HyDelta 2

WP6a– Hydrogen safety in the distribution network and built environment

D6a_2 – Applying QRA model to the Netherlands
D6a_3 – Results QRA model case studies

Status: final

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Executive Summary

To make an initial assessment of the risks of hydrogen in the Dutch distribution network, a quantitative risk assessment (QRA) has been conducted. It compares the risk between the current natural gas distribution system and the future hydrogen distribution system. The total risk in the analysis consists of the risk arising from leaks in the distribution network and the risk arising from leaks in the house itself.

The model simplifies the built environment in the Netherlands in order to control the number of variables and associated calculations. For this initial version, detached houses were chosen for validating the model. In addition, semi-detached houses were also used in the case study of a representative sample neighborhood. The distribution network is simplified by using a limited number of materials, pressures, and diameters. An important input parameter of the model is the failure frequency of the different components. The failure frequencies for the distribution network were determined based on historical failure reports. However, no reliable dataset for the components behind the meter (meter assembly, internal piping, and end-use appliance) could be found for the Netherlands, so values from the UK were used instead. Given the aforementioned assumptions, the model provides an approximation of the location-specific risk resulting from fires or explosions. All calculated location-specific risks in this study for both natural gas and hydrogen remain well below $1x10^{-6}$ per year, indicating a very limited risk.

Based on the aforementioned failure frequencies in the dwelling, it is found that the location-specific risk for natural gas due to leaks behind the meter aligns well with the (limited) historical data. The probability of a fatal accident in the Netherlands resulting from an explosion or fire per dwelling, based on historical data, is 0.06×10^{-6}, excluding cases involving intentional gas releases. Additionally, the probability of injuries is 1.1×10^{-6}. The model yields respective values of 0.02×10^{-6} for fatal accidents and 0.4×10^{-6} for injuries, indicating a similar order of magnitude to the historical data. The risk scales linearly with the failure frequency.

With the same set of parameters and without additional mitigating measures, it is found that the effect of explosions with hydrogen is more severe than with natural gas. The location-specific risk for hydrogen is 3.8 times greater, i.e., 0.18×10^{-6}, when the risk of carbon monoxide poisoning is not considered. When comparing the risk between hydrogen and natural gas in the house, the risk due to carbon monoxide poisoning should also be taken into account. The mortality risk due to carbon monoxide poisoning is 0.37×10^{-6} per natural gas connection. When this risk is included in the comparison, it is found that there is a shift from reduced risk due to carbon monoxide poisoning to increased risk from explosions. The total location-specific risk with the chosen set of assumptions and without additional mitigating measures is lower for hydrogen than for natural gas.

The effect of ventilation on the accumulation of (dangerous) concentrations in the house was determined by analyzing ten identical houses with different ventilation rates. For hydrogen, halving the ventilation rate increases the risk by a factor of 1.8, while doubling the ventilation rate reduces the risk by a factor of 2.2. Ventilation has a stronger effect on the risk in the dwelling for hydrogen compared to natural gas.

The factor between the total risk from the distribution network without additional measures for hydrogen and natural gas is nearly 2.5 times. Based on the assumptions made in the model and averaged per connection (7.2 million), the risk from the distribution network in the dwelling is approximately 0.2×10^{-6} for hydrogen, assuming no additional mitigating measures are taken.

To gain a better understanding of the relative effects of leaks behind the meter and from the distribution network, a case study of a representative neighborhood was analyzed. This neighborhood consists of 57 homes connected to a 100mbar main pipe through service lines. The 100mbar network is fed by an 8 bar steel pipe running through the neighborhood. The 100mbar network is modeled in several segments with different materials and diameters. The homes are modeled based on their surface area and include both detached and semi-detached houses. Additionally, the risk posed by leaks behind the meter has been determined for each of the homes.

The likelihood of leaks leading to the accumulation of gas inside a home is higher for leaks behind the meter. For hydrogen, it appears that the majority of the location specific risk is caused by leaks behind the meter (approximately 73%). The remaining portion is caused by the main pipe and service line connected to the home, as well as nearby sections of the mains. Generally, the contribution of the 100mbar pipe is greater than that of the 8 bar pipe, depending on the distance between the homes and these pipes. The risks are highest for semi-detached houses compared to detached houses. Similar to the aforementioned risks, the impact of explosions is greater for hydrogen than for natural gas. However, the overall risk per dwelling in the neighborhood is lower for hydrogen compared to the risk posed by natural gas when considering the contribution of carbon monoxide poisoning, as indicated in the summary below. It is important to note that even without additional measures, the total risk remains well below $1x10^{-6}$ in both cases, indicating a relatively small risk.

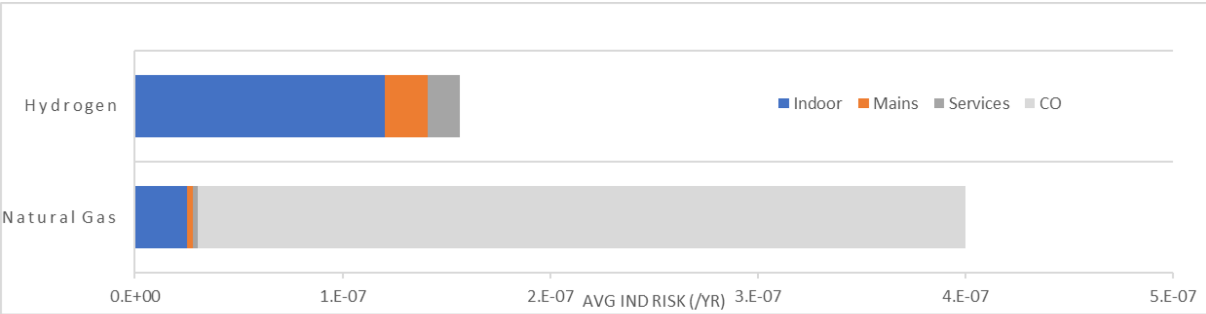

Figure 1 Average location-based risk per home in the example district for hydrogen and natural gas

In summary, it is concluded that the risks calculated in the model are relatively small. In perspective, the total number of fatal accidents in the Netherlands in 2021 was approximately 6,500. The majority of these accidents were caused by accidental falls (5,430, corresponding to a risk per resident of approximately $3x10^{-4}$/year). The total number of fatal accidents caused by smoke, fire, and flames in 2017 was 43, corresponding to a risk of $2x10^{-6}$. The share caused by natural gas in the built environment is a fraction of this.

The risk associated with hydrogen can be reduced by achieving lower failure frequencies. It is found that spontaneous leaks in frequently occurring parts of the network (100mbar) contribute most to the total risk. Damage from interference is detected earlier, resulting in less frequent accumulation of gas to dangerous concentrations in enclosed spaces. The greatest effect can be achieved through mitigating measures that reduce the frequency of spontaneous failures in pipelines or components, such as periodic leak detection or the replacement of couplings that often lead to leaks. An initial assessment has been made of the impact of excess flow valves and gas sensors with acoustic signals applied to the risk of hydrogen in the case study of a typical neighborhood. This is based on (yet) unpublished initial calculations applicable to the UK situation. The approximation shows that excess flow valves, depending on the assumptions in the model, can achieve a potential risk reduction for hydrogen of approximately 20%. For gas sensors, the estimated reduction is about 27%.

The results described in this report were obtained considering the set of assumptions as described. In this simplified model of the distribution network and built environment, several refinements of the model are possible. It is recommended to further improve the model by incorporating a greater variety of housing types. The model mainly used detached houses. The effect of explosions is calculated for nearby homes in the model, resulting in a higher risk for semi-detached houses. In a refined version of the model, a distribution of housing types (detached/semi-detached/row houses/small apartments, etc.) should be applied. One of the assumptions used, considered currently as a limitation of the model, is that PVC pipes have the same leak size distribution as PE pipes. In practice, this may be different. Hard PVC has a more brittle character and may potentially lead to more brittle fractures. This results in a different leak size distribution, which consequently affects the calculated risk. Further research on the leak size distribution is recommended. Lastly, it is recommended to model the effect of the excess flow valve and gas sensors. Based on initial outcomes from the UK, an initial estimation has been made. It is advisable to expand the model for the Netherlands by simulating the implementation of these measures.

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1 Introduction

To make an estimate of the risks associated with the use of hydrogen in the distribution network and built environment compared to natural gas, it is important to know the differences in failure probabilities and their impact. The probability relates to the possibility of a dangerous situation occurring; The effects can be expressed in terms of damage caused by a resulting fire or explosion. Mitigating measures are then aimed at reducing either the probability of a dangerous situation arising or its impact.

To this end, the HyDelta program defines the work package 'Hydrogen and Safety' in which the main objective is formulated as:

Identify risks regarding the behavior of hydrogen in the event of leaks in homes and in the distribution network and define mitigating measures based on the risks.

To make an initial assessment of the risks of hydrogen in the Dutch distribution network, a Quantitative Risk Assessment (QRA) was carried out. It compares the risk between the current natural gas distribution system and the future hydrogen distribution system. In the analysis, the total risk consists of the risk that arises from leaks in the distribution network and the risk that arises from leaks in 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 to reduce this risk. The QRA model developed by DNV for a similar analysis in the United Kingdom forms the basis for this analysis.

The schematic approach as shown in Figure 2 is used to map the risks of the behavior of hydrogen in the event of leaks in homes and in the distribution network and to define mitigation measures based on the risks. In this approach, two processes can be recognized: a vertical process in which recommendations are made through a quantitative risk analysis to arrive at an acceptable risk, and a horizontal process aimed at improving the risk model for the given situation.

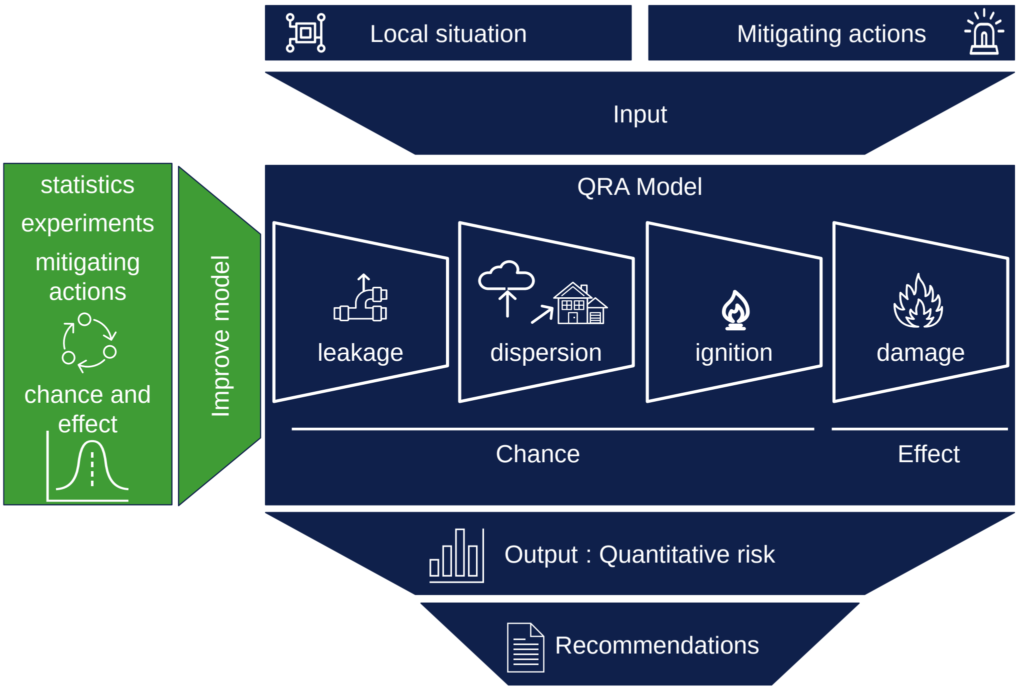


Figure 2 Model-based approach to risk analysis

Logically, the model will first have to be made suitable for the given situation, the Dutch hydrogen distribution network, before it can be applied. The original model was developed for the situation in the United Kingdom (UK) and has been validated for the risks of natural gas based on historical data. In order to demonstrate the applicability of such a model to the Dutch situation, the first phase of HyDelta made an initial effort to translate the model to the Dutch situation. There is a particular focus on the components that have a major effect on the risk and that clearly deviate in the Netherlands from the situation in the UK. In the current phase of HyDelta, the model will be further translated and the results will be validated against the historical data available for natural gas. The risks for both natural gas and hydrogen are determined below for a number of situations. Subsequently, the specific cause of increased risks is determined and the influence of mitigation measures can be estimated using the model.

1.1 Preconditions of the model

The model developed in HyDelta considers the gas distribution system for pressures up to 8 bar, as operated by the regional network operators. Gasunie's regional and high-pressure transmission network is not included in this analysis. More specifically, we focus on the following points in the model:

- Underground mains in the distribution network
- Connecting service pipes between the mains and the meter connection in the house
- The indoor installation in the house

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

1.2 In this report

In this report, an analysis is carried out for the risks of hydrogen in the Dutch distribution system using the quantitative risk assessment model. Chapter 2 discusses the historical data of natural gas incidents as a starting point for the validation of the model results. In Chapter 3 the methodology is given by describing the general steps that the risk model follows. Chapter 4 focuses on the translation of the model to the Dutch situation. The starting points and thus import values for the Dutch situation are also discussed here. Chapter 5 presents the calculated risk for leaks behind the meter for both natural gas and hydrogen. The effect of ventilation and a sensitivity analysis of the introduced failure probabilities are also discussed. Chapter 6 presents the calculated risks that arise in the home from a leak in the distribution network. The calculated risks are compared with the historical data available for natural gas. In Chapter 7, the outcomes of the models for risks of leaks in the indoor installation and in the distribution network are combined in a case study of a specifically defined typical neighborhood. The effect of mitigating actions is approximated in the Chapter 8. The report concludes with the discussion and conclusion in Chapter 9.

With this setup, the report combines two Deliverables for the HyDelta 2.0 project:

- D6a_2 – Applying QRA model Netherlands
- D6a_3 – Results QRA model case studies

2 Historical data for incidents

The starting point for the risk analysis in the transition from natural gas to hydrogen in this study is that the safety level of the future hydrogen network remains at least the same as the safety level for natural gas at the moment. Natural gas has been used in the built environment for decades. The associated safety level has greatly improved during that period.

In the Netherlands, failures involving natural gas in the distribution network must be reported by network operators to the relevant regulator. This historical data of incidents that have taken place in the Dutch natural gas distribution network in recent years play a major role in validating the QRA model. Where relevant, the risk calculations are always carried out in duplicate: for natural gas and for hydrogen. The results for natural gas are plotted against the available historical data and this allows the validity of the model to be determined. If the results are sufficiently similar for natural gas, the results of the same calculation for hydrogen are also considered realistic, without available historical data.

In this report, the validation of results makes use of the analysis of incident registration in the Netherlands in natural gas distribution networks, carried out by Kiwa in HyDelta WP1a (D1A1) [1]. A distinction is made between incidents caused by a leak behind the meter (2.1) and by a leak from the distribution network up to the gas meter (2.2).

2.1 Risk in home due to leak behind the meter

Kiwa's analysis of the incidents after the meter, which is usually located in the house itself, can be found in Table 1. The table contains data on incidents (such as numbers), which is translated into a quantitative expression in the form of the probability of a victim per gas connection. For this purpose, a distinction is made between carbon monoxide poisoning and fire and/or explosion. Instances involving an intentional incident, deliberate cases, are listed separately for the latter type of incidents.

Table 1 Overview of natural gas incidents in the Netherlands behind the meter (period 2010-2020) by average number per year. Chance per connection (≤G6), for 7.2 million connections. There may be multiple victims per incident.

Type of incident behind the gas meter	Number of natural gas incidents	Probability per connection x 10^{-6}	Number of fatalities	Number of injured *	Number of major damages #)	Chance of victim per gas connection x10^{-6}
Carbon monoxide poisoning	39,5	5,5	2,64	138,2	-	0.37 (fatality) 19.2 (injured)
Fire and/or explosion (excluding intentional cases*)	14,5	2,0	0,45	7,8	14,5	0.06 (fatality) 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 releasing a lot of natural gas, etc.*
#) Major material damage: more than € 10,000.
**) Injured persons: persons who are treated after an incident and/or transported to the hospital for further treatment*

The QRA model bases the outcome of the risk calculations on the consequences of explosions and fires. For the validation of the results for the risk of natural gas behind the meter we consider the "Probability per connection" for "Fire and/or explosion (excluding intentional cases)" as listed in the Table above. The values in the table are expressed in fatalities (0. 06 x 10^{-6}) and injuries (1. 1 x 10^{-6}) with a ratio of about 20 (injuries to fatalities). The consequences of carbon monoxide poisoning are not calculated by the model and therefore the corresponding historical data is not used for model validation. However, this risk must be taken into account when comparing the total risk behind the meter between natural gas and hydrogen. According to Table 1, the probability of a victim of carbon monoxide poisoning is 0.37 x 10^{-6} per natural gas connection. With hydrogen, no carbon monoxide is formed during (incomplete) combustion.

2.2 Risk in home due to leak from distribution network

Kiwa's analysis of the consequences of leaks in the distribution network for the period 2014 – 2020 can be found in Table 2. The table shows the number of fatalities and injuries per year as a result of leaks in mains and services, which together form the distribution network. These data cannot be subdivided into pipe materials, pressure regimes and diameters. We assume that the materials used during this period will almost correspond to the intended materials for the future hydrogen distribution network[1].

Table 2 Overview of the number of gas incidents in the distribution domain leading to injuries (dead or injured person in the Netherlands)

	Fatalities	Injuries (bystanders/ residents)
2020	0	0
2019	0	10
2018	0	1 (+1 doubtful if this was due to the gas)
2017	0	2
2016	0	8
2015	0	8 (of which 2 due to meter cupboard fire with unknown cause)
2014	2	10 (+6 inhalation of gas + 10 inhalation of smoke)
Average	**0.3**	**~ 6**

Fortunately, the number of fatalities due to gas incidents from the distribution domain in the Netherlands is very low. A single incident, or lack thereof, has a major impact on the average number of fatalities per year that can be used to validate the results of the natural gas model. With the available data, this figure amounts to approximately 0.3 fatalities per year as a result of leaks from the distribution network. Regarding injuries, this number comes to about 6, based on the consequences of fires and explosions. The ratio of the number of injuries to fatalities is about 20.

