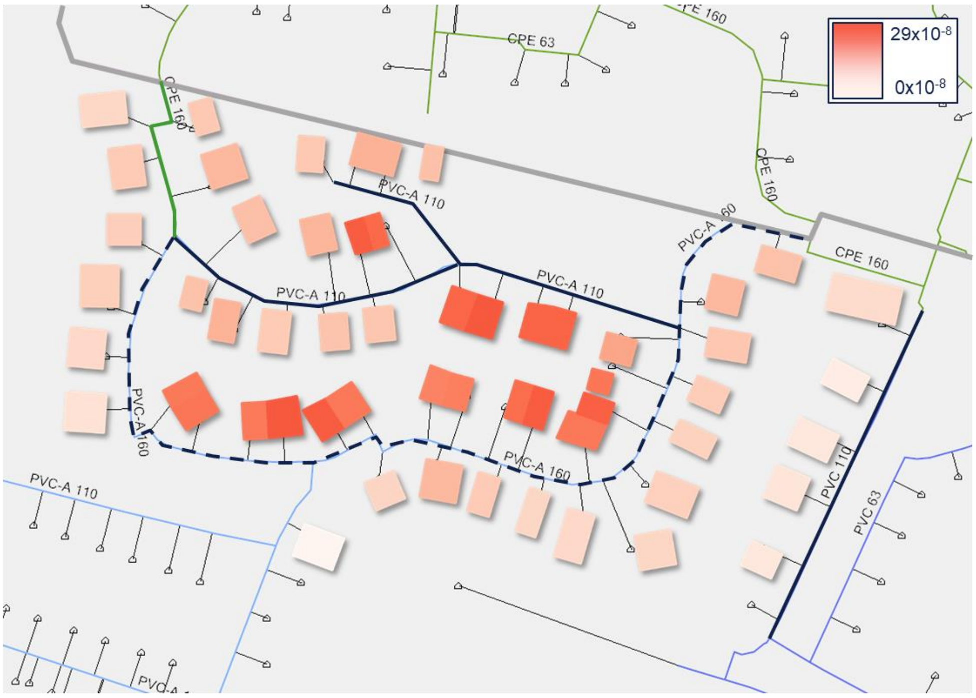


Figure 10 Total risk hydrogen for houses in the case-study neighbourhood.

By far, the largest contribution to the total risk for hydrogen is the indoor installation, followed by the 100 mbar main pipelines. Semi-detached houses, houses that are relatively close to each other, and houses with multiple main pipelines nearby have the highest individual risk. Detached houses near a single main pipeline have the lowest individual risk.

3.5 Difference between hydrogen and natural gas risk

Figure 11 below shows the average total individual risk for both hydrogen and natural gas for the 57 homes in the case-study neighbourhood.

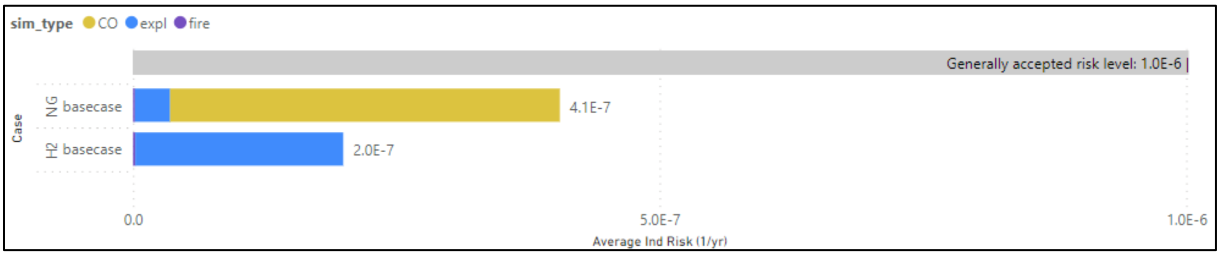


Figure 11 Average individual risk per house in the case-study neighbourhood for hydrogen and natural gas.

A comparison of the risks in houses from hydrogen versus natural gas shows an increased risk for hydrogen due to explosions from both indoor installations and the distribution network. Because the explosion of hydrogen is more intense compared to natural gas, the risk in nearby homes relative to the leak location is greater. For natural gas, the risk of carbon monoxide poisoning is also presented (dark yellow), which will not be present with hydrogen. Although the combined risk from leaks in both the distribution network and indoor installations is higher, the total risk for hydrogen for each home is approximately half or less. When the risk of CO poisoning is included in the comparison, it shows a shift from the reduced risk of CO poisoning to an increased risk from explosions. The total average individual risk is, with the chosen set of assumptions and without additional measures, lower for hydrogen than for natural gas. By applying mitigating measures, the increased effect of explosions with hydrogen can be reduced. These will be further discussed in the next chapter.

4 Effect of mitigating measures

This chapter discusses the impact of mitigating measures on the risk level for hydrogen. Odorisation of both natural gas and hydrogen is already included in the QRA model calculations. Additional mitigating measures considered in this study include increased ventilation of the house, the installation of an excess flow valve, and a gas sensor. Reducing the (spontaneous) failure frequencies is also an important mitigating measure taken into account. This can be achieved through periodic inspections, replacing materials, and renewing equipment.

4.1 Increased ventilation

Increasing ventilation in a house can eliminate the possibility of creating a flammable gas-air mixture at a certain leak or at least limit the concentration that can be achieved. Additionally, the time required to reach a flammable gas-air mixture extends as the ventilation rate increases. The higher ventilation rate of a house significantly reduces the risk within the home. This has been demonstrated in QRA studies for H21 and Hy4Heat, and is also evident from the analyses done in HyDelta 2. This reducing effect is stronger for hydrogen compared to natural gas. Therefore, increasing the ventilation rate in homes is a significant potential mitigating measure for a hydrogen distribution system.

To estimate the effect of ventilation, the ventilation rate of the houses in the case-study neighbourhood was doubled. This means that the build-up of concentrations in all rooms in the house is reduced. Doubling the ventilation rate from the reference value of 0.8 per hour to a ventilation rate of 1.6 per hour results in a reduction of the individual risk by 54%, on average, across the houses in the neighbourhood. The measure affects both the risks from the network, the main and service pipelines, as well as leaks within the house. The effect is shown in the figure below.

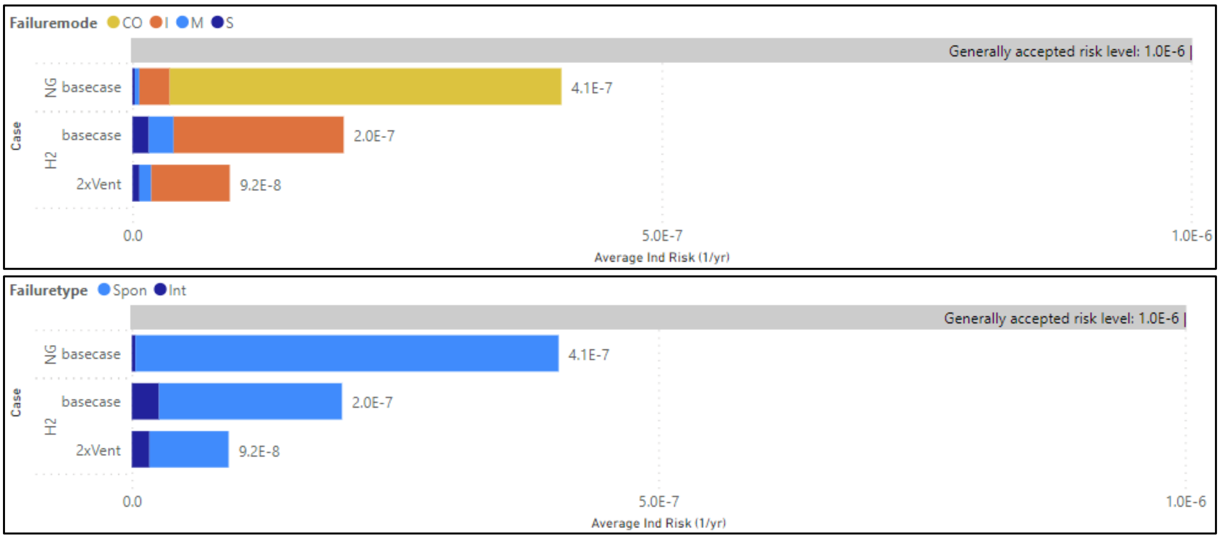


Figure 12 Effect of doubled ventilation on the risk, broken down by cause (main (M), service (S), indoor (I) and CO; top) and type of leakage (interference or spontaneous; bottom).