[1] As described below, 4% of the length of the pipe network still consists of cast iron and asbestos-cement pipes. In the modeling we assume that these have been replaced by modern materials.

3 Methodology

3.1 Description risk model

Within DNV, a standardized risk analysis method has been developed for risks of the distribution network (CONIFER: Calculation of Networks and Installations Fire and Explosions Risk). The model was originally developed as a risk analysis model for the UK gas network to determine prioritization in replacing cast iron pipes with polyethylene (PE). The model has been further developed over the years. The model is based on incident data, measurement data (specific to the model) and validated model data. As part of the H21 project in the UK, the model has been adapted and validated for hydrogen transport systems. To this end, additional experiments have been carried out in the UK and the results have been implemented in modules in the model.

Details for the model and its development are given in the QRA reports for H21 [2] [3] [4]. The modules in the model are built in a software package by DNV and allow modeling of the risk, given the following input parameters:

- Materials, such as steel and polyethylene (PE), gas pressures and diameters for the mains and services.
- Natural gas, fully hydrogen and all blends in between as gas that flows through the pipeline.
- Various causes of leakage: Spontaneous and third-party damage (external interference)[2]. The failure frequency for these causes is input to the model.
- Physical phenomena such as outflow, dispersion, accumulation and ignition of gases.
- The layout of the indoor installation including the meter[3], piping and household appliances.
- Different layouts of houses, such as type of houses (bungalows, terraced houses, semi-detached houses and detached houses) including different sizes of rooms, presence of cellars and presence of residents.

The results, including the effects of explosions and fires, are ultimately translated into locational specific individual risks or societal/group risks.

The model can be used for both leaks due to external interference and for leaks due to failure of the infrastructure itself. Even if these causes are treated differently, both can lead to above-ground fires, or dispersion of the gas through the subsurface to enclosed spaces (e.g. houses) and possibly lead to explosions there. The results of the model are risks of fatalities but also probabilities of fires or explosions.

The model is modular and consists of several individual models, as shown in Figure 3, Figure 4, Figure 5 and Figure 6. Each of the numbered steps in the figures contain detailed submodels that go beyond a single (set of) equation(s). Details about these submodels are given in [2], below is a brief summary. A distinction has been made between leaks from the distribution network and leaks behind the meter. The first three figures deal with the leaks from the grid, the leaks from the indoor installation are discussed afterwards.

[2] Damage by third parties or external interference is caused by human interaction such as excavation damage in which a pipe is accidentally hit. Spontaneous damage is defined as damage without direct human interaction. For example, the failure of couplings or corrosion.

[3] In the Netherlands, the meter, together with the service, belongs to the connection for which the network operator is responsible. However, the model includes leaks in the meter setup in the indoor installation.

3.2 Leaks in the distribution network

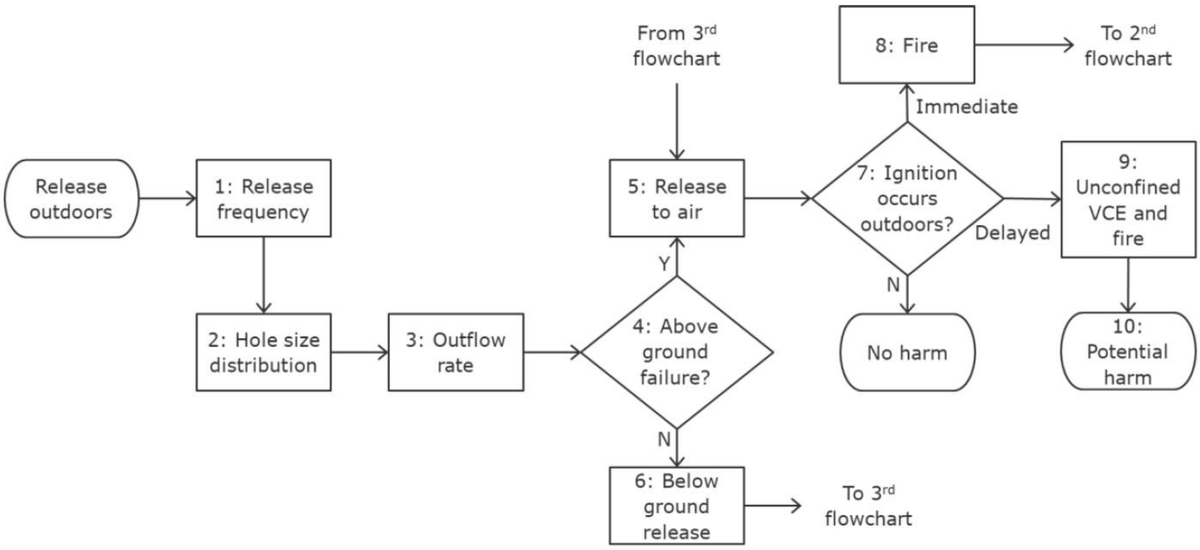


Figure 3 Structure of the QRA model: risk of leakage from the grid. (first flow chart)

For leaks from the distribution network, the model starts with an outflow of gas, in which the failure frequency, the number and size of the leaks and the outflow quantity are determined in the first steps. Based on the materials, pressures and diameters used in the natural gas system, an estimate can be made for the failure frequencies in the pipe fracture model based on incident data. In the Netherlands, leaks and incidents in the distribution network are registered in the 'Nestor' registration database. The vast majority of these were found in services and were classified as urgent. The nature of the leaks varies in terms of size and speed of development. Aging and corrosion are often smaller leaks that slowly increase in size while the failure of couplings, saddles, loosening of connections due to sagging soil and the like and fractures in brittle materials occur suddenly and directly result in significant gas outflow. Due to differences in materials used, pressures and layout of the distribution network, the data used in the model for the UK will not be 1-on-1 applicable for the Netherlands.

In the Dutch version of the QRA model developed for HyDelta, the following steps are taken, based on Dutch historical leak data and the structure of the distribution network.

- The frequency of each leak is determined by the pipe properties (such as pressure, diameter and construction details) and failure mode (interference and/or spontaneous). Each failure mode is considered sequentially in the following steps.
- Based on the same data used in the first step, the probability is determined across a range of leak sizes. Specific data for the leak size is rare, in the event of incidents the size of the leak is often not recorded. In the model for the UK, a set of assumptions has been made for natural gas, it is assumed that this distribution also applies to hydrogen.
- The outflow rate is determined for each leak size. The differences between the amount of hydrogen and natural gas that are released at a given pressure and leak size have been validated in practice in H21.

The amount of gas flowing out of a leak is determined by the leak size, the gas pressure (30 mbar, 100 mbar, 1 bar, 4 bar and 8 bar), the back pressure that the outflowing gas experiences, whether and what kind of ground cover and top layer (tiles, pavers, asphalt, grass) and where it can flow to (crawl space, basement, meter cupboard, house, ground surface and the like).

The underground behavior and the probability of ingress to a cellar and the like can be approximated from the statistical data for natural gas. Models are also available that simulate the behavior of flow through different soil types, indoors and in the open air. This can provide a good indication of the possible differences in behavior between hydrogen and natural gas.

It is important to determine which types of soil form the coverage of pipes and which pavement is present, which volume basements, crawl spaces, meter cupboards and other indoor spaces have. Based on the experimental program of H21 (phase 1b), an adapted model has been developed for the flow of hydrogen through the soil towards a house.

In Figure 3 step 4, a distinction is then made for outflow to the open air resulting in a fire, and underground movement of the gas to enclosed spaces. This last step is further elaborated in Figure 5. From the data described above, it can be deduced which concentrations will occur in relation to weather conditions (moist soil is less permeable; wind changes the size and concentration in the gas "cloud") and how these can be detected, for example during leak detection.

The energy required to ignite hydrogen and natural gas varies with the concentration of the respective gas-air mixture. In the model, a probability of ignition is estimated based on the presence of potential ignition sources, but also on the basis of the duration of presence of residents in the home and their reaction to detecting a leak. On the one hand, the probability of the presence of residents determines the potential damage to persons, as described in the following flow chart (Figure 4). On the other hand, residents can reduce the risk of damage by, for example, acting whenever smelling odorant, such as opening windows and doors and alerting the emergency services.

Should an ignition lead to a fire, Figure 4 describes the steps taken to determine the risk. Based on the heat radiation of the ignited hydrogen, the probability is determined for the house to catch fire and that residents will not be able to escape the house. In the event of a burning house, these probabilities are no different for hydrogen than for natural gas, so that the existing model for natural gas can also be applied here. The model assumes that 10% of residents do not escape the house, which is a conservative assumption. Because most fires as a consequence of excavation damage occur during the day, this chance appears to be smaller in practice.

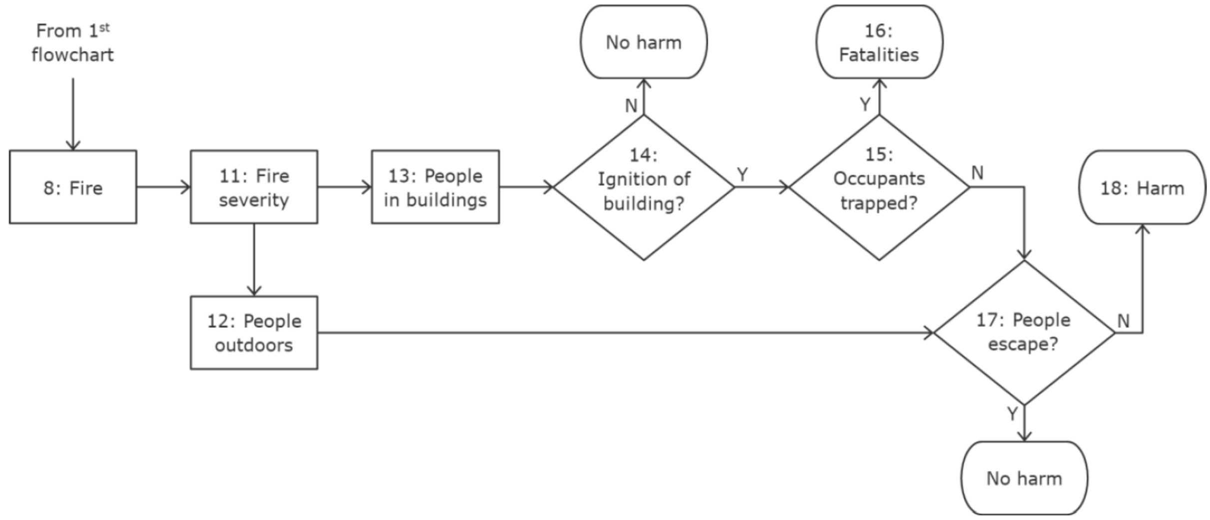


Figure 4 Structure of the QRA model: effects of fires. (second flow chart)

In the case of a gas ingress, which arises outside the house and moves into an enclosed space, there is a probability of an explosion. Figure 5Figure 5 shows the steps that are followed.

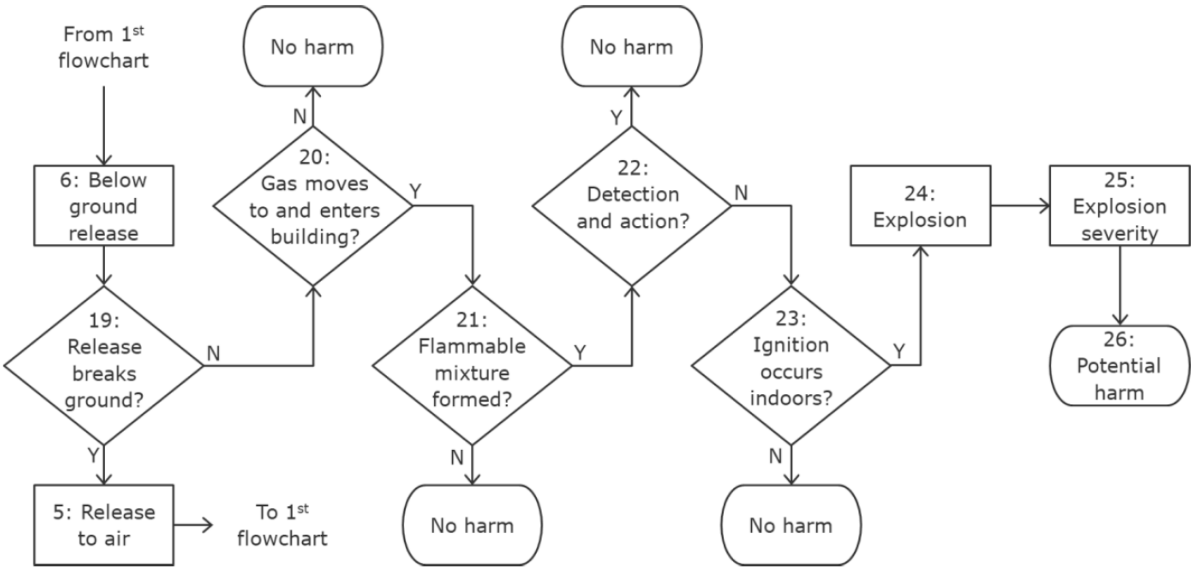


Figure 5 Structure of the QRA model: effects of explosions (third flow chart)

The accumulation of hydrogen in the house (step 21) takes into account the effect of ventilation in the house and the dispersion of hydrogen to different rooms in the house. Based on experimental research in H21, these models for hydrogen have been validated. Depending on the presence of persons in the home, who may notice a leak due to odorized gas or by sensors, the probability that potential ignition sources cause an ignition in the home is estimated. The concentration of hydrogen at the time of ignition is included in the models. Especially for explosions, the overpressure is very dependent on the concentration of hydrogen. Potentially, hydrogen explosions are much more harmful than natural gas explosions, close to a stoichiometric mixture. At lower concentrations (between 5 and 10 vol%), the effects of hydrogen are equal or less compared to natural gas.

For explosions, the overpressure is calculated in the model. In case of explosions of hydrogen (above 10 vol%) the overpressure is greater than for natural gas. Based on the overpressure, an estimate is made for the number of victims. As with the fires, this estimate for victims at a given overpressure for hydrogen is the same as for natural gas.

3.3 Leaks behind the meter

For leaks behind the meter a simplified scheme is used in the indoor installation as shown in Figure 6. Based on the historical data for natural gas an estimate is made of the failure rate of the various components of the indoor installation. In the model the indoor installation is divided into the meter installation, the interior piping and the end-user equipment. For each component the spontaneous and interference probability of failure is the input for the model. Given the distribution of leak sizes, the amount of gas entering the house is determined. The chance of the formation of a flammable mixture is determined on the basis of the concentration that is formed, partly determined by the ventilation rate. The ventilation rate can be adjusted in the model per house. In the risk calculations in this study, the sensitivity of the ventilation rate was determined. Finally, the risk of ignition, just like ignition of gas due to accumulation of gas in homes as a result of leaks outside the home, determines the strength of the explosion and therefore the consequences.

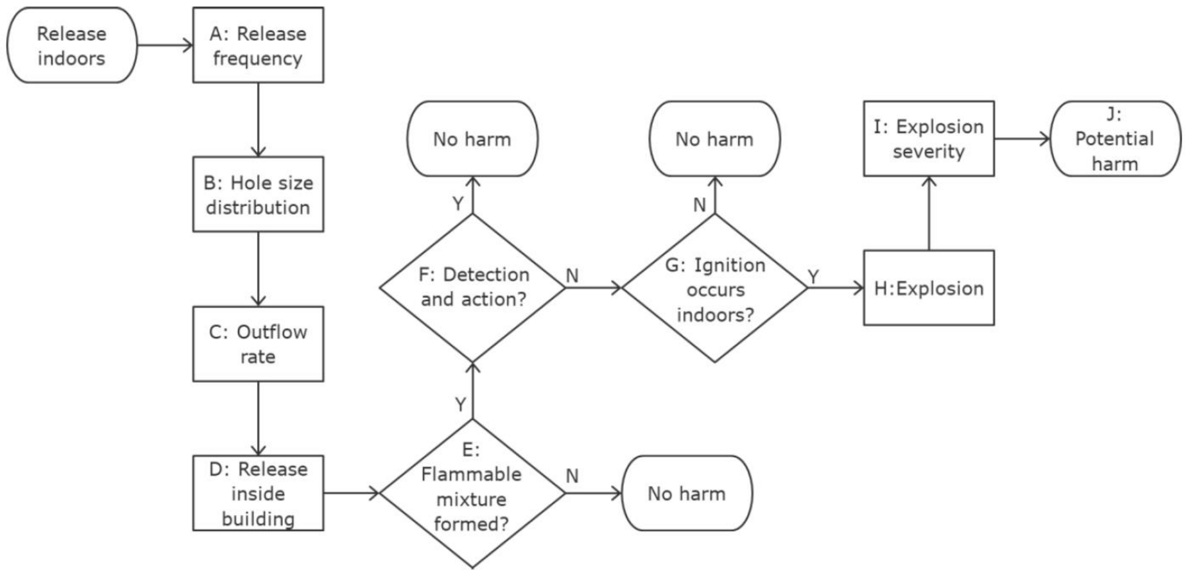


Figure 6 Structure of the QRA model: leaks in the indoor installation

4 Modifications Dutch model

In a quantitative risk analysis, the probability of leakage and its impact are calculated for a given situation or configuration of the network and connected homes. The developed model takes into account a number of parameters for the distribution network:

- Pressures used
- Variation in diameter of the mains
- Materials used in the mains (e.g. steel or PE)
- PE couplings (e.g. electro welding)
- Depth of pipes in the ground
- Configuration of the service construction
- Configuration of the indoor installation
- Failure frequencies per system component (split into spontaneous and interference)

In the QRA model developed for the Netherlands, the above parameters are described in this chapter. The focus is on the variation in pressures, diameters and materials and the distance from the houses to the mains which specifically occurs in the Netherlands.

4.1 The current network

This chapter describes the assumptions for the Dutch network and homes as they are included in the modelling. In order not to make the model unnecessarily complex, it was decided in this phase not to include the cast iron and asbestos-cement pipes that are still partly used in the current natural gas system (together only 4%). It is expected that these materials will not be used in the future hydrogen distribution networks and will be replaced by PE or (impact-resistant) PVC pipes.

The assumptions described here are used for the current natural gas network and for the future hydrogen network. It is also assumed that the composition in terms of materials will remain the same in both situations, with the exception of the aforementioned materials. New homes to be built are connected by PE or (impact-resistant) PVC services.

4.1.1 Mains

The risk analyses use five common pressures and four representative diameters. Each of the four diameters represents a range of diameters, for example 160 mm is used for all diameters between 125 mm and 200 mm.Table 3 shows the representative diameters used.

Table 3 Representative diameters with the corresponding range of diameters as used in the model

	Outside Main pipe diameter (mm)			
Range of diameters	≤ 63	75 –110	125 – 200	>250
Representative diameter in the model	63	110	160	315

The common pressures and material types in the main pipeline network are listed in Table 4. Data from 2020 was used. The values in the table indicate the fraction of these pressures and materials in the total grid.

Table 4 Percentage of mains by pressure and material type for the Netherlands

	30 mbar	100 mbar	1 bar	4 bar	8 bar	Total
PE	0.8%	9.6%	0.6%	5.1%	1.1%	17.2%
Hard PVC	1.1%	15.2%	0.0%	0.0%	0.0%	16.3%
Impact PVC	5.7%	43.0%	0.0%	0.0%	0.0%	48.7%
Steel	0.1%	3.3%	0.2%	0.5%	9.7%	13.7%
Grey cast iron	1.0%	1.1%	<0.1%	<0.1%	0.0%	2.2%
Ductile cast iron	0.2%	0.5%	0.1%	0.0%	0.3%	1.2%
Asbestos-cement	0.2%	0.4%	0.0%	0.0%	0.0%	0.6%
Other	0.0%	<0.1%	0.0%	<0.1%	<0.1%	<0.1%
Unknown	0.0%	<0.1%	0.0%	<0.1%	0.0%	<0.1%
Total	9.2%	73.1%	0.9%	5.6%	11.1%	100.0%

As mentioned earlier, in this version of the model, the cast iron and AC pipe sections are not included in the calculations because they only make up a small fraction (4%) and will not be used in the hydrogen network. The small fractions in the table are assigned to the four modelled materials (PE, Hard PVC, Impact PVC and Steel). Table 5 and Table 6 show the diameter, pressures and materials used as modeled in the QRA model as a fraction of the total length of the mains network for both lower and higher (>100 mbar) pressures. The total distribution network consists largely of low-pressure pipelines (about 82%).

Table 5 Fraction of low-pressure pipes in relation to the total length, per material, pressure and diameter in the Netherlands

Fraction of the total length	30 mbar				100 mbar			
	63 mm	110 mm	160 mm	315 mm	63 mm	110 mm	160 mm	315 mm
PE	0.3%	0.3%	0.2%	<0.1%	5.2%	3.4%	1.0%	0.1%
Hard PVC	<0.1%	0.6%	0.4%	0.1%	1.8%	9.1%	4.0%	0.3%
Impact PVC	0.4%	3.1%	2.0%	0.3%	8.2%	24.9%	9.6%	0.4%
Steel	<0.1%	0.6%	0.6%	0.2%	1.2%	2.2%	1.3%	0.3%

Table 6 Fraction of high-pressure pipes in relation to the total length, by material, pressure and diameter in the Netherlands

Fraction of the total length	1 bar				4 bar				8 bar			
	63 mm	110 mm	160 mm	315 mm	63 mm	110 mm	160 mm	315 mm	63 mm	110 mm	160 mm	315 mm
PE	0.3%	0.2%	0.1%	0.1%	2.0%	2.1%	0.9%	0.1%	0.1%	0.6%	0.4%	<0.1%
Hard PVC	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Impact PVC	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Steel	<0.1%	<0.1%	0.1%	0.2%	<0.1%	0.1%	0.3%	0.1%	0.5%	3.7%	4.9%	0.9%

PVC is not used in the UK and is therefore not available within the database underlying the QRA model. For the Dutch model, it is therefore assumed that both hard and impact-resistant PVC behaves the same as PE: it is assumed that the distribution of leak sizes in both spontaneous and interference damage is the same with PVC as with PE. Differences in leak sizes between (hard and impact-resistant) PVC and PE pipes for different types of leaks will have to be further investigated and then implemented in the code of the model. This was not feasible within the current scope of the project. However, the frequencies of leakage in both PVC and PE are adjusted based on available Dutch data (see chapter 4.2).

It is assumed that the PE pipes are coupled by electrofusion. PE pipes that have been pulled through old steel or cast-iron pipes are not included in the model. The NEN standard prescribes a minimum ground cover of 0.8 m for mains. It is assumed in the model that all pipes are at a depth of 1 meter underground. The depth of the pipeline is important for determining the tracking of gas along the pipeline, whereby the ground does not break open. The studies in the UK show that these situations do not add much to the overall risk. In practice, this depth may be less and this assumption is on the conservative side. The model predicts further tracking of gas along the pipe at deeper lying pipes.

4.1.2 Services

The following assumptions have been made in the model with regard to the services, which are located between the main described above and the houses:

- All service pipes are made of PE.
- The service ends in the house at the meter.
- The length of the service is estimated at 120% of the minimum distance between the building and the main pipe.
- The diameter of the service is 32 mm by default, unless otherwise specified as for example in the case study. Larger diameters used in apartment buildings or commercial connections are not covered by the current analysis.
- The distribution of the services over the pressure regimes (30 mbar, 100 mbar, 1 bar, 4 bar and 8 bar) was determined on the basis of the supplied lengths of the connection pipes from Enexis and Alliander and was extrapolated for the total network in the Netherlands. The table below shows the distribution used. The services on the higher pressure main pipes (1 to 8 bar) are modeled at 100 mbar, because in practice no higher pressure service to homes are used[4]. For the lower pressures, the pressure in the main is adopted for the service (30 and 100 mbar).

Table 7 Distribution of pressure class services

Pressure	Share
30 mbar	15.28%
100 mbar	83.99%
1 bar	0.07%

[4] This can occur with large consumers, but these are not included in this study.

4 bar	0.27%
8 bar	0.39%

- As for the mains, a depth of 1 meter is assumed for all connection pipes. Again, this assumption is conservative and only affects a limited number of leaks. [5]

4.2 Failure frequencies

No distinction is made between natural gas and hydrogen pipelines for the probabilities of failure. This basically assumes that no new causes of leakage are introduced by the switch to hydrogen.

This report provides failure probabilities in two different categories:

- 'Interference' damage is caused by human actions in which the pipeline is damaged. Common causes of failure are excavation work, for example for structural or agricultural reasons, or work on nearby utilities, which accidentally hit the gas pipeline. Interference damage also includes intentional damage to the pipes, but this is more relevant for services than for mains.
- In the case of 'spontaneous' failures, no human interaction is required. Examples are leaks in pipes or couplings due to, for example, corrosion or ground subsidence, as listed in the table below.

Table 8 Classification of failures in NESTOR

Categories	Cause
Interference	Excavation
	Vandalism / theft
Spontaneous	Construction error (in the past)
	Corrosion / aging
	Internal defect
	Installation error (recent)
	Product failure
	Point loads
	Soil movement

Details for the leak size distribution used in the risk assessment are provided in the H21 Phase 1B project reports [2] [3] [4]. Note that the term "leak size" in this report is used for any potential leak from which gas can escape. For interference and spontaneous leaks, different leak size distributions are used. Based on natural gas statistics, a probability distribution has been made for a full-bore rupture as a function of the diameter of the main in case of interference damage. In addition, a similar probability distribution has been made for the probability of an incomplete rupture, taking the ratio between the hole area and the cross-sectional area of the pipe. For PE pipes it appears that 60% of the damages lead to a leak with a hole surface/cross area of 0.2. For spontaneous leaks, such as the leakage of a coupling, the chance is more than 90% that the hole width divided by the circumference of the

[5] According to the standard, services need a minimum ground deck of 0.4m in private land and 0.5m in public land.

pipe is less than 0.01. Spontaneous leaks mainly lead to smaller leaks compared to damage caused by third parties.

The failure data for the Dutch distribution networks is collected in Nestor. This study used the data for the years 2018-2021. Initially, the data for 2020 was used and later a sensitivity analysis was carried out for the other available years. The data from Nestor has been analyzed and combined with the pipe length data also provided for 2020, in order to calculate both spontaneous fault and fault failure frequencies for both main lines and connection lines. A subdivision is made for the diameter used, working pressure and pipe material. Due to limitations on the amount of failure data or the associated pipe lengths, in some cases the data categories were combined to provide more statistically reliable frequencies.

4.2.1 Mains

For a representation of the mains pipeline network, four different diameters were modelled for five different pressure classes and four different materials. The tables below show the probability of failure for these parameters based on the Nestor failure data and the distribution of common pipes in the Dutch distribution network.

Table 9 Failure rates per km per year, for mains with a diameter of 63mm

Cause	Material	Probability of failure (# per km per year)				
		30 mbar	100 mbar	1 bar	4 bar	8 bar
Interference	PE	0.009	0.009	0.004	0.004	0.004
	Hard PVC	0.030	0.030	N/A	N/A	N/A
	Impact PVC	0.011	0.011	N/A	N/A	N/A
	Steel	0.003	0.003	0.001	0.001	0.001
Spontaneous	PE	0.017	0.017	0.030	0.030	0.030
	Hard PVC	0.053	0.045	N/A	N/A	N/A
	Impact PVC	0.028	0.021	N/A	N/A	N/A
	Steel	0.188	0.186	0.084	0.084	0.084

Table 10 Failure rates per km per year, for mains with a diameter of 110mm

Cause	Material	Probability of failure (# per km per year)				
		30 mbar	100 mbar	1 bar	4 bar	8 bar
Interference	PE	0.009	0.009	0.004	0.004	0.004
	Hard PVC	0.019	0.019	N/A	N/A	N/A
	Impact PVC	0.010	0.010	N/A	N/A	N/A
	Steel	0.003	0.003	0.001	0.001	0.001
Spontaneous	PE	0.036	0.036	0.032	0.032	0.032
	Hard PVC	0.053	0.045	N/A	N/A	N/A

	Impact PVC	0.028	0.021	N/A	N/A	N/A
	Steel	0.134	0.316	0.023	0.023	0.023

Table 11 Failure rates per km per year, for mains with a diameter of 160mm

Cause	Material	Probability of failure (# per km per year)				
		30 mbar	100 mbar	1 bar	4 bar	8 bar
Interference	PE	0.009	0.009	0.004	0.004	0.004
	Hard PVC	0.011	0.011	N/A	N/A	N/A
	Impact PVC	0.008	0.008	N/A	N/A	N/A
	Steel	0.003	0.003	0.001	0.001	0.001
Spontaneous	PE	0.048	0.048	0.038	0.038	0.038
	Hard PVC	0.053	0.045	N/A	N/A	N/A
	Impact PVC	0.049	0.041	N/A	N/A	N/A
	Steel	0.240	0.158	0.023	0.023	0.023

Table 12 Failure rates per km per year, for mains with a diameter of 315mm

Cause	Material	Probability of failure (# per km per year)				
		30 mbar	100 mbar	1 bar	4 bar	8 bar
Interference	PE	0.009	0.009	0.004	0.004	0.004
	Hard PVC	0.011	0.011	N/A	N/A	N/A
	Impact PVC	0.008	0.008	N/A	N/A	N/A
	Steel	0.003	0.003	0.001	0.001	0.001
Spontaneous	PE	0.208	0.208	0.038	0.038	0.038
	Hard PVC	0.053	0.045	N/A	N/A	N/A
	Impact PVC	0.121	0.066	N/A	N/A	N/A
	Steel	0.279	0.215	0.023	0.023	0.023

4.2.2 Services

Since all services are modelled as 32 mm PE pipes, only one set of spontaneous and failure probabilities is used in the QRA for the different working pressures. Table 13 shows the chances of failure used for the connection pipes in the Dutch grid.

Table 13 Failure probabilities per km per year, for connection pipes with a diameter of 40mm

Cause	Probability of failure (# per km per year)				
	30 mbar	100 mbar	1 bar	4 bar	8 bar
Interference	0.038	0.045	0.081	0.081	0.081

Spontaneous	0.058	0.051	0.233	0.233	0.233

4.2.3 Behind the meter

There is also data available in Nestor for failures behind the meter. Compared to UK data, however, the Dutch data appears to be incomplete. Failures behind the meter are less frequently registered compared to failures in the distribution network, for which the network operators are responsible. For the risk calculations behind the meter, the failure probabilities for the UK are used in the model. These are shown in Table 14.

Table 14 Failure probabilities per million years, behind the meter

Probability of failure per connection per 10-6 years	Spontaneous	Interference
Meter	5720	2040
Inner piping	1460	4810
Appliances	916	3370

4.3 Distance between the houses and the grid

Two Dutch grid operators provided data on the representative distances between the mains of the network and the nearby buildings. This data has been analyzed to obtain a distribution of the proximity of buildings for each operating pressure. This approach takes into account the likelihood that a particular main is close to buildings. For example, high-pressure pipes (>200 mbar) are usually located further from buildings than low-pressure pipes. Based on this data, the number of houses located at a certain distance from each main pipeline is calculated. Table 15 gives an overview of the percentage of dwellings located close to each type of main pipeline.

Table 15 Distribution of distance of houses to the main

Distance (m)		Low pressure mains (≤200 mbar)	High pressure mains (>200 mbar)
Distance Range	Average distance		
0 to 4	2.5	25.3%	15.2%
4 to 10	8	41.2%	20.3%
10 to 20	15	19.1%	24.8%
20 to 40	30	7.8%	17.3%
> 40	50	6.5%	22.3%
Total		100.0%	100.0%

4.4 Houses and residents

To determine the societal risk, it is necessary to specify the characteristics of the homes connected to the grid, in addition to the configuration and assumptions about the gas network itself. In the model, the composition of homes in the Netherlands has been simplified and the same assumptions have been made as in the model for the UK. This includes the type and layout of the house but also the indoor systems such as pipes, the meter and end-user equipment. Furthermore, the total number of homes and the occupancy per home are important factors for determining the societal risk.

4.4.1 Definition of property

The houses are defined as follows for determining the risk from a leak both in the indoor installation and for the distribution network. For the case study, the housing configuration is modeled in a more varied way as described in Chapter 7.

- All houses are assumed to be detached houses with two floors. In the case study, semi-detached houses are also modeled. Apartment buildings cannot be included in the model.
- The house is assumed to have three rooms per floor with a total built-up floor area of 37.2 m^2. It is further assumed that:
    - The ground surface is divided per floor into rooms of 20.7 m^2, 9.9 m^2 and 6.6 m^2.
    - The ceiling height of the rooms is assumed to be 2.4 meters.
    - There is a meter cupboard.
- The facade of each building, parallel to the route of the main road, is assumed to be 7 meters wide.
- All houses have double glazing, which affects the predicted overpressure in case of internal explosions.
- The houses do not have a basement or crawl space.
- Different ventilation rates are applied to the houses (0.04 – 4 h^{-1})
- The indoor installation consists of a meter in the meter cupboard, inner pipes distributed over the three rooms and a gas appliance.

4.4.2 Number of houses and number of persons per house

The Dutch QRA is based on the following population and attendance assumptions:

- 7.2 million homes connect to the network
- Average of 2.4 people per house
- 75 % presence of persons

Note that the English model is capable of using more advanced attendance patterns than described above. Three generic attendance patterns are used to represent the population of homes in the H21 Phase 1B project. The three patterns represent 50%, 75%, and 100% occupancy for the individual, and can be combined to specify the total occupancy pattern of all occupants of a home. The 50% and 75% occupancy patterns are more likely to have a person in the house at night than during the day, taking into account different population levels in three-hour periods.

The explosion risk calculations can consider the probability of fatalities in houses physically connected to those in which the explosion takes place. However, the initial modelling only considers individual houses and casualties that may occur there.

4.5 Other assumptions

Various other assumptions used in the risk calculations include:

- For a pipeline, the probability of failures is the same at each location along their length.
- In the event of a failure from a main, statistics from the UK suggest that in 6% of cases the release finds a tracking route through the ground and flows along a pipe to a nearby building. This applies to all types of gases, but the amount of gas depends on the physical properties. This is applied for each building individually, so the chance increases if there is more than one building near the release point. It doesn't account for leaks that find tracking routes to multiple homes, which could divert gas away from the home being assessed. In the event of a given failure from a service, this ratio is 24% for the house to which the pipeline connects. This is roughly equivalent to a gas leak in the service, for which in 50% of cases the gas finds a tracking route that leads to the connected house in half of those cases.
- In the event of leaks outside buildings, both from main and service, the properties of the soil are taken into account when predicting the outflow flow.

With the aforementioned assumptions, it is assumed that the greatest influences on the risk have been included in the calculations. For further details of assumptions, please refer to H21's reports.

5 Results risk due to a leak in the indoor installation

Based on the assumptions described in the previous chapter for the configuration of the indoor installation in the house and the associated chances of failure, the gas inflow and its consequences in the house are calculated. To validate the model, the situation for natural gas is considered first. Then the results for hydrogen are discussed and the effect of ventilation in the house is examined.

We note that the results shown in this chapter are calculated based on a simplified representation of reality, for example, only one type of home has been used. The purpose of the validation is therefore to get in the right order of magnitude.

5.1 Natural gas

5.1.1 Ingress

Based on the chosen failure probabilities of both the meter installation and the indoor pipe and the gas appliance, the number of times in which an ingress will occur in the house is determined. The frequencies per year per home are shown in Figure 7. In the reference situation[6], a ventilation rate of approximately 0.8 hours^{-1} is assumed. Due to the size of the rooms, physical properties of the gas and the ventilation rate, the concentration in the house can increase or decrease. Compared to the total number of gas ingresses, 2.4% of cases reach a concentration of 20% of the lower flammability value (LFL). At this concentration, the odorized gas will be smellable. In 0.9% of all inflow cases, the concentration will exceed the LFL and a flammable mixture is present in the house. Based on the probability of ignition of this mixture, an explosion will occur in 0.01% of all ingress cases.