However, some caveats can be made about the implementation of double ventilation. A higher ventilation rate also impacts the heating demand in homes. It is possible that any additional ventilation is negated by residents who intentionally close ventilation openings and prevent draughts to, for instance, reduce heating costs. This makes the feasibility and enforceability of this measure potentially problematic.

4.2 Increased inspection frequency of the indoor installation

In the transition to hydrogen and its subsequent operation, regular inspections could reduce the chance of spontaneous leaks. As described in section 2.4.2, it is assumed that for a yearly inspection, the chance of spontaneous leaks is reduced by 20% for the meter installation and indoor pipes, and by 50% for end-user equipment. It is assumed that with high-frequency automatic daily measurement of the pressure drop in the indoor pipe, the chance of spontaneous leaks is reduced by 80%. In both cases, leaks caused by third parties (interference) are not impacted. The effect of this reduction in failure probability leads to a risk reduction of 19% with a 20% reduction in probability, and 51% with an 80% reduction in probability. This reduction naturally only applies to leaks behind the meter. Generally, the risk scales linearly with the failure frequency. In this way, any potential reduction through increased inspection of the distribution network can also be estimated. For the time being, no assumption is made for this in this study.

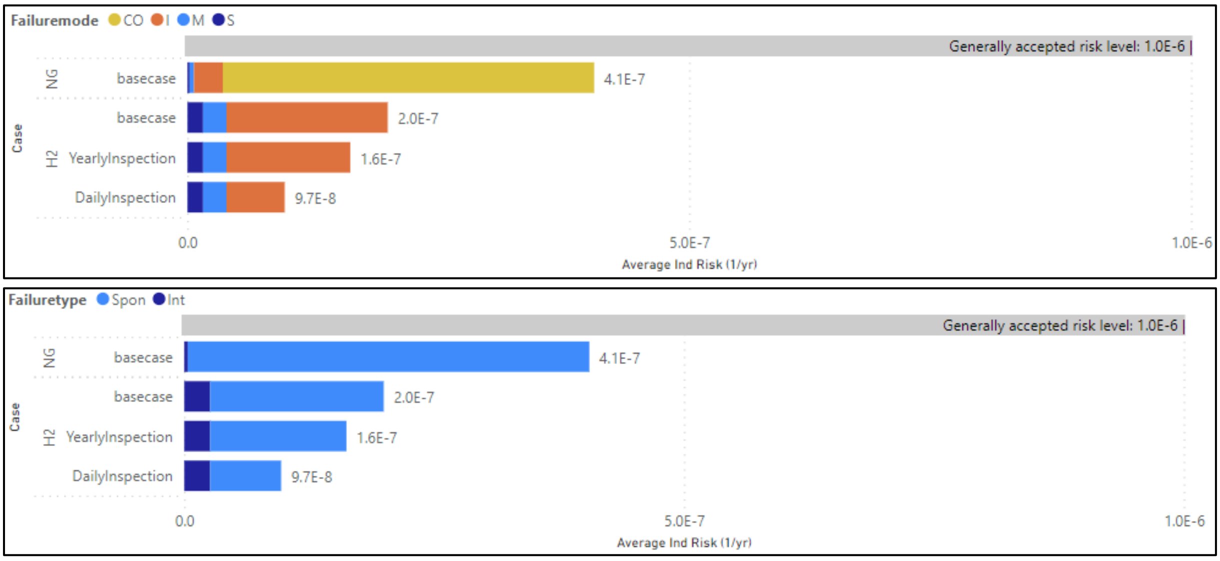


Figure 13 Effect of increased inspection on the risk, broken down by cause (main, service, indoor and CO; top) and type of leakage (interference or spontaneous; bottom). YearlyInspection has a 20% lower chance of spontaneous leaks, DailyInspection has an 80% lower chance of spontaneous leaks.

Regular inspections of the indoor installation require considerable labour unless done automatically. Such inspections could potentially be combined with annual inspections of heating installations. Regulations may need to be adjusted to ensure inspectors have proper access for inspections behind the front door. An automatic inspection using pressure sensors in the indoor installation needs further development and must demonstrate reliable execution.

4.3 Excess flow valve

For the use of an excess flow valve with a capacity of 20 m^3/hr for hydrogen, the risk reduction has been determined in the case-study neighbourhood. Two scenarios have been considered:

1. In the first scenario, the excess flow valve is **placed directly at the meter**, which takes into account that the use of appliances in the house affects the closing conditions of the valve. The valve closes at a flow rate higher than 20 m^3/hr, meaning, for example, that with a total consumption of appliances in a house at 8 m^3/hr, the valve closes with a leak of 12 m^3/hr. To approximate this in the model, assumptions are made regarding the timing and magnitude of appliance usage. The excess flow valve directly at the meter is not yet available on the Dutch market.

2. In the second scenario, the excess flow valve is **placed at the connection (saddle) between the main and the service**. This means the valve also impacts the risk of leaks in service lines. Further assumptions are used as described for the first scenario.

The risk reduction from applying the excess flow valve is shown in the figure below. An excess flow valve with a set value of 20 m³/hr reduces the risk in the indoor installation by 20%, on average, across the 57 homes in the neighbourhood. The risk contribution from leaks in the distribution network remains the same as in the reference situation. When the excess flow valve is placed at the saddle of the service to the main, the risk from leaks in the service is reduced by an additional 2.5%, resulting in a total risk reduction of 22.5%.

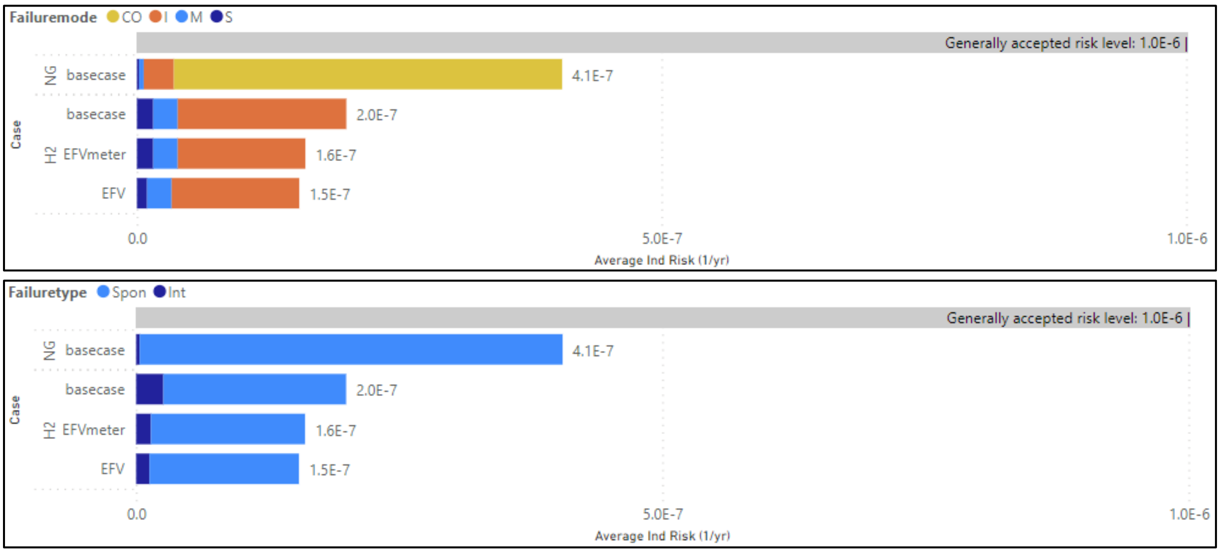


Figure 14 Effect of the excess flow valve on the risk, broken down by cause (main, service, indoor and CO; top) and type of leakage (interference or spontaneous; bottom). With EFVmeter the EFV is placed at the meter, with EFV it is on the saddle of the main.

To investigate the effect of the size of the excess flow valve on the risk, a newer version of the CONIFER software package (v8.0.9.16) was used. This version includes several changes to the underlying models, which may affect the calculated risks. Therefore, the results of this version are not directly comparable with the results of the previous version (v8.0.8.39), which was used for most calculations in this report and previous research in HyDelta 2. The figure below provides an indication of how the risk changes when the size of the excess flow valve varies. The size of the excess flow valve was varied with a limit value of 15 to 30 m³/hr. The reduction in risk compared to the reference situation is 14%, 32%, and 46% for 30 m³/hr, 20 m³/hr, and 15 m³/hr, respectively.

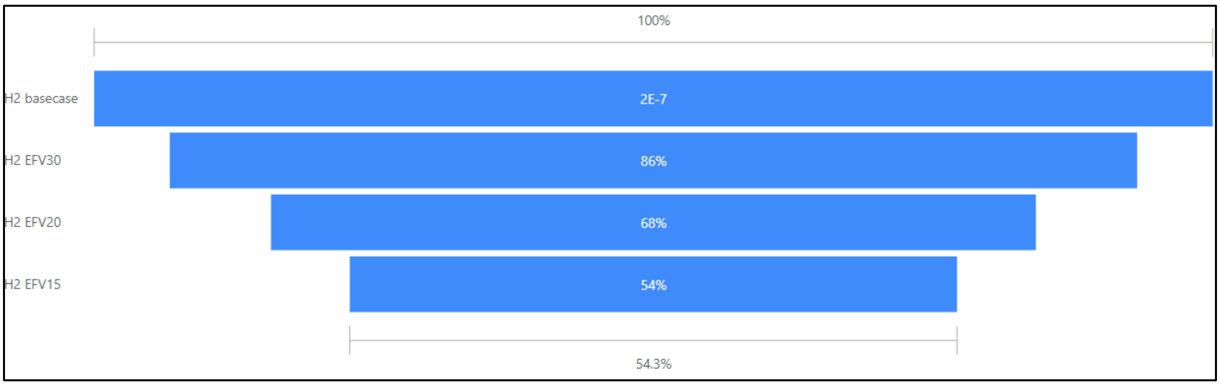


Figure 15 Effect of the size of the excess flow valve on the risk.

The excess flow valve is a relatively inexpensive solution, especially when installed at the meter. Installation on the saddle of the main might incurs higher installation costs and has a limited additional effect on risk according to the model. The excess flow valve operates mechanically and is thus less prone to malfunctions. It is an invisible measure to the resident, which could help in the sense of safety. Preliminary calculations indicate that an excess flow valve with a lower capacity has a greater risk mitigating effect. However, it should be avoided that an excess flow valve with too low a capacity closes unnecessarily during higher gas demand, such as when boilers are starting up. Coordination between the allowed peak demand of boilers and the capacity of the excess flow valve is therefore advisable.

It is important to note that the results in this report do not include intentional leaks in the internal installation. In such situations, the excess flow valve will likely also activate, helping to prevent an explosive mixture in the home.

4.4 Gas detection

By installing a gas sensor with an acoustic signal in a house, a gas leak can potentially be detected earlier than solely through odorization and detection by the residents. This is particularly useful if a leak occurs at night or if a sound signal is noticed by neighbours. This also applies to high-risk areas like meter cupboards or basements where residents are rarely present. After an alarm, it is assumed that the gas supply will be shut off sooner and that residents will ventilate more, resulting in lower concentrations in the house and fewer potential explosions. The effect of sensors is modelled by a higher likelihood of detecting a given concentration in the house. The impact of gas sensors on the total risk is a 31% reduction. If the gas detection is directly linked to close the gas supply (Emergency Close Valve), a reduction of 77% is achieved.

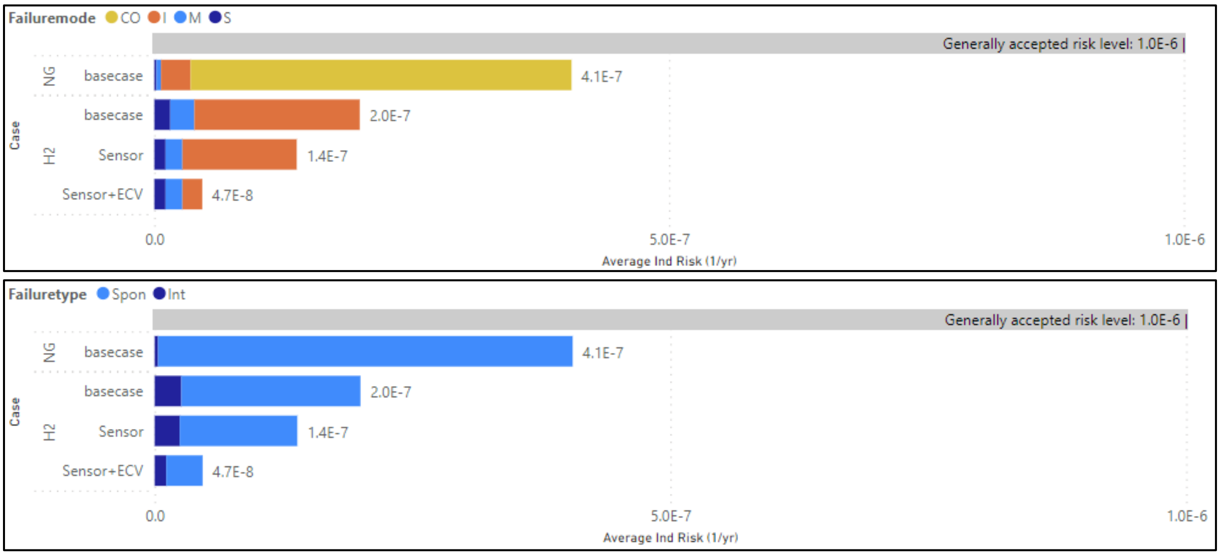


Figure 16 Effect of a sensor on the risk, broken down by cause (main, service, indoor and CO; top) and type of leakage (interference or spontaneous; bottom). Sensor+ECV is a sensor coupled to an automatic shutter of the supply ('Emergency Close Valve').

Hydrogen gas detection is similar to common smoke or CO detectors. Thus, it is a measure likely to be quickly accepted. The required technology is very similar to current CO detectors. Combining a sensor with an automatic gas supply shut-off appears to be a very effective measure. However, this measure is still conceptual and not yet available on the market. It must be demonstrated that such a system can operate reliably and without interference. The potential frequent and unwarranted shut-off of the supply could lead to inconvenience and thus reduced acceptance of this measure.

4.5 Combined effect of measures

In the sections described above, the various contributions per mitigating measure are listed. Figure 17 shows the contribution of individual measures compared to the reference situation for hydrogen as well as for natural gas, in increasing effect. In this figure, the calculated risk reduction of the measures is shown. It should be noted that when determining the desired measures, not only the calculated risk reduction is important but also the social impact, costs, and reliability play a significant role. Early automatic detection of a leak by a sensor that automatically shuts off the hydrogen supply in the house seems to be the most effective measure, with the calculated risk approximating that of natural gas without CO contribution. Regular daily inspection with an 80% reduction in spontaneous leaks gives a similar risk reduction to doubling the ventilation rate in the house. Both achieve a reduction of more than 50% compared to the reference value. The excess flow valve of 20 m^3/hr and the installation of a hydrogen sensor with an alarm provide a reduction of 20-30% compared to the reference.