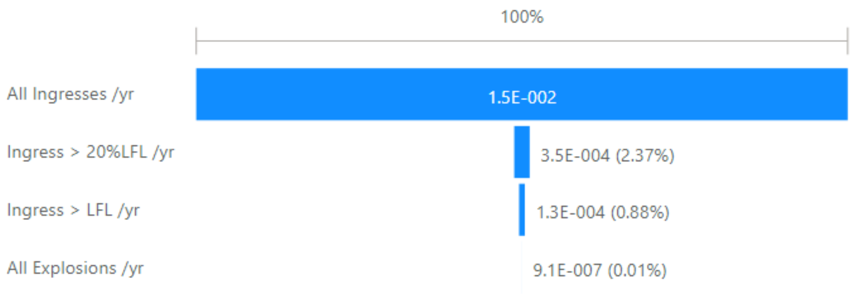


Figure 7 Inflow and concentration build-up frequencies for natural gas in the reference home due to a leak in the indoor installation.

5.1.2 Risk validation

The model thus indicates that the probability of an explosion per year is about once every two million gas connections (1.8 x 10^{-6}). Based on the concentration of the gas in the event of an explosion and the associated overpressure of the explosion, the risk of injury or fatality is determined. These probabilities are shown in Figure 8. The model calculates that roughly half of all explosions can result in at least injuries, and about 8% have the power to cause fatalities. If the presence of people in the home is taken into account, this leads to an average individual risk of more than 2 x 10^{-8} per year.

[6] Based on ventilation measurements at the test house on Spadeadam. This property is probably slightly worse ventilated than the average in the UK.

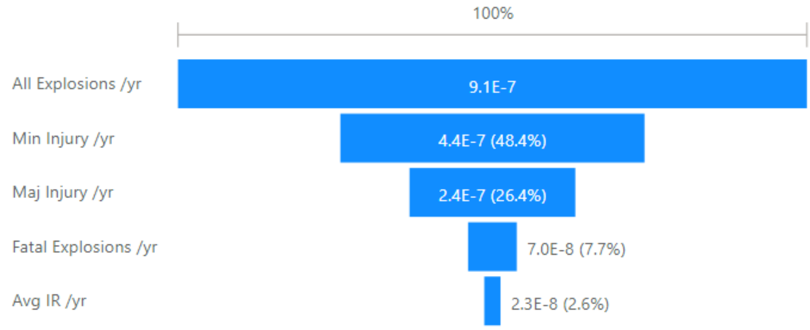


Figure 8 Individual risk in natural gas explosions due to a leak in the indoor installation.

The calculated individual risk corresponds well with the historical accident data for natural gas as described in Chapter 2. Table 1 shows that the probability of a fatality in the Netherlands as a result of an explosion or fire per house is 0.06 x 10^{-6}, excluding intent. In addition, the probability of injuries is 1.1 x 10^{-6}. The model gives respectively 0.02 x 10^{-6} for fatalities and 0.4 x 10^{-6} for injuries and thus delivers the same order of magnitude as historical data. The ratio of injured victims to fatalities is also almost the same in both the historical data and the results of the model (historical: 1.1/0.06 = 18; model 0.44/0.023=19). These risks do not include the risk of carbon monoxide poisoning which is greater with natural gas than the risks shown here. The probability of a victim from carbon monoxide poisoning is equal to 0.37 x 10^{-6} per natural gas connection according to Table 1.

The individual risk as calculated by the model scales linearly with the probability of failure, as shown in Figure 9. With twice as large or small a chance of failure of the indoor installation, the risk will be twice as large or small, respectively. If mitigating measures can reduce the risk of leakage by a factor – for example by regularly testing for leaks of the indoor installation – it is expected that the risk can be reduced by the same factor based on the calculations. Because the results of the default values for the probability of failure already correspond well with the historical data, the probability of failure will not be further adjusted in the remainder of this study.

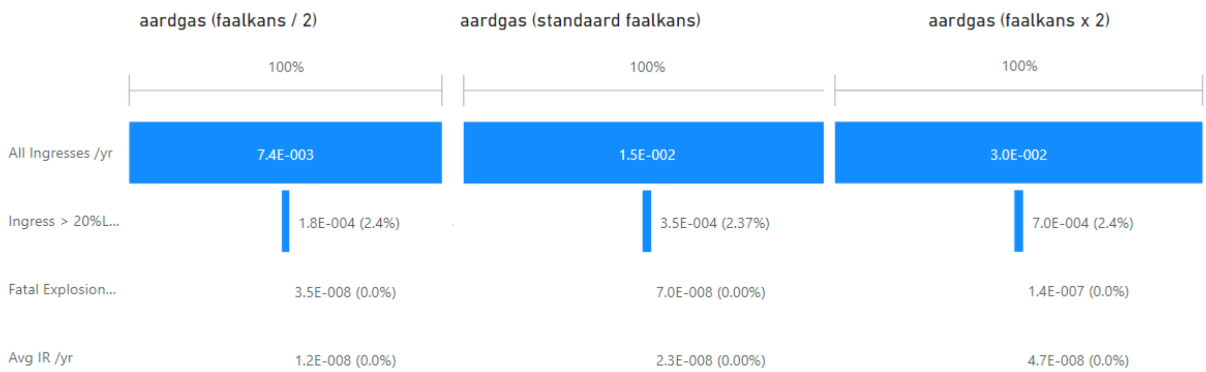


Figure 9 Effect of failure frequency on natural gas model outcomes in the event of a leak in the indoor installation.

5.2 Hydrogen

By using the same settings as for natural gas in the calculations for hydrogen, the difference in risk between the two gases can be understood. This assumes that the same indoor installation is used for both gases and that it has the same failure frequencies as is currently the situation for natural gas.

There will probably be fewer hydrogen appliances per home, and therefore fewer indoor pipes. This assumption is therefore conservative.

5.2.1 Difference in ingress due to a leak in the indoor installation

Figure 10 shows the differences in concentration build-up between natural gas and hydrogen. Because both calculations use the same failure probabilities of the indoor installation, the total number of ingress events is identical in both situations and the same distribution of outflow size is used. However, due to a difference in the physical properties of both gases, the amount of gas that escapes will be different. With the same ventilation rate in the houses, but different LFL and UFL values of both gases, different chances of a concentration build up arise. With hydrogen, the lower ignition limit will be reached about 1.5 times more often, see Figure 10. The high upper flammability limit of hydrogen (75 vol.%) is not reached, according to the calculations, in contrast to the situation for natural gas. The total number of explosions when the accumulated concentrations are ignited is more than 2 times higher with hydrogen.

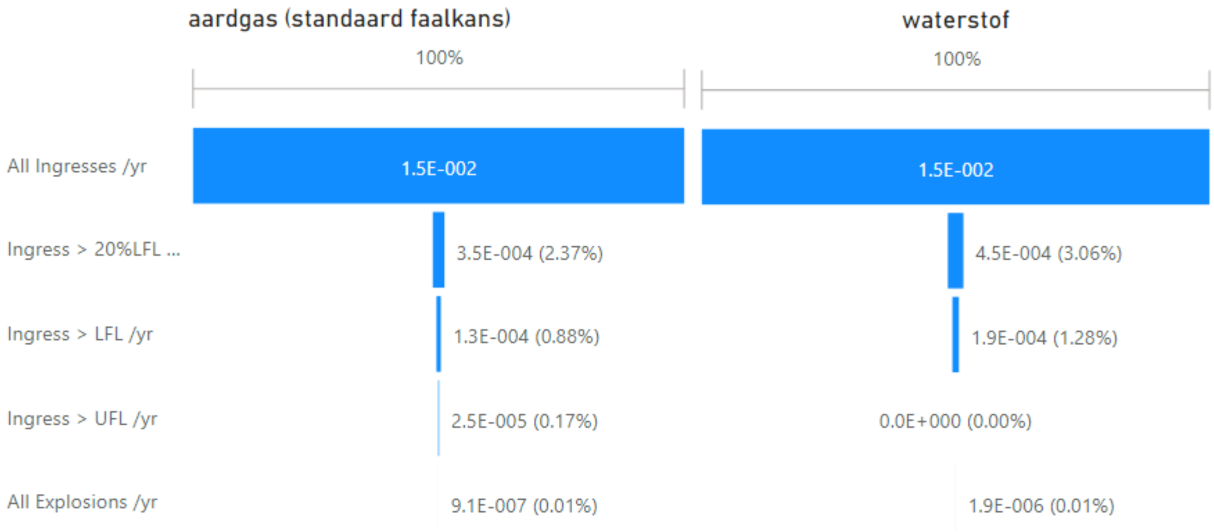


Figure 10 Difference in inflow and concentration build-up of natural gas and hydrogen with equal chances of failure of the indoor installation.

5.2.2 Difference in risk due to a leak in the indoor installation

The effect of the explosions on hydrogen is more severe than on natural gas, as shown in Figure 11. The upper part of the figure shows the number of explosions per year with at least an overpressure of 40 to 200 mbar. It is clear that the larger explosions with higher overpressures occur more often with hydrogen compared to natural gas. As a result of these larger overpressures, the number of injuries and fatalities is also higher with hydrogen. Taking into account the presence of people in the home, the individual risk of a fatality is a factor of 3.8 greater with hydrogen, without additional measures. In order to reduce the difference in risk, leaks that lead to explosive concentrations in the home (>10vol%) will therefore have to be prevented by targeted measures. In the next section, the effect of ventilation is discussed further.

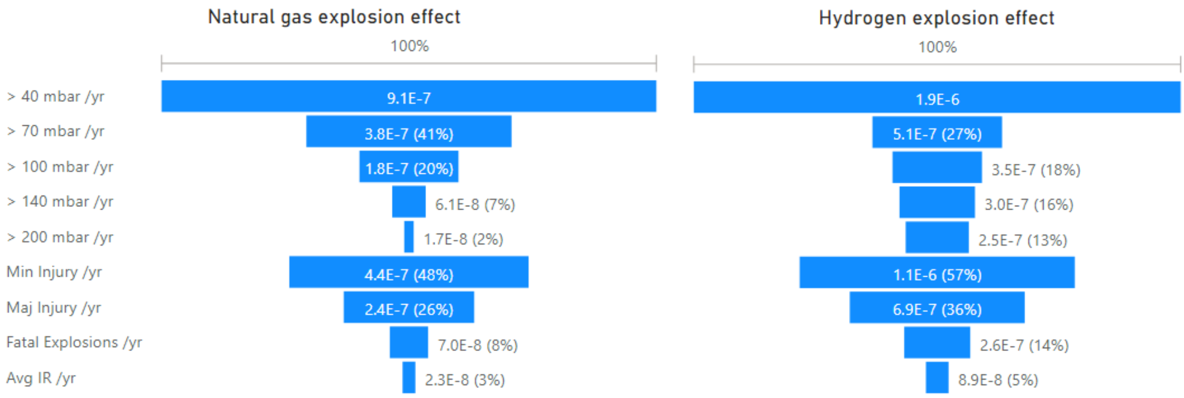


Figure 11 Difference in the effect of explosions between natural gas and hydrogen due to a leak in the indoor installation.

A comparison of the risk between hydrogen and natural gas in the home will also need to include the risk due to carbon monoxide poisoning. Table 1 indicates that the risk of a fatality due to carbon monoxide poisoning is 0.37 x 10^{-6} per connection. When this risk is included in the equation, it appears that there is a shift from the reduced risk due to carbon monoxide poisoning to an increased risk from explosions. As the next section will show, with hydrogen, the risk for explosions due to leaks in the distribution network will also increase. In addition, the simulations described here do not consider the effects of an explosion in a home on nearby homes. The case study (Chapter 7) does consider this effect.

Figure 12 Comparing individual risk of hydrogen and natural gas for explosions due to a leak in the indoor installation and CO poisoning.

5.3 Effect of ventilation

The effect of ventilation on the build-up of (dangerous) concentrations in the home was determined by calculating a dozen identical homes with different ventilation rates. In this calculation, all other parameters are kept constant and we assume the previously used failure probabilities. The concentration build-up and associated individual risk has been determined for both natural gas and hydrogen. The model offers the possibility to increase or decrease the ventilation rate of the reference by a factor. It was decided to model a series of houses with a factor between 0.05 and 5. Given the reference situation with a ventilation rate of 0.8 $hours^{-1}$, this results in a ventilation rate between 0.04 $hours^{-1}$ and 4 $hours^{-1}$. Changing the ventilation rate has an effect on the build-up of concentration in the home. For natural gas, this effect is shown in Figure 13.

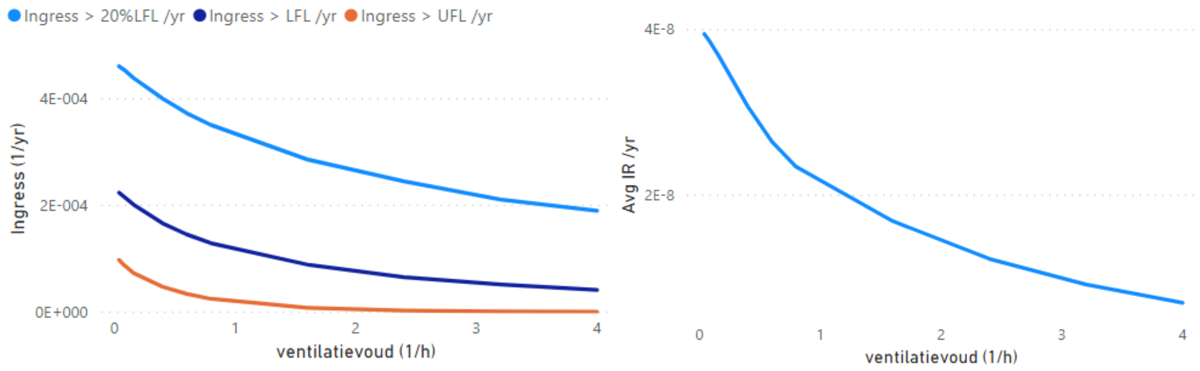


Figure 13 Effect of ventilation on the concentration build-up (left) and the individual risk (right) in the event of leakage in the indoor natural gas installation.

At lower ventilation levels, the number of times a concentration exceeds the LFL increases sharply. As a result, the individual risk also increases. In the case of natural gas, halving the ventilation rate increases the risk by a factor of 1.3, while doubling the ventilation results in a reduction of the risk by a factor of 1.3. With hydrogen, this effect is stronger.

In the case of hydrogen, halving the ventilation rate increases the risk by a factor of 1.8, while doubling the ventilation results in a reduction of the risk by a factor of 2.2. In the case of both natural gas and hydrogen, an increase in the ventilation rate results in approximately equal reductions in the probability of a concentration above the LFL. Because the effects of a possible explosion are greater with hydrogen, the risk decreases more strongly. The ratio between the risk of natural gas and hydrogen therefore decreases with increasing ventilation and increases as the ventilation rate decreases further. This is shown in the figure below.

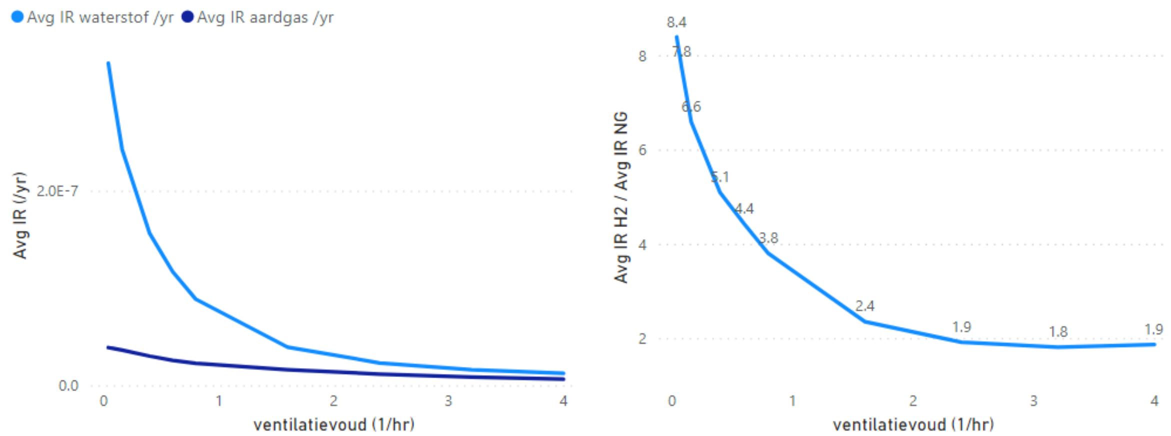


Figure 14 Individual risk hydrogen and natural gas (left) and their ratio (right) as a function of the ventilation rate in the event of leaks in the indoor installation.

6 Results of risk due to leakage from the distribution network

Unlike doing a quantitative risk analysis on an object, such as a leak in the indoor installation of a home, making an analysis of the entire distribution network is a lot more complex. Given the size of the calculations, it is impractical to calculate the entire distribution network and all connected homes directly.

To still be able to make a statement, the distribution system is divided into typical configurations. For example, the risk of a main with a given pressure, diameter and material properties on a house at a set distance can be determined (see Figure 15). By doing a number of calculations in which each of the parameters (pressure, diameter, material) are varied, a database with contributions to the total risk can be constructed. The parameters used for the individual risk calculations are listed in Table 16.

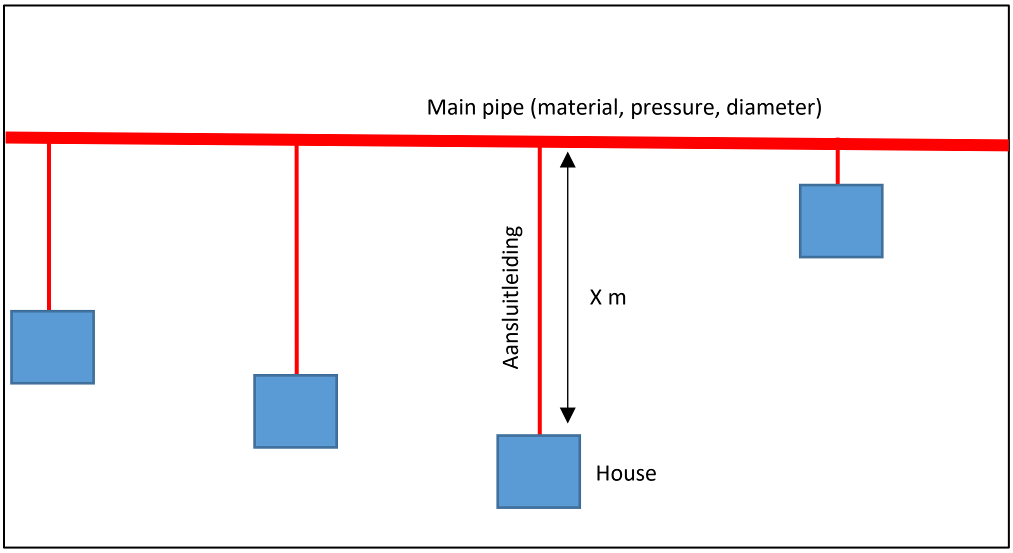


Figure 15 Example of the layout showing the positions of a main and a service in relation to a number of houses.

Table 16 Modelled parameters for distribution network

Parameter	Values
Pressure	0.03 – 0.1 – 1 – 4 – 8 bar
Main pipe material	PE – PVC – impact PVC – Steel
Diameter main	63 – 110 - 160 – 315 mm
Diameter service	32 mm
Distance main– house	2.5 – 8 – 15 – 30 – 50 m
House type	Detached
Ventilation house	0.8 – 1.6 $hours^{-1}$

For each combination of the modelled parameters, the risk is determined on the basis of the corresponding failure frequency. The failure frequencies, as written in Chapter 4.2, are based on the available historical data. It is only known that a leak occurred, not what the corresponding outflow amount was, nor what the consequences were. Based on the probability of a leak in a pipe with a certain pressure, diameter and material, the individual, site-specific risk is determined in the model. This individual risk due to fire or explosion cannot be validated per pipe type (pressure, diameter, material).

To calculate the total risk associated with leaks in the entire distribution network, individual risks for each type of pipeline are taken into account and weighted based on their frequency of occurrence in the Netherlands. A similar weighting is also made for the distribution of distances from the main line when determining the total risk. In this way, the total risk to the distribution network is expressed in a Potential Loss of Life (PLL), an expected (average) annual number of victims. This value can be compared with the available historical accident data.

An example of the difference between the individual locational risks and their contribution to the total risk is given in Figure 16. The risk due to a leak in a PE main with a diameter of 110 mm in a house at a given distance from this pipe increases with increasing pressure in the pipe and decreases the further the dwelling is from the pipe. However, because 100 mbar pipes of this material and this diameter are more common in the Netherlands, the contribution of these pipes to the total risk in homes close to the pipeline is greater than the risk of an 8 bar pipe.

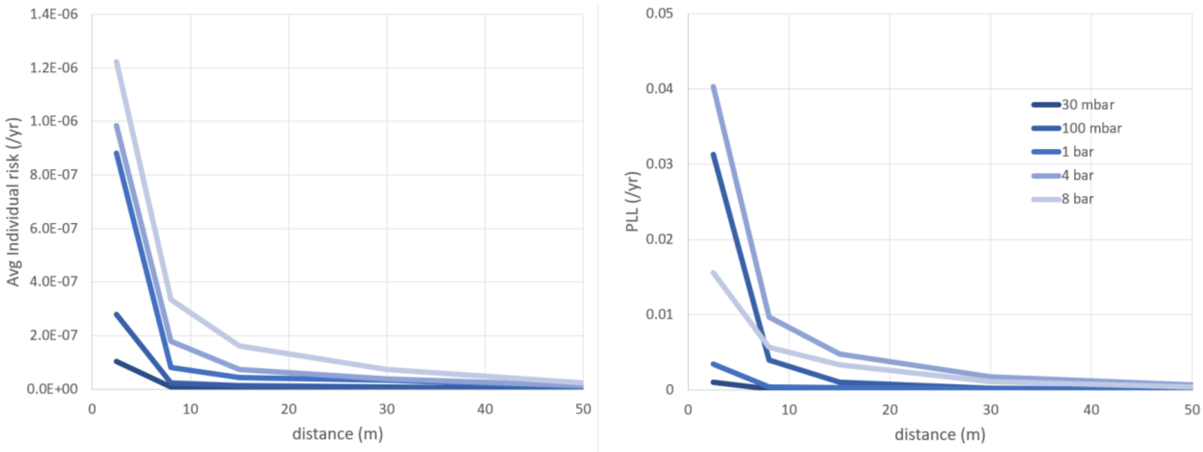


Figure 16 Individual risk (left) and the contribution to the total PLL (right) for PE main lines with a diameter of 110 mm and hydrogen

Similarly, two pipes can occur equally frequently and have the same probability of failure, but still have a different share in the total risk due to a difference in diameter or pressure. The probability of failure only indicates the probability of leakage and not the effect.

For each risk, the contribution for the type of leak (spontaneous or interference), type of pipe (main or service) and effect (fire or explosion) are stored separately. In this way, the total risk from the distribution network can be determined and the largest contributions to this risk can be determined. Analogous to the procedure of the risks from the indoor installation, the model for natural gas was first validated and compared with hydrogen. Finally, the effect of adding ventilation on the risk was investigated.

6.1 Natural gas

The total risk of leakage in the distribution network is shown in Figure 17 and subdivided into the contributions of the different materials, diameters, pressures and distances. The 32 mm pipes represent the services and all other diameters the mains.

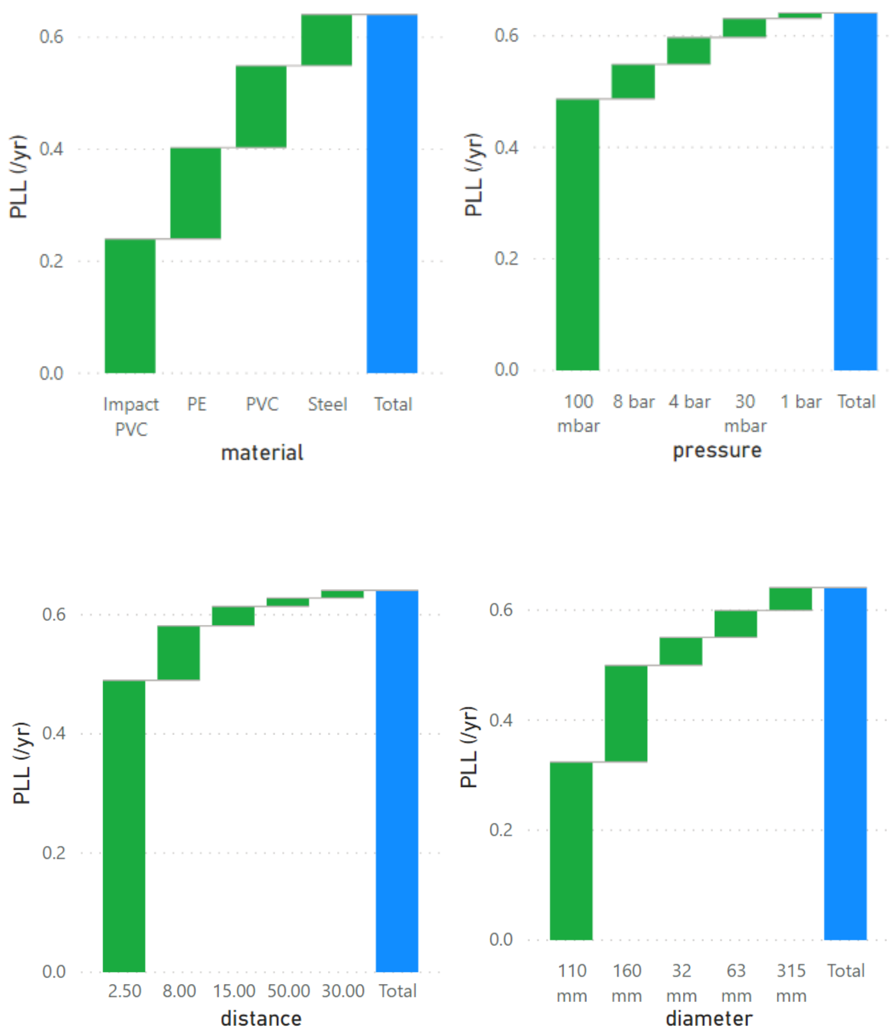


Figure 17 Total risk from the distribution network (PLL=0.64) for natural gas and the breakdown by pressure, diameter, material and distance.

The figures show that the largest contribution to the total risk is caused by the 100 mbar network and by houses that are close to the main line (2.5 meters). In the model, all services are made of PE, which means that this pressure and material combination makes a major contribution to the total risk. As shown earlier, the higher pressures pose a somewhat greater risk, but due to the more frequent occurrence of low-pressure networks, their contribution to the overall risk is greater. The calculated total risk in terms of PLL is 0.64 per year. This is considered to be the same order of magnitude as the practice data (~0.3 based on a very limited number of incidents).

6.2 Hydrogen

By using the same set of assumptions as for natural gas in the calculations for hydrogen, the difference in risk between the two gases can be determined. This assumes that the same net configuration is used for both gases and that it has the same failure rates as is currently the situation for natural gas.

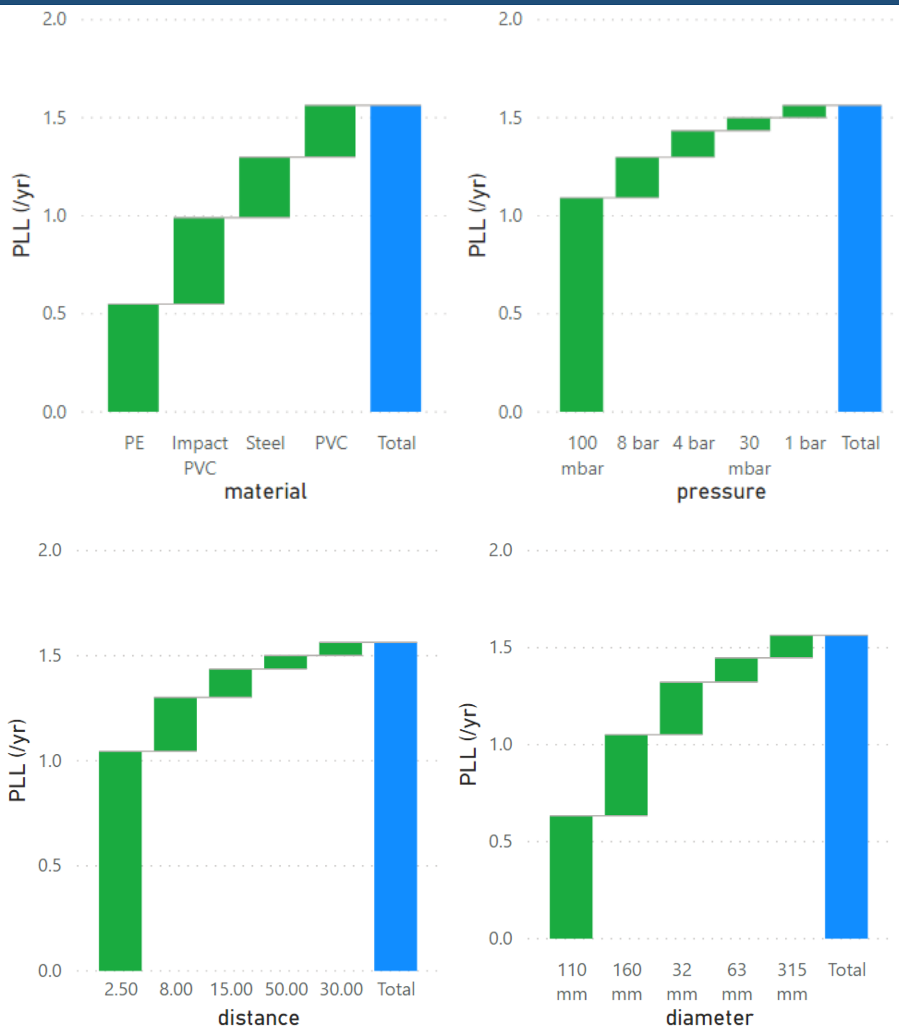


Figure 18 Total risk from the distribution network (PLL=1. 56) for hydrogen and its subdivision by pressure, diameter, material and distance.

For hydrogen, the share of the higher pressure parts (1 to 8 bar) in the total risk is greater than for natural gas: 26% versus 19%. However, the greatest risk with hydrogen remains to be caused by the 100 mbar grid, because this is the most common. A small shift can also be observed in the materials used. In the case of hydrogen, the largest contribution is made from the PE pipes, followed by the PVC parts. With natural gas, the contributions of these two materials are inversed when it comes to the largest contribution, although the difference is small.

The factor between the PLL from the hydrogen and natural gas distribution network is almost 2.5 (1.56 versus 0.64), which is lower than the factor for the risk of leaks behind the meter. In addition, the total risk from the distribution network is very small compared to other, generally accepted, risks. Based on the assumptions made in the model and on average per connection (7.2 million), the individual risk in the home due to leaks from the distribution network is approximately 2×10^{-7} for hydrogen, assuming that no additional mitigating measures are taken.

Various measures can be taken to further reduce the risk for hydrogen (and also for natural gas). The contribution of both explosions/fires and spontaneous/interference leaks to the risk can be further broken down to provide more insight into which measures have most impact on reduction of the risk.

6.2.1 Difference in explosion/fire contribution

A clearer difference can be seen in the share of explosion risk compared to the fires, as shown in Figure 19 and Figure 20. Proportionally, most natural gas victims are caused by fires, nearly 60%. The largest contribution to the risk with hydrogen is caused by explosions (70%), in contrast to the situation with natural gas. This is in line with the results as found for risk from leaks behind the meter in the previous chapter. Leaks in higher pressure pipes lead to larger amounts of hydrogen that are released and can build up to higher concentrations in the home. In case of ignition, this leads to more violent explosions and therefore a higher risk.

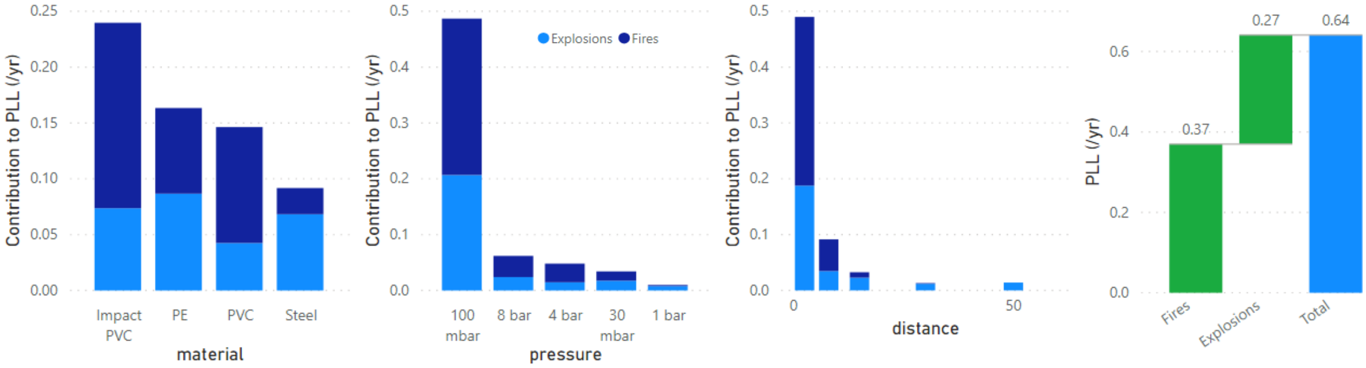


Figure 19 Distinction between the contribution of fires and explosions to the risk from the natural gas distribution network.

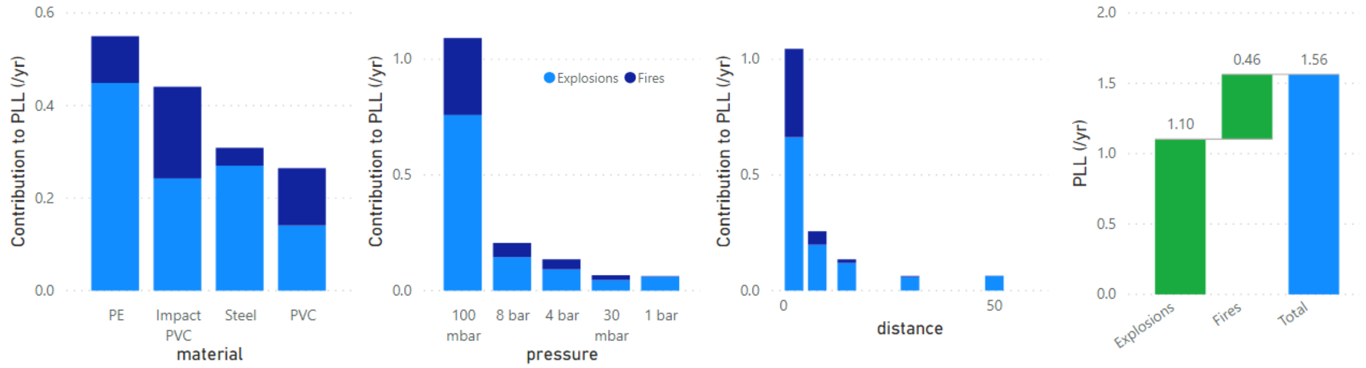


Figure 20 Distinction between the contribution of fires and explosions to the risk from the hydrogen distribution network.

6.2.2 Difference in spontaneous/interference cause

The model for both natural gas and hydrogen uses the same failure rates in the different pipeline types. However, the contribution to the overall risk is different as shown in Figure 21 and Figure 22. In the case of hydrogen, the contribution due to spontaneous leaks is greater than in the case of natural gas. In the model, third-party leaks (interference) are generally detected more quickly and action is taken faster compared to leaks that occur spontaneously. The latter category can go unnoticed for a longer period of time, with the result that higher concentrations can be built up. In the case of hydrogen, this results in a higher risk due to a greater effect of the explosion. In the model, the risk scales linearly with the probability of failure of the pipes. This means that if the risk of failure of spontaneous leaks can be reduced by more inspections, the risk is reduced by the same factor. Spontaneous leaks in the PE pipes of 100mbar have an in particular high contribution.