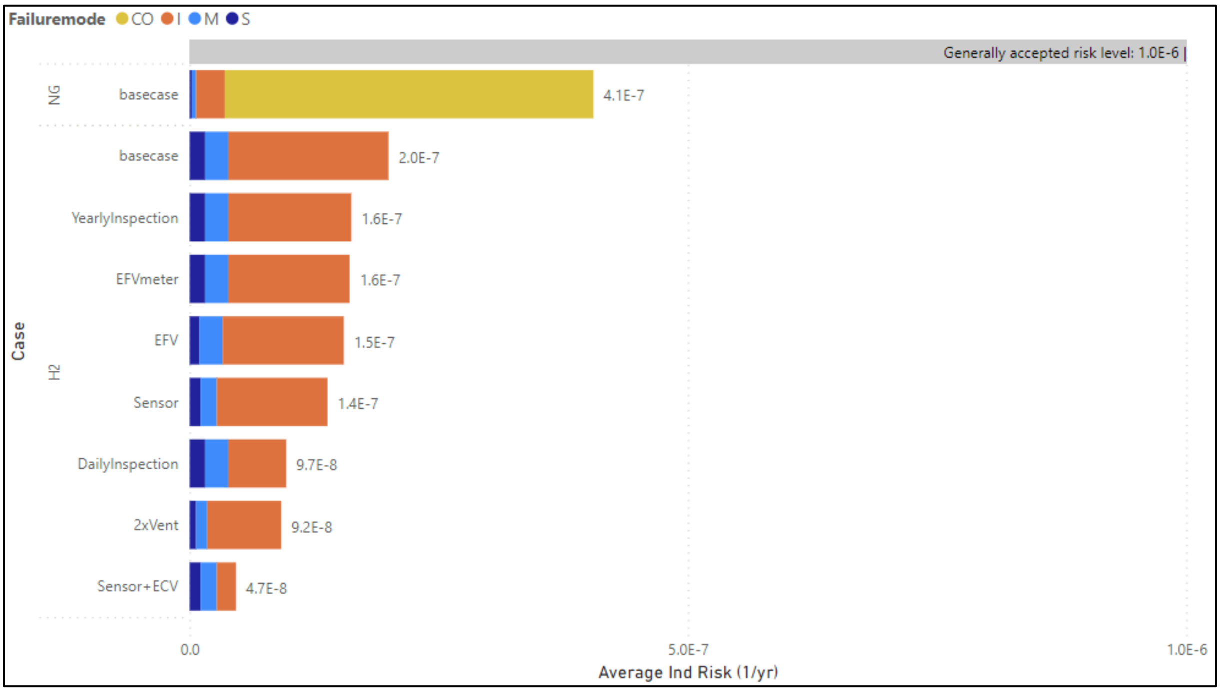


Figure 17 Overview of the contribution of individual measures to the risk.

In addition to individual measures, combining measures could further reduce the risk. Figure 18 provides an overview of the simulated measures and several combinations of individual measures.

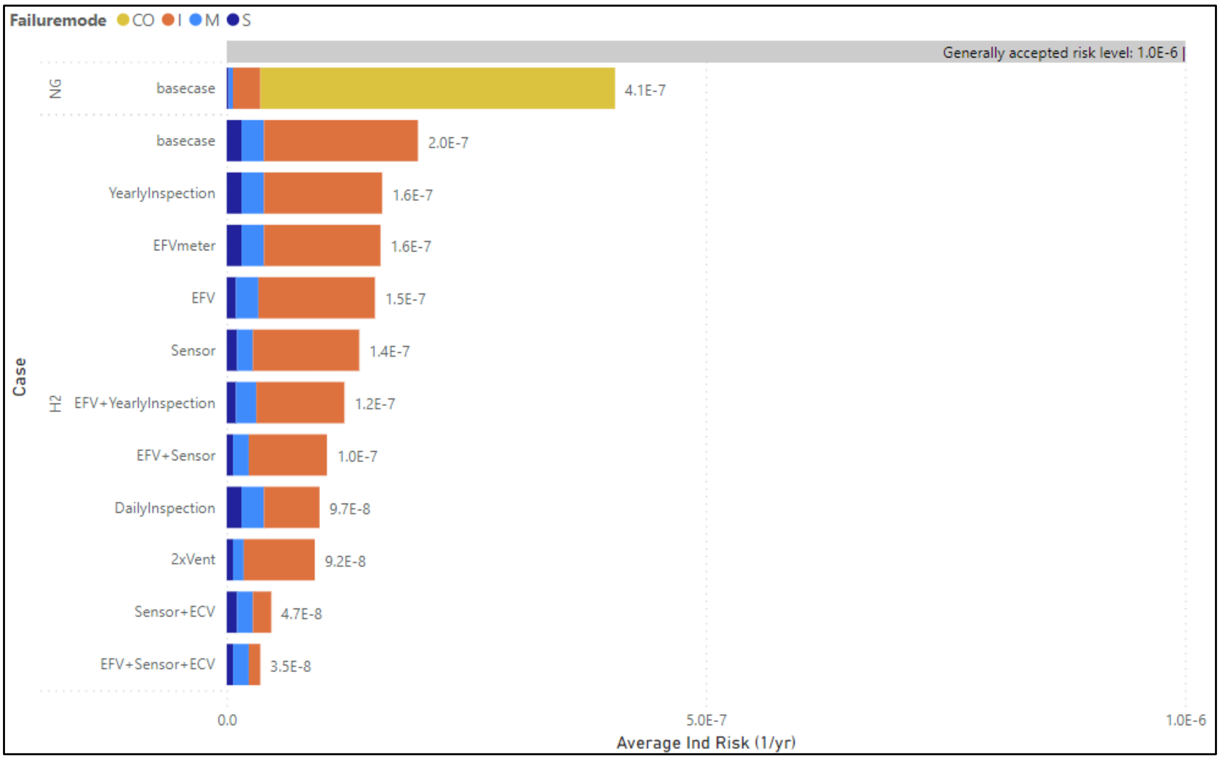


Figure 18 Overview of the contribution of individual and combinations of measures to the risk.

When combining measures, the reduction is not automatically the sum of the individual measures' reductions. For example, if an excess flow valve is combined with a sensor, the combined reduction is

50%. This is because a sensor already prevents some of the leak risks that would otherwise be prevented by the excess flow valve. By choosing a combination of an excess flow valve with a sensor that automatically shuts off the supply, a risk lower than that for natural gas would be realized under the assumptions chosen in the model.

5 Effect of other housing types

5.1 Property types

In the case-study neighbourhood, a combination of detached and semi-detached houses was chosen. However, in the total housing stock in the Netherlands, there are more types of homes, such as row houses and flats or apartments. It is interesting to know the effect of the type of housing on the overall risk.

According to CBS[6], there are approximately 8 million homes in the Netherlands, of which about 13% are detached, 9% are semi-detached, 42% are row houses (of which 13% are corner houses and thus comparable to semi-detached houses in the model), and 36% are multi-family homes (flats or apartments).

The distribution of the number of houses by type varies by region, depending on urbanization, historical development, and available space. Generally, detached houses are more common in rural areas, while flats and apartments are more prevalent in urban areas. Row houses and semi-detached houses are spread throughout the country but are also concentrated in certain neighbourhoods or districts.

The chosen change in the case-study gives an initial indication of the difference in risk for different types of houses. In this neighbourhood, the distribution network was kept the same. Row houses and apartment blocks come in various forms and configurations, with corresponding distribution network setups. To provide a representative picture for the entire Netherlands, different combinations of house types and infrastructure should be simulated and based on their share in the total mix in the Netherlands, a group risk for the entire country (PLL) should be determined. This generalization would require multiple calculations and falls outside the scope of the current project.

5.2 Case-study neighbourhood with row houses and apartments

To get an indication of the risks in row houses and apartment blocks, several model calculations have been made in the same case-study neighbourhood but with different types of houses. For this purpose, 40 row houses, consisting of 10 corner houses and 30 mid-terrace houses, were placed in the case-study neighbourhood. Additionally, five apartment blocks were added. These consist of three apartments side by side and four on top of each other. The apartment blocks are connected to the main with one service per block. Figure 19 shows the schematic layout of the neighbourhood.

[6] https://opendata.cbs.nl/statline/#/CBS/nl/dataset/85035NED/table?ts=1658417234523

Figure 19 Case-study neighbourhood with row houses and apartments.

The results of the model for the different housing types are shown in Figure 19. This figure shows the average individual risk per housing type for both the original case-study neighbourhood with detached and semi-detached houses and the new neighbourhood with row houses and apartments. For the latter two categories, a distinction is made between the corner house of a row or apartment block ("appC" and "rowC") and the mid-terrace houses ("app" and "row"). The results indicate that the risk in homes that are close together (apartments and rows) is higher than for detached houses. Corner houses of row houses and semi-detached houses have a comparable risk, with differences explained by their location relative to the main and the size of the house. The figure also provides a comparison with the situation for natural gas. In this situation, the risk is again dominated by the effect of CO, which is estimated to be the same for all house types. For each of the housing types, the risk with hydrogen is well below the $1x10^{-6}$ standard and in all cases smaller than the risk of natural gas including CO.

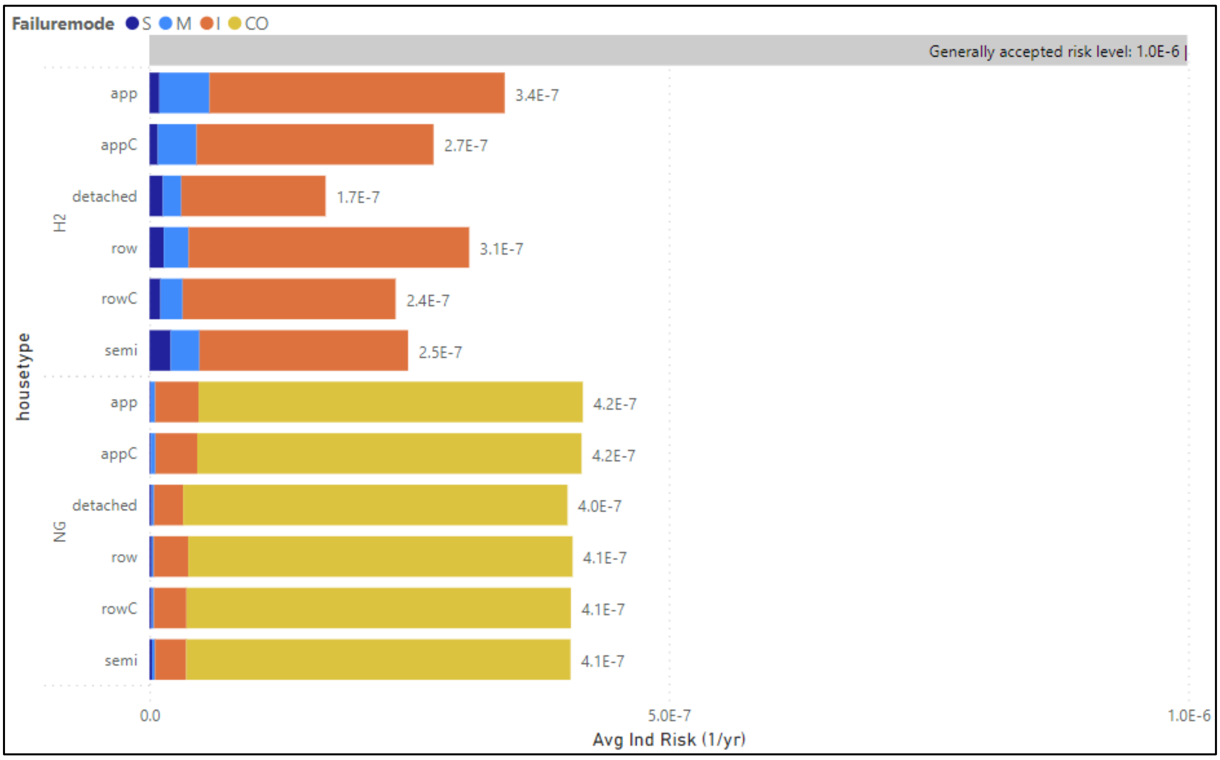


Figure 20 Average individual risk for different housing types without mitigating measures: Corner apartment (appC), intermediate apartment (app), detached (detached), (corner) row house (row, rowC) and semi-detached house, divided into contributions from the grid, the indoor installation and CO.

Several mitigating measures were also considered for the different housing types. The results are shown in Figure 21. The excess flow valve provides a reduction of 22% to 26% from the reference risk value. With the sensor, the risk is reduced between 26% and 31%. The sensor with an automatic shut-off valve results in a reduction between 76% and 80%. In all cases, there is a difference in reduction between the various housing types in the order of magnitude of 5%. The sensor achieves the greatest reduction in detached and semi-detached houses, while the excess flow valve has the most significant effect in apartments. Row houses show the largest reduction with the excess flow valve with an automatic shut-off compared to the other housing types.