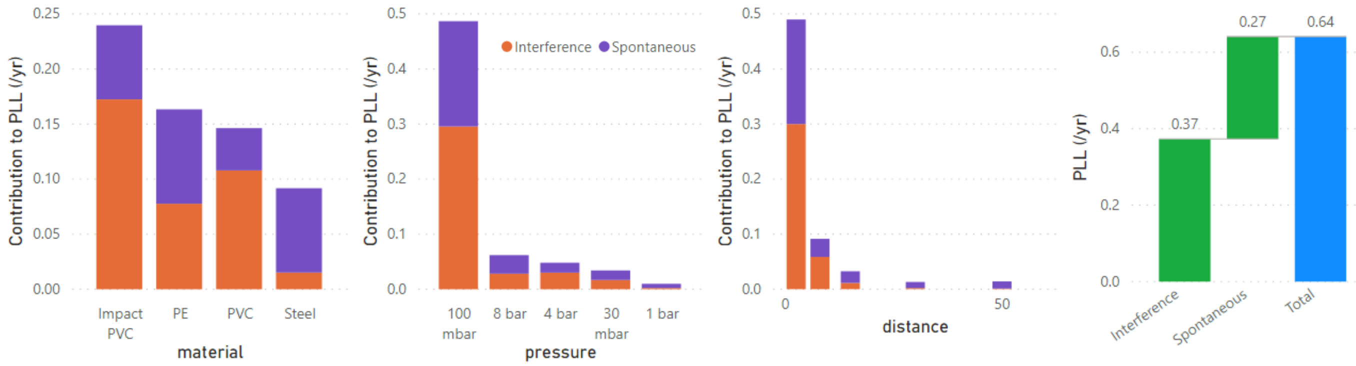


Figure 21 Distinction between contribution of spontaneous and interference to the risk from the natural gas distribution network.

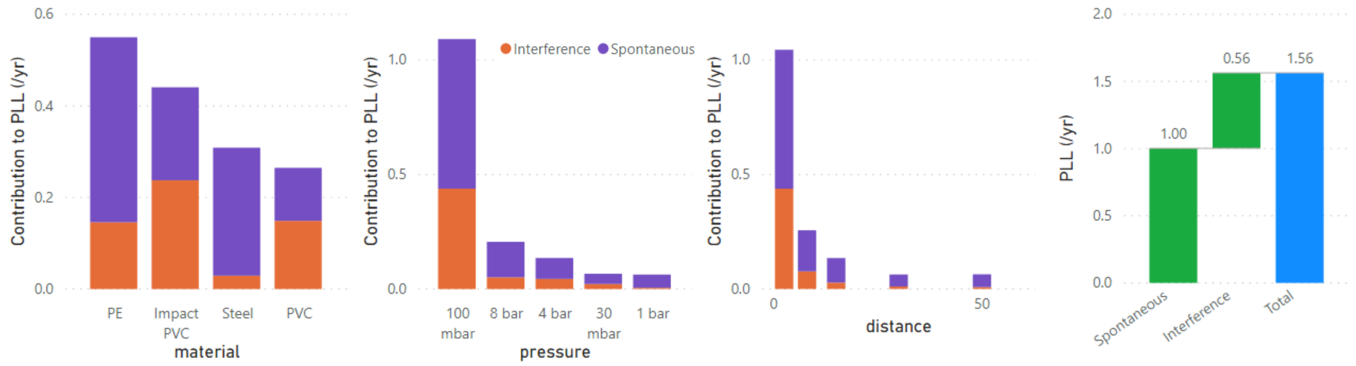
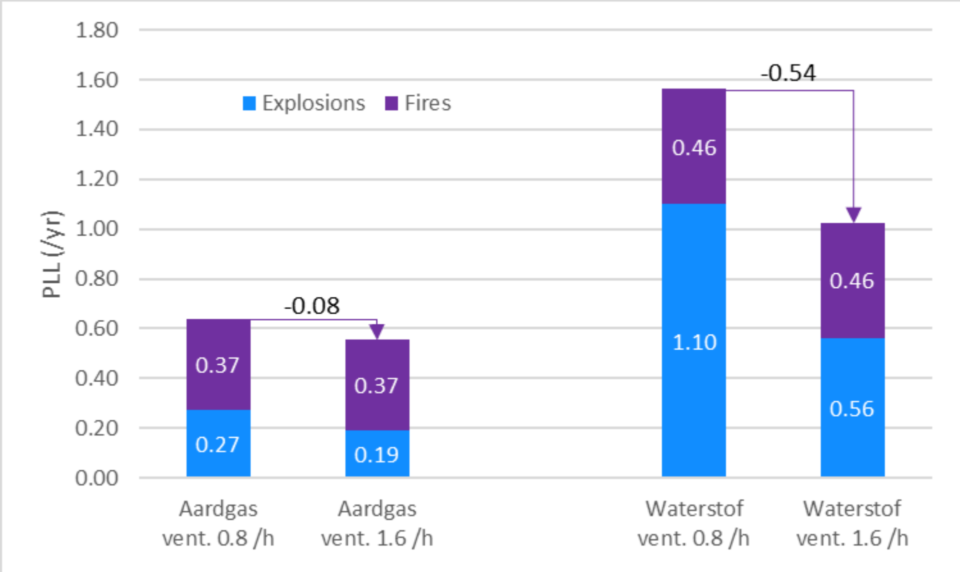


Figure 22 Distinction between contribution of spontaneous and interference to the risk from the hydrogen distribution network

6.3 Effect of ventilation

The analysis in Chapter 5 shows that ventilation has a major effect on the risk in the home, especially with hydrogen. The effect of ventilation on the total risk from the distribution network was calculated by repeating all the above calculations with homes with a doubled ventilation rate (1.6 hours^{-1}). The results are summarized in the graph below.



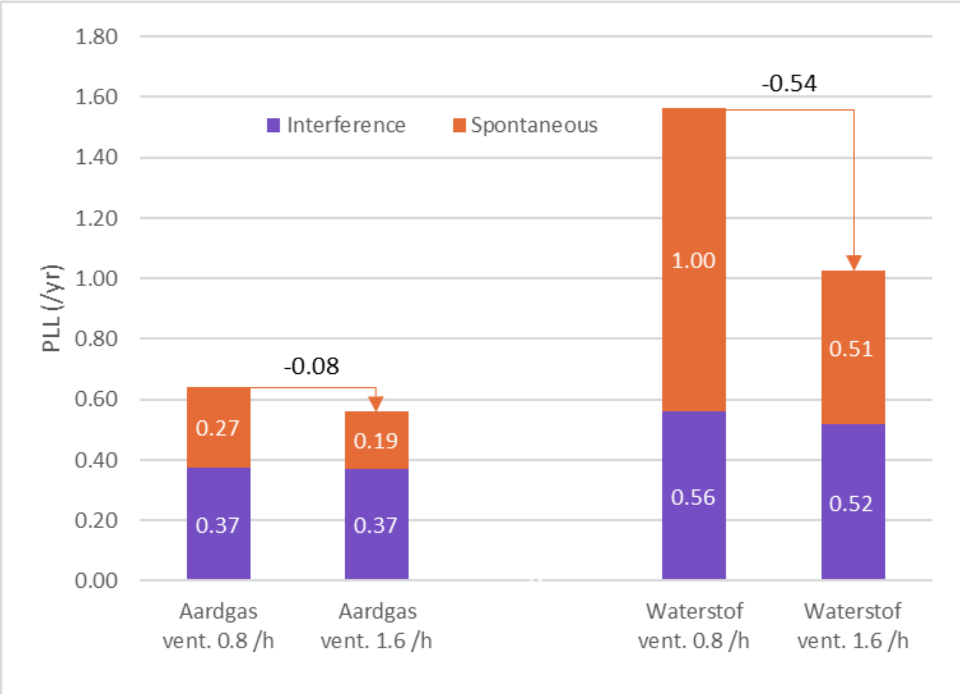


Figure 23 Effect of doubling the ventilation rate in the home on the risk of natural gas and hydrogen arising from a leak from the distribution network, broken down by contribution of explosions/fires (top) and interference/spontaneous leaks (bottom).

The ventilation rate seems to mainly influence the effects of explosions. This effect is much greater with hydrogen, a reduction in the total risk with a PLL of 0.51 per year compared to natural gas (0.08 per year reduction). If the distribution of the risk according to the cause of the leakage is made, it appears that the spontaneous leaks in particular have a lower contribution: from a PLL of 1.0 to 0.5 /year. The same effect, although to a much lesser extent, is also the case with natural gas (-0.08). Damage caused by third parties usually results in leaks exposed to the open air, which tend to be detected more quickly. The effect of ventilation therefore has more effect on preventing the build-up of dangerous hydrogen concentrations in enclosed spaces that ultimately lead to explosions.

7 Results of risk in the case study

The previous two chapters discussed the risks of hydrogen for leaks in the indoor installation and distribution network. Together, this forms a picture of how the overall safety risk changes when replacing natural gas with hydrogen. This chapter presents and discusses the impact of hydrogen in the gas network in a piece of a typical Dutch residential neighborhood. By putting this neighborhood as a case study into the QRA model, a comparison in individual risk can be made between natural gas and hydrogen, valid for a detailed and realistic distribution network with homes included. This is in addition to the risk results for the general Dutch situation. The impact on the individual risk of pipeline failure can thus be examined at the local level. Of interest is, for example, the influence of dwellings on each other, such as densely packed or semi-detached houses, but also the difference in risk between dwellings near, for example, high or (multiple) lower pressure pipelines.

7.1 Case study in the QRA model

The composition of the case study is very important for the relevance of the results. That is why the definition of the case study was done in consultation with the grid operators. The district had to look like a typical piece of a village or town. Furthermore, differences in the topology of the distribution network are interesting such as common materials, pressures and diameters. Some variation in the type of houses and the distances to the distribution network increases the value of the results.

Figure 24 Map showing the numbered houses and the distribution network defined in the case study.

The map above gives an overview of the houses and the distribution network in the case study. The mains inside the dotted line and the houses numbered 1 to 57 are put into the model as input. Difference in color of the mains indicates a specific combination of material, diameter and pressure. This topology of the distribution network is shown in Figure 25.

Figure 25 Overview of houses and the distribution grid in the case study.

The neighbourhood consists of detached houses with different sizes and distances from each other and a distribution grid. There are also a number of semi-detached houses present, recognizable by the double services in Figure 25.

The distribution network consists of and is modeled according to the sectioning below;

- 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, PE, 32 or 25 mm

Furthermore, the input failure frequencies for the section of the distribution network are specific to the combination of diameter, pressure and materials used as given in Section 4.2. The configuration and failure frequencies of the indoor installation are assumed in analogy with Chapter 5. The individual risk was determined for each house for both hydrogen and natural gas.

7.2 Risk from a hydrogen leak in the distribution network

The risks of hydrogen due to a leak in the distribution network are given Figure 26 to Figure 28. For each segment of the mains in the overview in Figure 25 as well as for the services, the individual risk per house was calculated. The results are aggregated for the mains per pressure class. A color scale is used to indicate the difference in risk between the homes. In this section, the color scale is the same in different figures.

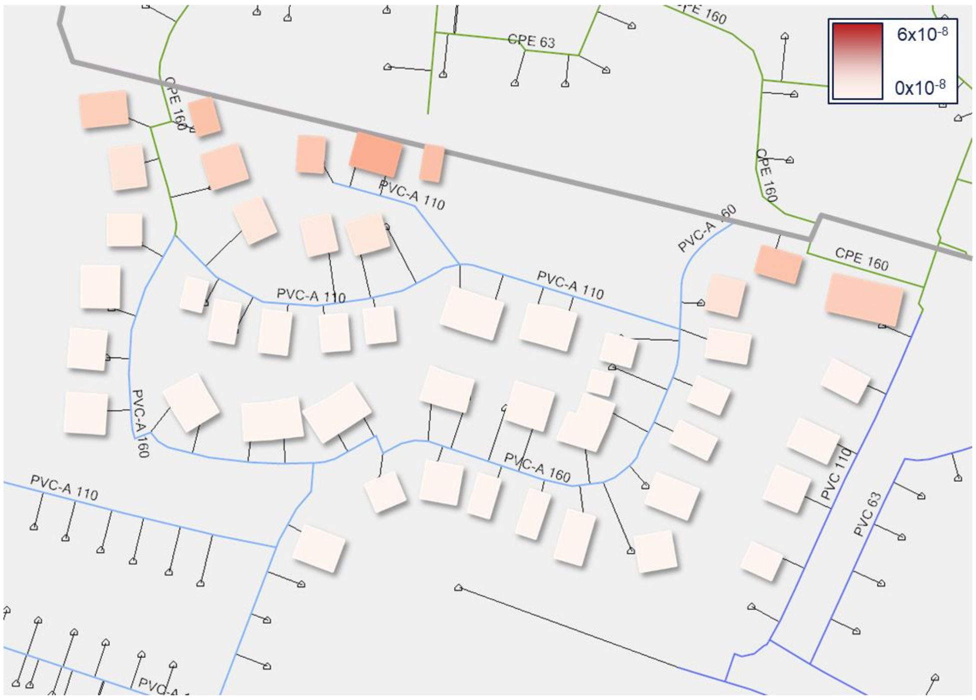


Figure 26 Risk due to leak in the 8 bar main.

As expected, the figure above shows that houses adjacent to or close to the 8 bar main are at higher risk compared to houses further away from the high pressure pipeline. The risk decreases rapidly with increasing distance. Compared to the risk from the 100 mbar mains in the following figure, the risk of the 8 bar pipeline is relatively small. The reason for this can be found in the input of the model. The failure frequencies of a 110mm 8 bar steel pipe are a factor of 2.7 lower compared to the failure frequencies of a 110 mm 100 mbar PVC pipe (Table 9). In addition, the total length of the 100mbar main pipe around the houses is larger compared to the straight 8 bar pipe, which also contributes to a higher risk.

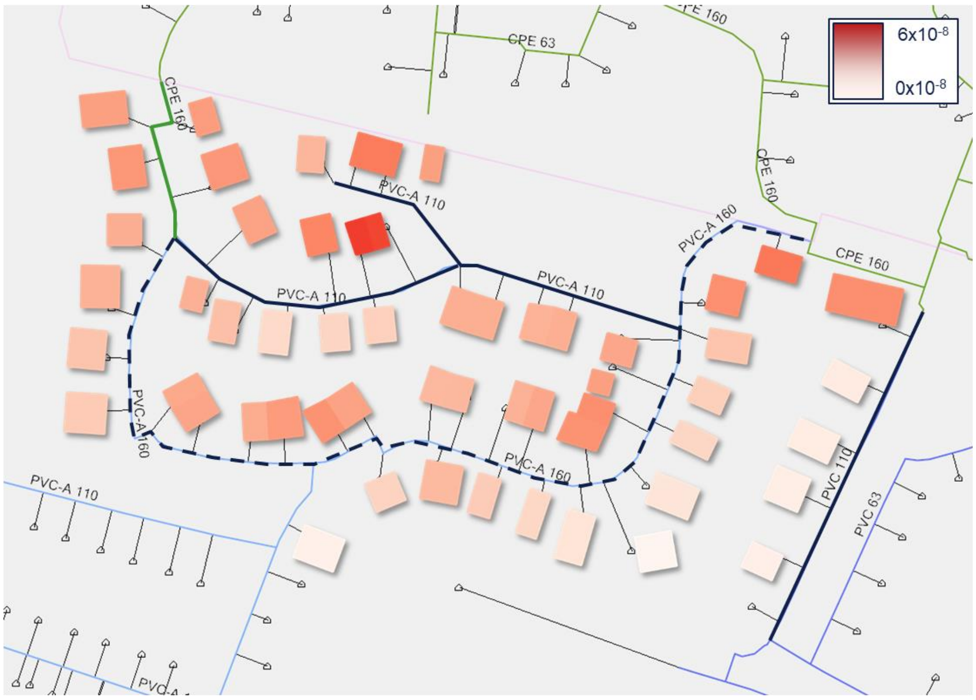


Figure 27 Risk due to leak in 100 mbar main line.

The figure above shows a clear relationship between the risk and the number of 100 mbar mains nearby. An example of this can be seen on the right side where a row of five houses is situated vertically. The bottom four experience a significantly lower risk compared to the upper ones. These four houses have almost exclusively risk from the PVC-110 (c) main section while the upper house additionally has a risk from the PVC-160 main section.

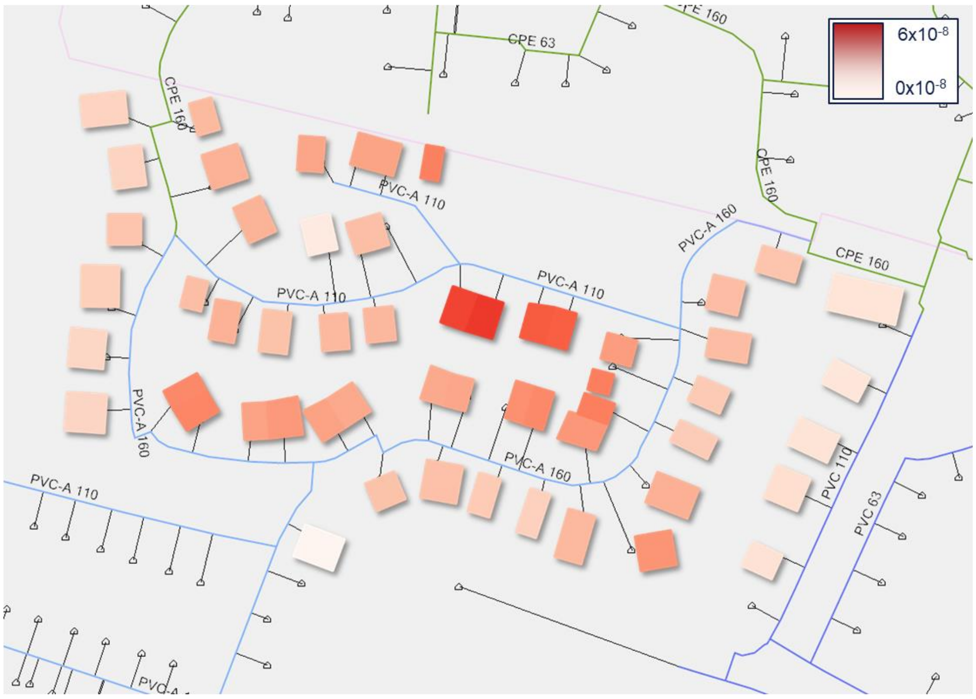


Figure 28 Risk due to leakage in service.