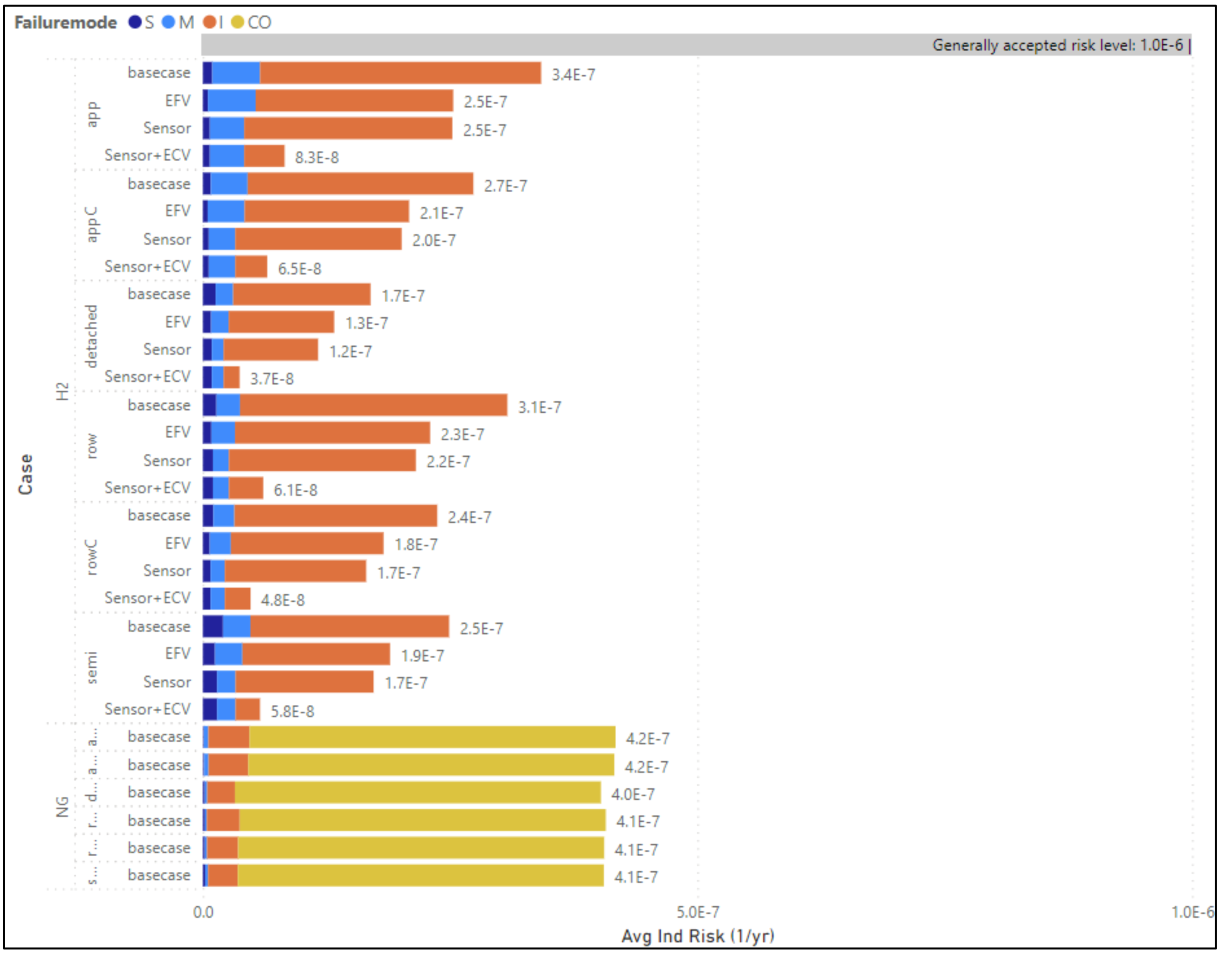


Figure 21 Average individual risk per housing type with different mitigating measures for hydrogen (excess flow valve, sensor and sensor with automatic shut-off valve).

6 Risk perception

In this chapter, we examine the public's perception of risks and how it differs from objective risk assessments. Often, the public struggles to understand the magnitude of a risk or to compare it with other risks. This presents a challenge when communicating about a quantitative risk approach. The risks from the QRA model for hydrogen are therefore put into perspective with other risks to which the general public is exposed.

6.1 Quantitative risk analysis versus risk perception

A quantitative risk approach is a method to calculate the risk of a particular situation or activity based on objective data and models. The risk is typically expressed as the probability of an undesirable event occurring multiplied by the severity of its consequences. For example, the risk of a hydrogen leak in a house can be calculated by multiplying the probability of a leak by the probability of ignition and the potential damage to people and property.

One challenge in communicating a quantitative risk approach is that the public often struggles to understand the magnitude of a risk or to compare it with other risks. A commonly used measure for individual risk is the 10^{-6} contour, which means that the probability of a fatal accident within a certain area around the activity is equal to $1x10^{-6}$, or one in a million, per year. This is generally considered an acceptable or negligible risk according to some standards or guidelines.

However, for many people, a 1x10-6 contour is an abstract and difficult-to-understand concept that is hard to visualize or relate to their own situation or experiences. Additionally, the public may have different perceptions of what constitutes an acceptable or negligible risk, depending on the nature, context, and benefits of the activity. For example, some people might accept a higher risk for an activity they voluntarily choose such as smoking or driving, than for an activity they cannot control or avoid, such as living near a chemical plant or a nuclear power plant. People may also overestimate or underestimate certain risks based on personal or social preferences. For instance, the risk of an accidental fall might be underestimated by those who feel healthy and fit, or overestimated by those who are anxious or depressed. Risk perception is the subjective assessment of risk, influenced by various factors such as emotions, values, norms, experiences, media, trust, and knowledge.

The difference between a quantitative risk approach and risk perception can lead to misunderstandings, conflicts, or resistance when implementing measures to reduce or manage the risk. Therefore, it is important to present the risk not only with figures or contours but also with other methods that can help the public estimate or compare the risk with other known or relevant risks. For example, the risk can be expressed in terms of the frequency or duration of exposure, the likelihood or number of expected casualties, the comparison with other causes of death or illness, or the reduction in life expectancy or quality of life. However, it is crucial to avoid exaggerating or downplaying the risk, or providing inaccurate or misleading information. The goal is to inform and engage the public, not to manipulate or persuade them.

6.2 Compare hydrogen risk with other risks

In order to compare the risk of hydrogen with other risks and to communicate carefully with stakeholders, it is useful to look at the causes of death in the Netherlands. According to the statistics from the Central Bureau of Statistics (CBS) [7], there were approximately 170 thousand deaths in the Netherlands in 2022, as shown in Figure 22.

[7] https://opendata.cbs.nl/#/CBS/nl/dataset/7233/table?dl=92F2D

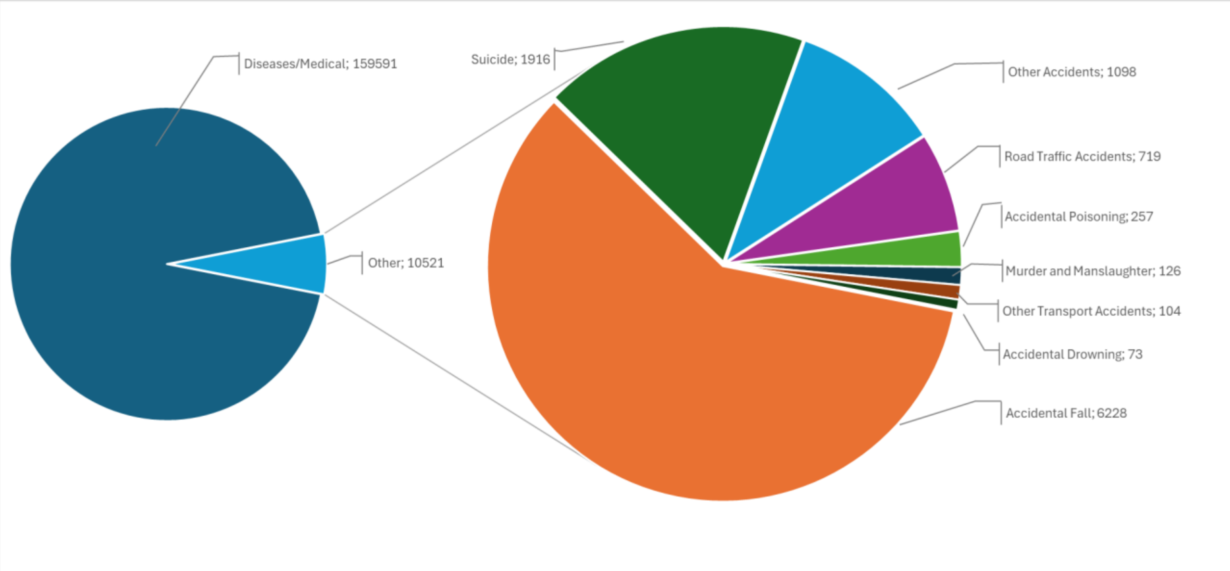


Figure 22 Causes of death in the Netherlands in 2022 (source: CBS).

Most of these deaths can be attributed to diseases or medical causes. Additionally, there were over 10,000 deaths from other causes, with accidental falls being the most significant external cause of death. According to statistical definitions, an "accidental fall" is an incident where someone unintentionally falls, trips, or slips. Deaths from accidental falls are associated with old age and certain diseases. Fatal falls are particularly common among people with dementia or other degenerative conditions (such as Alzheimer's disease, Parkinson's disease, or multiple sclerosis). CBS data reveals that four out of ten people who died from an accidental fall in 2021 had one of these conditions as an underlying or contributing cause of death. Other relatively significant causes of death include suicide (over 1900 cases) and traffic and transportation accidents (over 800 cases).

In the QRA calculations for the hydrogen/natural gas case-study, the risk is expressed as an average individual risk per year. By dividing the accidents reported by CBS by the total population, the individual risk for these causes of death is determined. To compare with the model outcomes, several of these causes are shown in Figure 23. Statistics for the period from 1996 to 2022 have been used.