The risk from the services is highest for homes that are close to each other, such as semi-detached houses. A good example can be seen in the middle of Figure 28. These two homes are at risk from their own service pipeline, those of the attached neighbors and also from nearby houses. Detached houses relatively far from other homes experience the least risk.

Figure 29 Total risk due to leaks from the distribution network.

The total risk per house in the case study area due to a hydrogen leak from the distribution network is shown in Figure 29. There is a clear relationship between homes close together in the proximity to multiple sections of main pipelines and higher risk. Therefore, the highest risk is posed by semi-detached houses. This effect on risk is greater than that of a house near the 8 bar main pipeline.

7.3 Risk from a hydrogen leak in the indoor installation

Below in Figure 30, the risk per home in the case study neighborhood is shown for leaks from the indoor installation. Note that for clarity, the color scale indicating risk is different from the figures in the previous section.

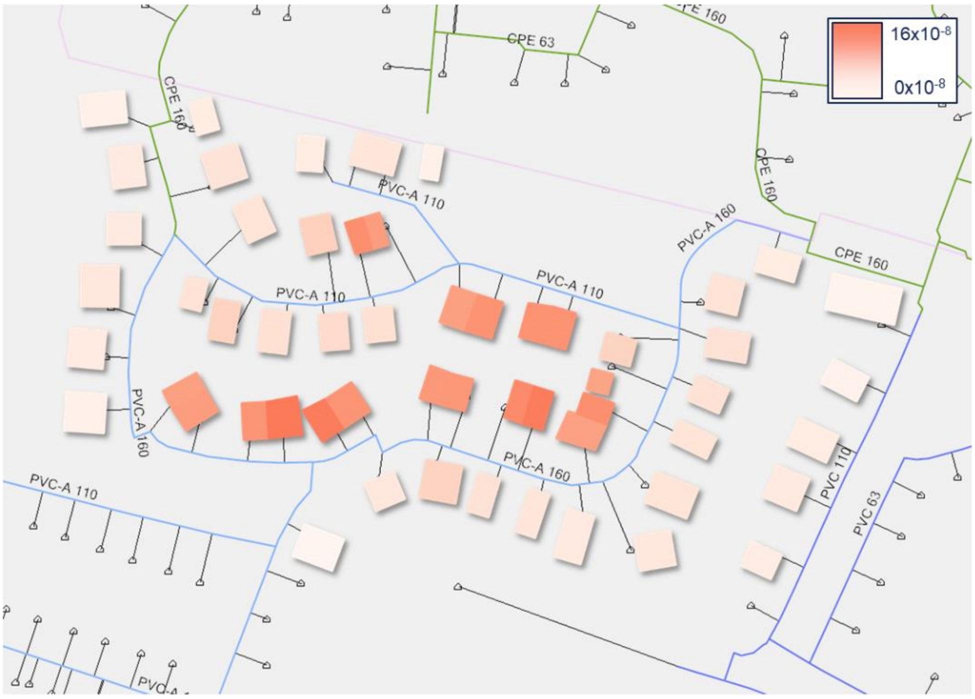


Figure 30 Risk in houses due to a leak beyond the meter.

The results of the model for a leak in the indoor installation shows a clear trend for the homes in the case study neighborhood. In addition to the fact that there is a risk in a house due to a leak in the own indoor installation resulting in an explosion, a strong influence of nearby homes is visible. In particular, semi-detached houses in the area have a greatly increased risk, as well as detached houses close to other houses. The risk caused by a leak in the indoor installation is significantly greater compared to the risk from a leak from the distribution network, taking into account the difference in color scale.

7.4 Total risk example district

The combination of the risks caused by both a leak in the distribution network and in the indoor installation gives the total individual risk per house in the case study. Figure 31 shows the total risk for hydrogen.

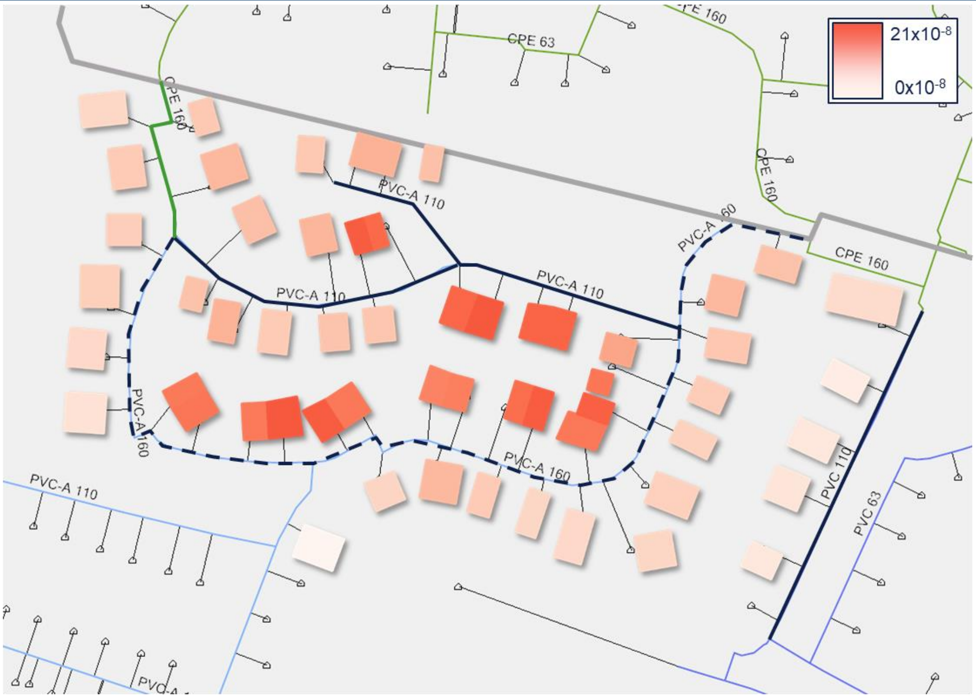


Figure 31 Total hydrogen risk for the houses in the case study

By far the largest contributor to the total risk for hydrogen is the indoor installation, followed by the 100 mbar mains. Therefore, the ratio of the total individual risk between the dwellings in the neighborhood in Figure 31 looks very much like a combination of the ratios in Figure 30 and Figure 27 The semi-detached houses, houses relatively close together and houses in the proximity of several mains pipes in the neighborhood have the highest individual risk. Detached houses near a single pipeline have the least individual risk.

In Figure 32 house number 40 is circled. This is a semi-detached house situated near two 100 mbar mains and near the 8 bar main. For this house specifically, Figure 33 shows the relative contribution of the individual risk of a leak in the indoor installation and in the distribution network. The latter is further broken down on the right side of the figure.

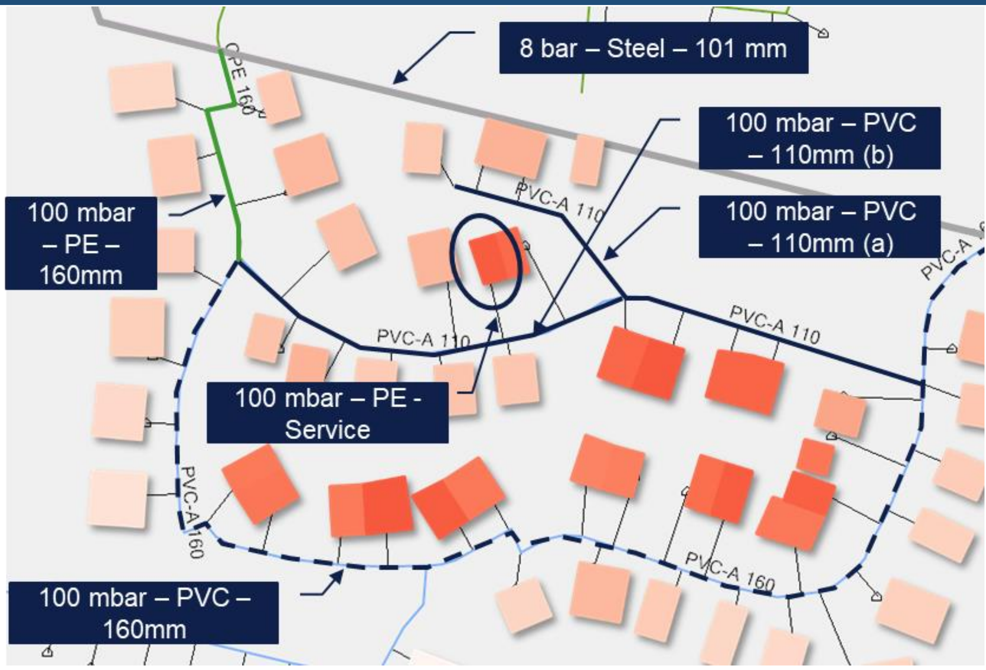


Figure 32 House number 40 circled in the overview of the neighborhood.

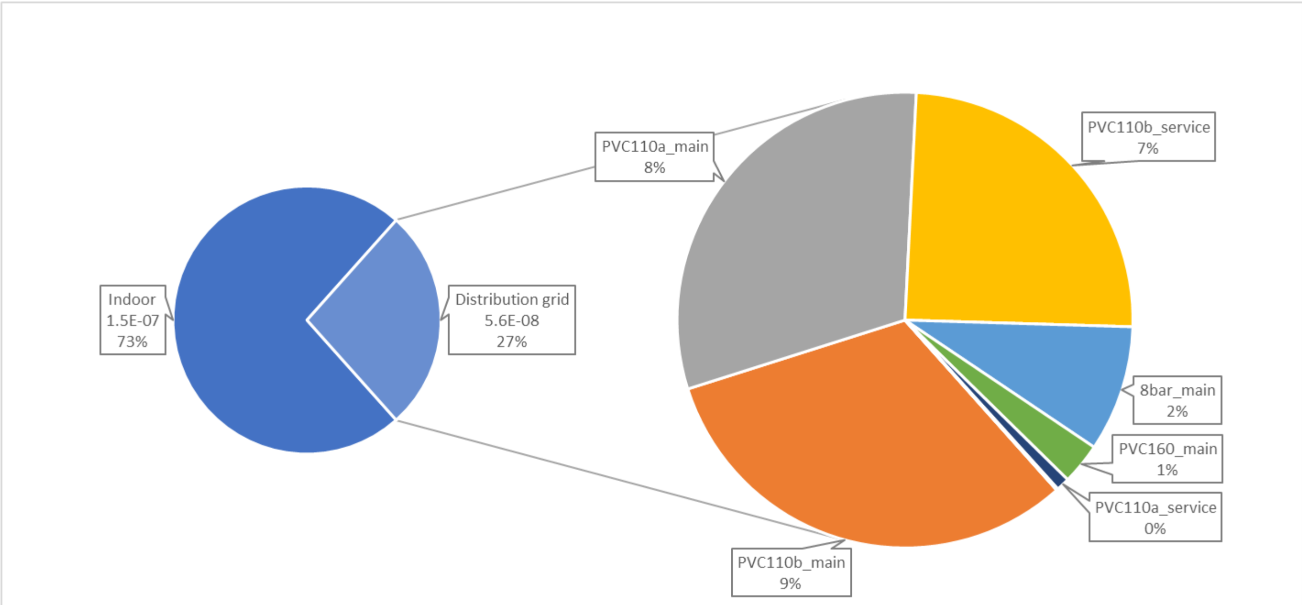


Figure 33 Risk for one house (number 40) in the case study district. The total risk (2x10^{-7}) is broken down in the contribution of the indoor installation and the segments of the distribution network.

The total individual risk of house number 40 (2 x 10^{-7}) consists for almost three quarters of risk due to a leak from the indoor installation (73%). The remaining risk due to a leak from the distribution network consists mainly of the 100 mbar main pipes on both sides of the house, and the service to the house as well as to nearby houses. The contribution to the risk of a leak in the 8 bar main is only 2% of the total.

7.5 Difference between hydrogen and natural gas risk

Figure 34 and Figure 35 show the total individual risk for hydrogen and natural gas respectively. For each house in the area, the contribution to the total risk is shown with a subdivision between risk due to a leak from the indoor installation, from mains and from services. For natural gas, the risk of carbon monoxide poisoning is also included. The scale of both figures is the same to make a good comparison.

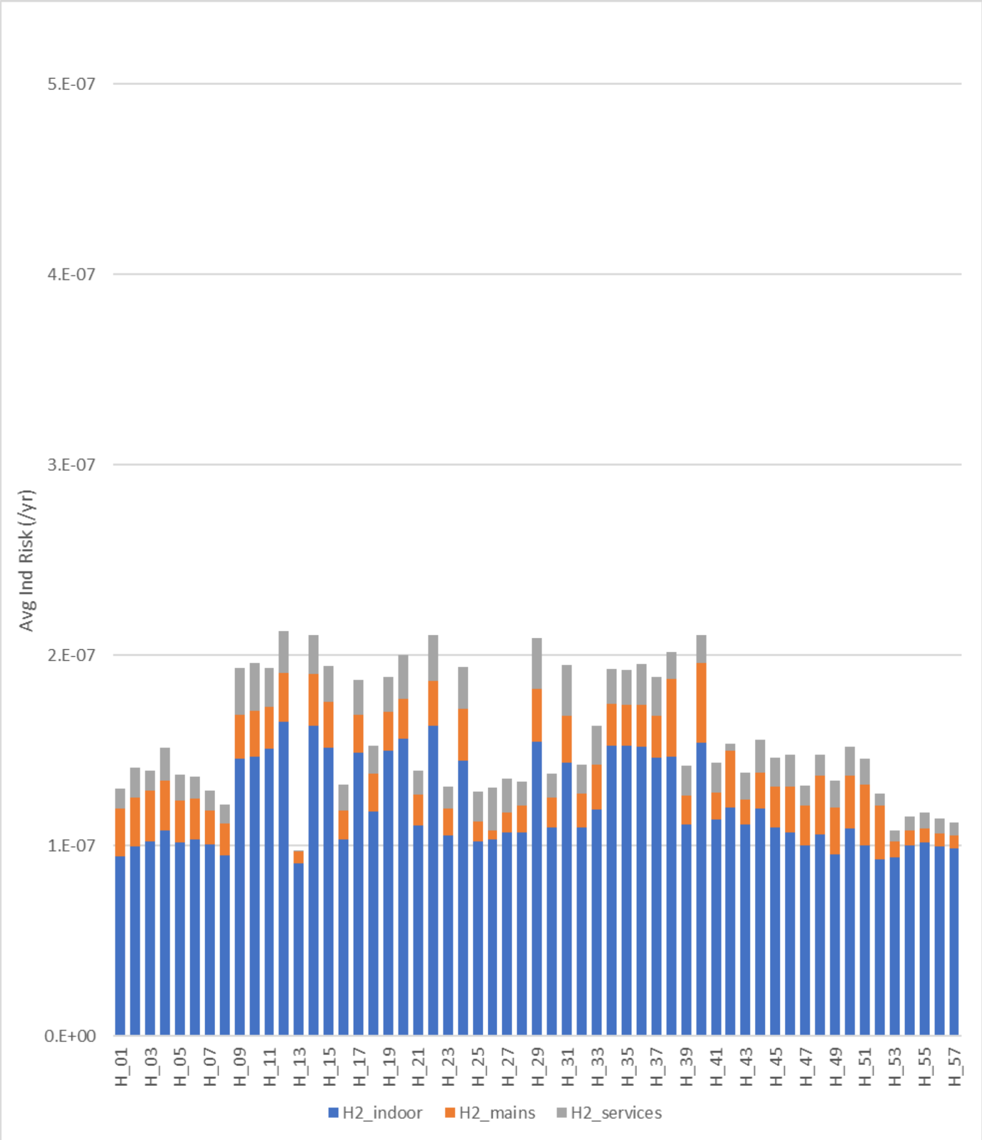


Figure 34 Individual risk of hydrogen per home in the case study

A comparison of the risks in homes of hydrogen versus natural gas presents a similar picture as found in Chapters 5 and 6, namely, the overall increased risk for hydrogen versus natural gas due to leaks from both the indoor installation and from the distribution network. Also striking for hydrogen is the mutual differences in individual risk between homes. For natural gas, these differences are relatively smaller. This is due to the sharp increase in risk from incidents in nearby homes and pipes due to the greater effect of explosions for hydrogen. The semi-detached houses therefore also experience the greatest risk. For natural gas, the risk per home in for leaks from the indoor installation and the distribution network is considerably more stable, as shown in Figure 35.