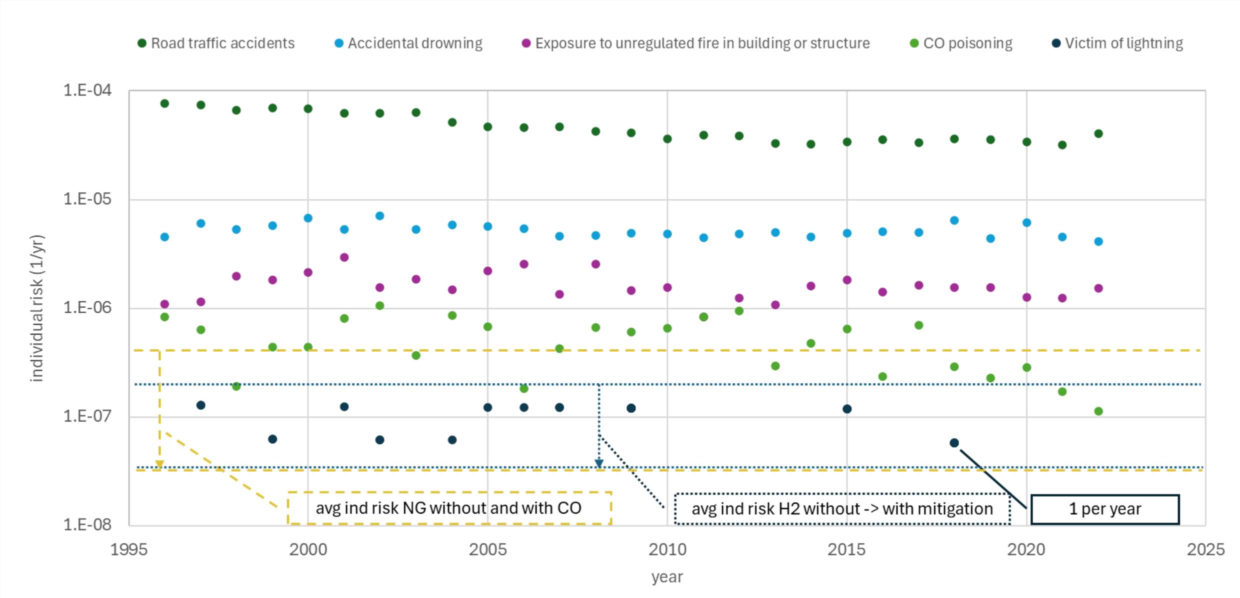


Figure 23 Comparison of different individual risks in the Netherlands between 1996 and 2022. The average individual risks for hydrogen in homes in the case-study are shown with dotted lines for both the reference situation and the case with mitigating measures (sensor with automatic gas supply shut-off). The average individual risks for natural gas with and without the effect of CO poisoning are shown as dark yellow dotted lines. Note that the y-axis is logarithmic.

The individual risk is plotted on a logarithmic scale. As the number of fatalities per year decreases, the spread becomes larger, which is clearly seen in the cases of CO poisoning and lightning strike victims. For the latter category, there are also years without victims, which cannot be represented on a logarithmic scale. The calculated risk for using hydrogen in the case-study neighbourhood is shown with two shaded lines. The upper line represents the reference situation with an average risk of approximately $0.2x10^{-6}$ per year. The lower line shows the situation with a gas sensor and automatic supply shut-off, with an individual risk of approximately $0.05x10^{-6}$ per year. Compared to other causes, the risk of hydrogen in the case-study neighbourhood, even without mitigating measures, is very low.

7 Conclusions

Quantitative Risk Analysis to Understand Hydrogen Safety in the Built Environment
To assess the risks of using hydrogen in distribution and transport networks compared to natural gas, it is crucial to understand the differences in probability and consequences. The probability concerns the likelihood of a hazardous situation occurring, while the consequences translate to damage from fire or explosion. Mitigating measures aim to reduce the likelihood of hazardous situations or minimize their consequences. Within the HyDelta program, a work package titled 'Hydrogen and Safety' has been established with the primary objective:

Mapping out risks related to hydrogen behaviour in leaks in homes and the distribution network, and based on these risks, defining control measures.

To explore the risks of hydrogen in the Dutch distribution network, a quantitative risk analysis (QRA) was conducted. This analysis compares the risks between the current natural gas distribution system and the potential future hydrogen distribution system. The total risk assessment includes risks arising from leaks in both the distribution network and the internal installation within the home. The results of this analysis provide a quantitative basis for assessing whether hydrogen distribution poses more societal risk and which measures are most effective in reducing these risks.

Risks are small, but what does small mean?
Given the approach to reality based on the previously mentioned assumptions, the model provides an approximation of the individual risk in the house due to fire or explosion. A commonly used measure for individual risk is the 10^{-6} contour, which means that the probability of a fatal accident within a specific area around the activity is equal to $1x10^{-6}$, or one in a million, per year. This is generally considered an acceptable or negligible risk. All calculated individual risks in this study for both natural gas and hydrogen remain well below $1x10^{-6}$ per year, thus presenting a very limited risk.
A common challenge in explaining a quantitative risk approach is that the public often struggles to understand the severity of a risk or compare it with other risks. For many people, a $1x10^{-6}$ contour is an abstract and difficult-to-visualize concept that is not easily related to their own situation or experiences. Moreover, the public has varying perceptions of what constitutes an acceptable or negligible risk, depending on the nature, context, and benefits of the activity. For example, some people may be willing to accept a higher risk for an activity they have chosen, such as smoking or driving, than for something over which they have no control, such as a chemical plant or nuclear power station nearby. Risk perception, or the subjective assessment of risk, is influenced by various factors such as emotions, values, norms, experiences, media, trust, and knowledge.

The difference between a quantitative risk approach and risk perception can lead to misunderstandings or resistance when implementing measures to reduce or manage risks. Therefore, it is important to present risks not only with numbers or graphs but also through other methods that help the public assess or compare risks with other known or relevant risks. For instance, risks can be expressed in terms of the expected number of fatalities, comparison with other causes of illness or death. However, it is crucial to avoid exaggerating or downplaying risks, and to avoid providing incorrect or misleading information. The goal is to inform and engage the public, not to manipulate or influence them.

The calculated risks for using hydrogen in the case-study neighbourhood in the reference scenario without additional risk-reducing measures are ~$0.2x10^{-6}$/year. With the most effective risk mitigation measure in this study, this risk is reduced to ~0.05x10^{-6}/year. The magnitude of these risks is in the same order as the number of lightning strike victims in recent years. Carbon monoxide poisoning victims are twice as high compared to the reference situation (0.4x10^{-6}/year). Annually, about 10 times as many people die from building fires (2x10^{-6}/year) or 25 times as many from accidental drowning (5x10^{-6}/year). Road traffic victims are approximately 250 times higher (50x10^{-6}/year). Compared to other causes of death, the risk of hydrogen (and natural gas) in the built environment is therefore very small[8].

Even though the risks are minimal, their perception can change rapidly due to initial incidents. It is, therefore, important to proceed diligently when introducing new technology, such as hydrogen in the built environment in pilot projects. New technology, after all, has not yet amassed statistics on its failure, which can lead to accidents. However, by implementing numerous additional safety measures during the introduction, the perception among the general public may also arise that the new technology is inherently unsafe. It is therefore important to gain a sense of the magnitude of the risks and the contribution of various measures in reducing this risk.

A calculation of the risks for a case-study neighbourhood provides insight

The original model was developed for the situation in the United Kingdom (UK) and validated for the risks of natural gas based on historical data. To demonstrate the applicability of such a model for the Dutch situation, the first phase of HyDelta initiated a translation of the model to the Dutch context. The focus was primarily on components that significantly impact the risk and that differ clearly in the Netherlands compared to the UK. In the second phase of HyDelta, the model was further translated, and the outcomes were validated against the historical data available for natural gas. In this second phase, the 'Case-study Neighbourhood' was introduced as a case study for a typical residential area where hydrogen can be applied. In the third, current phase of HyDelta, the specific focus is on the effect of mitigating measures on the risk, building upon the previously mentioned ' Case-study Neighbourhood'. The models used are based on the ongoing development of the model in the UK.

To gain better insight into the relative effects of leaks behind the meter and from the distribution network, a representative case-study neighbourhood was developed. This neighbourhood consists of 57 homes connected to a 100 mbar main via service pipelines. The 100 mbar network is fed by a steel 8 bar pipeline running through the neighbourhood. The 100 mbar network is modelled in several segments with different materials and diameters. The homes are modelled based on their area and consist of both detached houses and semi-detached houses. Additionally, for each of the houses, the risk of leaks in the indoor installation was determined. Based on failure frequencies in the home, it appears that the individual risk for natural gas due to leaks behind the meter closely matches the (limited) practical data.

The analysis shows that the individual risk for hydrogen is higher than for natural gas due to more severe explosions but lower when the risk of carbon monoxide poisoning is included. Carbon monoxide poisoning is a common result of incomplete combustion of natural gas but not of hydrogen. If this risk is included in the comparison, there is a shift from the reduced risk of CO poisoning to an increased risk of explosions. The total individual risk, with the chosen set of assumptions and without additional measures, is lower for hydrogen than for natural gas.

Various mitigating measures are possible with different effects

In the study, the effects of several mitigating measures were calculated. These measures can affect the likelihood of a leak occurring, for example, through regular inspection of pipes and equipment, or

[8] Another way to convey the risk of 2x10^{-7}: the chance is about as likely as flipping a coin and getting heads 22 times in a row.

by limiting the consequences of a leak. For regular inspections, a distinction is made between an annual check of the installation, with an assumed reduction in the chance of spontaneous leakage by 20%, and an automatic daily inspection with an 80% reduction in the chance of spontaneous leakage. To limit the consequences of a leak, one can consider excess flow valve (EFV), sensors, or increasing ventilation.

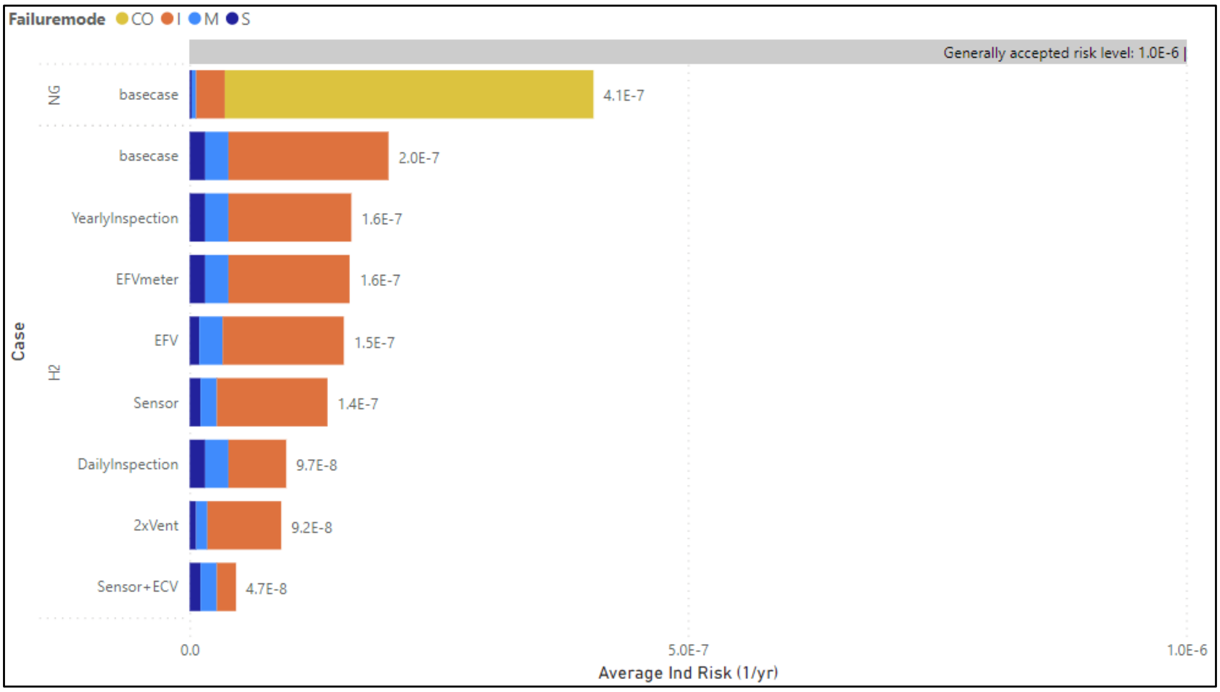


Figure 24 Overview of the contribution of individual measures to the risk of hydrogen compared to natural gas. The risk is broken down into the share due to leakages in the distribution network (M and S), the indoor installation (I) and CO.

The above figure provides an overview of the contributions of the measures. In this figure, the calculated risk reduction of the measures is shown. It should be noted that for determining the desired measures, not only the calculated risk reduction is important, but also the social impact, costs, and reliability play a significant role. Early automatic detection of a leak with a sensor that automatically shuts off the supply seems to be the most effective measure, approaching the calculated risk of natural gas without the CO contribution. Regular annual inspection with an 80% reduction in spontaneous leaks gives a similar risk as doubling the ventilation rate in the house. Both achieve a reduction of over 50% compared to the reference value. The excess flow valve with a trigger value of 20 m^3/hour and the installation of a hydrogen sensor with an alarm signal provide a reduction of 20-30% compared to the reference.

When modelling the measures, it is assumed that all measures are 100% effective. For example, this means that each excess flow valve always closes when the maximum flow is exceeded and that each concentration above the threshold value is detected by the sensor where it is placed. However, in practice, implementing the measures must consider uncertainty in their effectiveness. Some measures fall within the domain of network operators, such as the excess flow valve, while many of the other measures will be installed in the home and are therefore the responsibility of the homeowner. This means that besides the estimated risk reduction, the measures each also have their own advantages and disadvantages. The table below lists these advantages and disadvantages for each measure.

Mitigating Measure	**Risk reduction** (% compared to reference value)	**Advantages**	**Disadvantages**
Doubling ventilation in the house	54%	- Effective measure	- Poor controllability - Increases heat demand
Perform annual inspection	19%	- Limited impact on the home - Can be combined with boiler inspection	- Limited effect - Requires many inspections (personnel, high costs) - Adjusting regulations for access options
Installing Automatic Inspection	51%	- Effective measure - Limited impact on the home	- Susceptibility to interference and reliability must be demonstrated -
Excess flow valve at the gas meter (20m^3/hr)	20%	- Limited impact on the home, not visible - Cheap solution - Also effect in the event of deliberate leaks	- Limited effect - Not yet a standard solution
Excess flow valve between main and service	22.5%	- Limited impact on the home, not visible - Also effect in the event of deliberate leaks and leaks in the service pipe to the meter.	- Limited extra effect compared to excess flow valve at the meter - More expensive, labour-intensive solution
Gas sensor with alarm in the home	31%	- Low-cost, widely accepted solution	- Limited effect - Resident responsible (replace batteries etc)
Gas sensor with automatic shut-off valve in the house	77%	- Highly effective	- Conceptually, not yet on the market. Susceptibility to interference and reliability must be demonstrated - Privacy issues (being able to close remotely)

Finally, it is noted that the purpose of this study was to provide a quantitative basis for the risks of hydrogen in the built environment and to explore the effect of mitigating measures on these risks. The aim is not to impose mitigating measures. The described pros and cons of the individual measures will need to be weighed per situation. Additionally, it is important to gain experience with hydrogen as an energy carrier in the built environment through pilot projects in the coming period and to further investigate the effectiveness of measures.

8 Bibliography

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