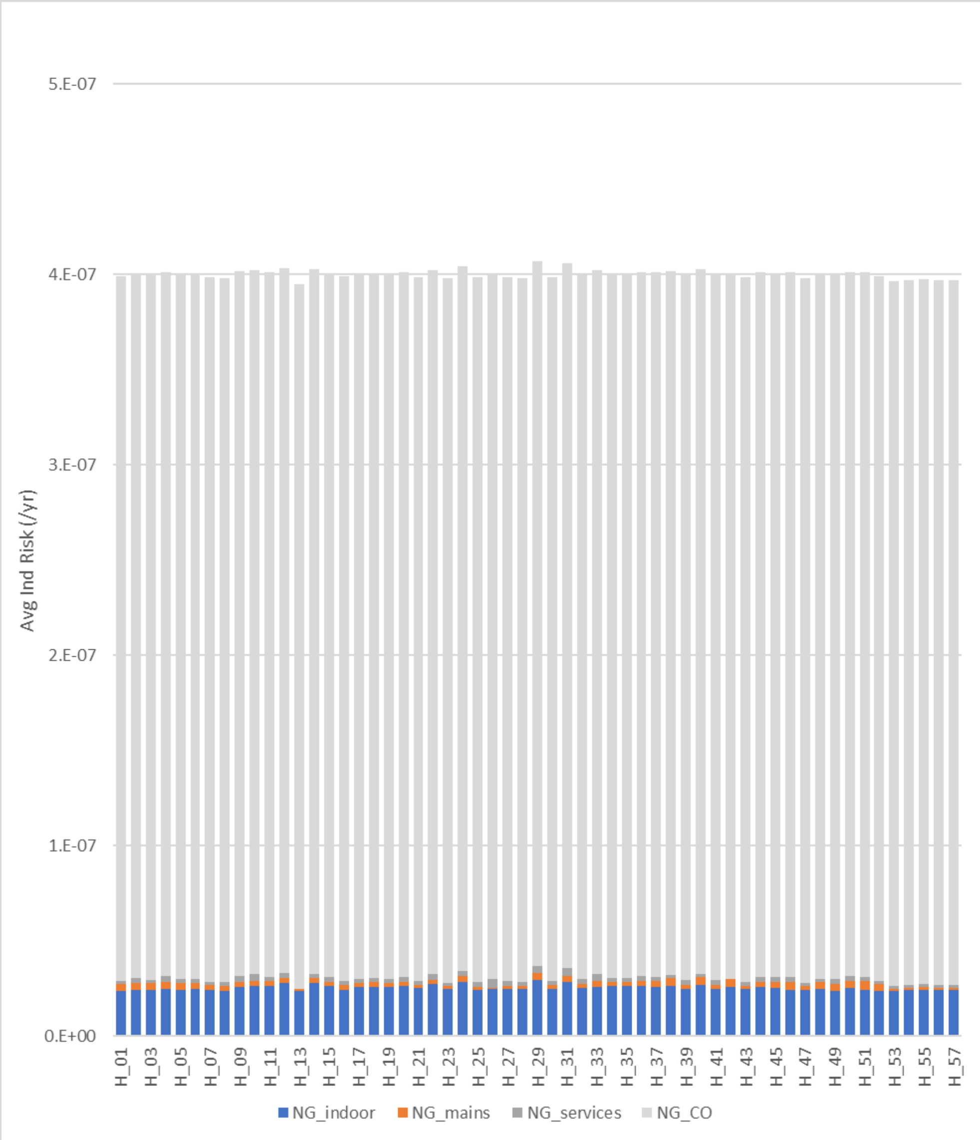


Figure 35 Individual risk of natural gas per home in the case district

For natural gas, the risk of carbon monoxide poisoning is also shown (in light gray), which will not be present with hydrogen. Even if the combined risk caused by leaks in the distribution network and in the indoor installation is greater, the total risk for hydrogen for each home is a factor of about two or more lower compared to natural gas with carbon monoxide poisoning. By applying mitigating measures, the increased effect of the explosions on hydrogen can be reduced. These will be discussed further in the next chapter.

Figure 36 shows the average total individual risk over the 57 homes in the case study for both hydrogen and natural gas.

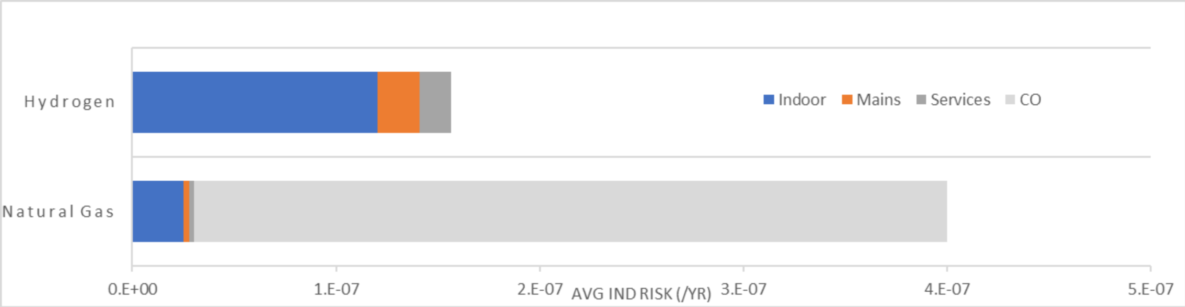


Figure 36 Average location-based risk per home in the area for hydrogen and natural gas

8 Mitigating measures

This chapter discusses the impact of mitigating measures at risk level for hydrogen. Odorization of both natural gas and hydrogen is already included by default in the QRA model calculations. As additional mitigating measures, ventilation of the house, an excess flow valve (EFV) and a gas sensors are considered in this study. However, reducing failure frequencies is also an important mitigation measure. This can be achieved through, for example, (periodic) inspections, replacing materials and renewal of gas appliances. The greatest effect can be achieved by reducing spontaneous leaks, especially behind the meter.

The influence of ventilation of the house on the risk has already been calculated for both a leak in the indoor installation as well as for a leak from the distribution network. This is discussed in Chapters 5 and 6, both for natural gas and hydrogen. In the version of the QRA model used for this study, it was not yet possible to model the effects of an excess flow valve or gas sensor for the Dutch situation. Simultaneously to this study, the second phase of the H21 project was carried out in the UK. In this phase, the effects of the EFV, gas sensors and other mitigating measures were implemented in the model. Initial insights into the effects of these mitigating measures on the risks for the UK situation are discussed in this chapter. The results of H21 Phase 2 have not yet been published at the time of writing. Based on these insights, a first estimate is made of the impact on the risks for hydrogen in the Dutch situation.

The ventilation of a home as a mitigating measure is discussed in the next section. The possible effect of EFVs and gas sensors is discussed in the subsequent sections, based on initial modelling from the UK.

8.1 Ventilation of the house

Increasing ventilation in a home can eliminate the possibility of the formation of a flammable gas-air mixture for a given leak, or at least limit the concentration that can be achieved. In addition, as the ventilation rate increases, the time it takes for a flammable gas-air mixture to reach flammable concentration is increased. The ventilation rate of a dwelling has a strong reducing effect on the risk in a dwelling. This has been demonstrated in QRA studies such as H21 and Hy4Heat and is also evident from the analyses done in Chapters 5 and 6. This reducing effect is stronger for hydrogen compared to natural gas. Therefore, increasing the ventilation rate in homes is an important potential mitigation measure for a hydrogen distribution system. However, it is possible that any additional ventilation could be negated by the residents intentionally closing vents and preventing drafts, for example, to reduce energy costs for heating the house.

8.2 Excess Flow Valve

An Excess Flow Valve (EFV) is a device installed on a gas pipeline that stops the gas flow above a set value. It is used to shut off free outflow of gas in the event of a leak or accident.

Several studies from the UK recommend a set maximum flow rate for hydrogen of 20 m^3/hour, which is equivalent to 6 m^3/hour for natural gas. This roughly corresponds to the maximum consumption of all household appliances in a home; a higher flow rate is often caused by a leak. The values recommended by research are used in the QRA model for EFVs.

In the initial calculations of the impact of an EFV on the risk for hydrogen in the UK, different scenarios were approached in the model:

A. Approach A includes an EFV installed directly at the meter that closes when a *leak* exceeds 20 m^3/hour. It does not affect the effects of leaks in the distribution network. The impact of an EFV on the overall risk with this approach is an 14% reduction.

B. With Approach B, the EFV also sits directly at the meter, but it now takes into account that appliances in the home affect the EFV closing conditions. For example, the EFV with a limit of 20 m^3/hour and a combined consumption of appliances in the house of 8 m^3/hour, closes at leak flows already exceeding 12 m^3/hour. To approximate this in the model, assumptions are made regarding the moment and extent of the consumption of devices. The effect of this approach is an 21% reduction in total risk.

C. Approach C uses the same assumptions made in B but situates the EFV from the meter to the coupling (saddle) between the main and service. As a result, the EFV also has an effect on the risk of leaks in services. The effect of this approach is a 25% reduction on the overall risk. This corresponds to an additional reduction of 4% compared to approach B with the same assumptions but different location of the EFV.

Based on the different approaches in the model of an EFV, an average risk reduction of 20% can be roughly assumed.

8.3 Gas sensors

Installing a gas sensor with audible alarm in a home can potentially detect a gas leak earlier than odorization alone. For example, if a leak occurs at night or because an audible signal is more likely to be noticed by neighbors. This also applies to areas at high risk of leakage, or where occupants are rarely or never present, such as the meter cupboard or basements. After alerting, it is assumed that the gas supply is shut off earlier and ventilation is increased, ultimately keeping concentrations in the home lower and reducing explosions. The effect of the sensors is modeled by a higher probability of detecting a given concentration in the home. The impact of gas sensors on overall risk is a 27% reduction.

8.4 Estimation of the effect of EFV and gas sensors in the case study

The effects of the EFV and gas sensors based on initial modelling based on the UK situation can be applied to the risk of hydrogen from the case study. This should be seen as a first approximation. Further elaboration and validation of the specific Dutch situation is needed, yet this approach can give a first impression of the possible effects of these additional mitigating measures on the risk of hydrogen.

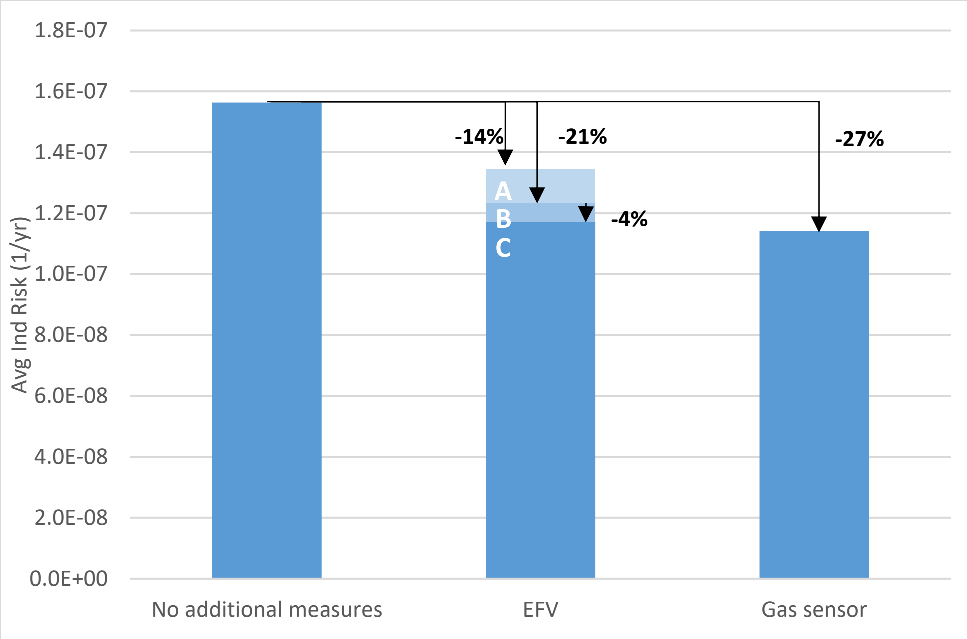


Figure 37 First approximation of the potential impact of additional mitigating measures[7], based on UK data, applied to the risk of hydrogen in the case study.

The effect of the EFV with approach A has an estimated effect of 14% risk reduction compared to the situation without additional mitigation measures. Approach B has an effect of 21% reduction. Moving the EFV from the meter to the coupling between the main and service pipeline (Approach C with assumptions Approach B) has an additional effect of -4% on the risk. This reduces the risk in the house that is affected by a leak in the service pipeline to this house. An advantage for an EFV close to the main pipe is that in the event of a house fire that is not caused by a gas leak, the gas is shut off when the indoor installation fails. Placing an EFV near the meter has the advantage that there is no need to dig in the streets. Placing a gas sensor with audible signal in a home has an estimated risk reducing effect of 27%.

With a combination of EFVs and sensors, the risk reduction is not proportional to that of the isolated measures. This is because some of the leaks are already prevented by one measure before the other can intervene.

[7] Odorization is standard in the model. 'Additional measures' refers to additional to odorization.

9 Discussion and conclusion

To make an initial assessment of the risks of hydrogen in the Dutch distribution network, a quantitative risk analysis (QRA) was performed. This compares the risk between the current natural gas distribution system and the future hydrogen distribution system. In the analysis, the total risk consists of the risk arising from leaks in the distribution network and the risk arising from leaks in the home itself. The results of such an analysis provide a quantitative basis of whether hydrogen distribution poses more risk to society and, if so, what measures have the most impact to reduce this risk.

The risk model is a concatenation of a number of modules that calculate the probability of component failure, gas dispersion and accumulation, the probability of ignition and its consequences, respectively. The outcome of the model is ultimately location-specific risk (average individual risk). Intermediate outcomes of the various modules also provide insight into, for example, the number of times a certain concentration of gas is reached in a home. Both the intermediate outcomes and the calculated site-specific risks were used to validate the model for natural gas. The model is split into a part with leakages behind the meter (the indoor installation) and a part with leakages in the distribution network.

The model simplifies the built environment in the Netherlands in order to control the number of parameters to be varied and associated calculations. It was chosen to calculate with detached houses in this first version for model validation. In the Case Study, semi-detached houses were additionally used. The distribution network was simplified by using a limited number of materials (PE, impact-resistant PVC, PVC and steel), pressures (0.03-0.1-1-4-8 bar) and diameters (63 - 110 - 160 - 315mm).

An important input parameter of the model is the failure frequency of the various components. For the distribution network, the failure frequencies were determined from historical failure reports as recorded in the Nestor system. Based on these failures and the distribution of pipeline lengths with different pressures, materials and diameters, a failure frequency per kilometer was determined. For the components behind the meter (meter setup, indoor piping and end-user appliances) no reliable dataset for the Netherlands was found and it was decided to use the values from the UK.

Given the simplification of reality based on the aforementioned assumptions, the model provides an approximation of the site-specific risk due to a fire or explosion. The “Besluit Kwaliteit Leefomgeving” states a maximum for the site-specific risk of no more than one in a million per year ($1x10^{-6}$/year) for (very) vulnerable buildings and vulnerable locations. The environmental plan[8] must guarantee this limit value. This means that people in (very) vulnerable buildings, such as homes, schools and hospitals, and in vulnerable locations, such as large recreational areas, may not be exposed to a site-specific risk of more than one in a million per year. (Very) vulnerable buildings and vulnerable sites should therefore not be constructed within the site-specific risk-10^{-6} contour of an activity. The risks calculated in this study, based on the assumptions, fall within the 10^{-6} contour for both hydrogen and natural gas.

[8] See: https://www.rivm.nl/omgevingsveiligheid/handboek/toelichtingen-kernbegrippen/afstanden-en-gebieden

9.1 Risk behind the meter

Based on failure frequencies in houses discussed above, it appears that the site-specific risk for natural gas from leaks behind the meter agrees well with (limited) historical data. Based on historical data, the probability of one fatality in the Netherlands from an explosion or fire per house is 0.06 x 10^{-6}, excluding cases where there was intentionality. In addition, the probability of injury is 1.1 x 10^{-6}. The model yields 0.02 x 10^{-6} for fatalities and 0.4 x 10^{-6} for injuries, respectively, providing the same order of magnitude as historic data gives. The risk is found to scale linearly with failure frequency.

For the same set of parameters and without additional measures, the effect of explosions is found to be more severe with hydrogen than with natural gas, and the total number of explosions is a factor of 2 higher compared to natural gas. Explosions with higher overpressures occur more frequently with hydrogen compared to natural gas. As a result of these higher overpressures, the number of injuries and fatalities is also higher with hydrogen. Taking into account the presence of people in the home, the site-specific risk with hydrogen is greater by a factor of 3.8: 0.18 x 10^{-6}, if the carbon monoxide poisoning risk is excluded. A comparison of the risk between hydrogen and natural gas in the home will also have to include the risk due to carbon monoxide poisoning. The risk of a fatality due to CO is 0.37 x 10^{-6} per natural gas connection. If this risk is added, it appears that there is a shift from the reduced risk due to CO poisoning and an increased risk from explosions. The total site-specific risk, under the chosen set of assumptions and without additional measures, is thereby lower for hydrogen than for natural gas. In both cases, nevertheless, the site-specific risk is well below the 1x10^{-6} value and thus a very limited risk.

The effect of ventilation on the accumulation of (hazardous) concentrations in the house was determined by calculating a dozen identical houses with different ventilation rates. For hydrogen, halving the ventilation rate results in an increase in risk by a factor of 1.8, while doubling ventilation results in a reduction in risk by a factor of 2.2. For both natural gas and hydrogen, increasing the ventilation rate produces approximately equal reductions in the probability of a concentration above the LFL. Because with hydrogen the effects of a possible explosion are greater, the risk decreases more sharply. Therefore, the ratio between the risk of natural gas and hydrogen decreases with increasing ventilation and actually increases as the ventilation rate decreases further. Ventilation has a stronger effect on risk in the home with hydrogen. Experimental research within this Hydelta work package determines the concentration build-up at different ventilation rates and shows that for common ventilation rates in homes, the concentration build-up for small leaks remains very limited (well below 10 vol%).

9.2 Risk from the distribution network

Unlike doing a quantitative risk analysis on an object, such as a leak in the indoor installation of a home, doing an analysis of the entire distribution network is a lot more complex. Given the size of the calculations, it is impractical to calculate the entire distribution network and all connected homes directly. To still be able to make an assessment of the risk, the distribution system has been broken down into typical configurations. For example, the risk of a main with a given pressure, diameter and material properties at a home at a set distance can be determined. By doing a series of calculations in which each of the parameters (pressure, diameter, material) are varied, a database of contributions to the total risk can be constructed. The total risk is expressed as a Potential Loss of Life (PLL). Pipelines with higher pressures (>1 bar) provide a somewhat higher risk, but due to the more frequent occurrence of low pressure networks, their contribution to the total risk is greater. The calculated total risk for natural gas in terms of PLL is 0.64 per year. This is considered to be in reasonable agreement with field data (~0.3 based on a very limited number of incidents).

The factor between the total risk from the distribution grid without additional measures for hydrogen and natural gas is almost 2.5x. Based on the assumptions made in the model and averaged per connection (7.2 million), the risk from the distribution grid in the home is about 0.2 x 10^{-6} for hydrogen, assuming no additional mitigation measures are taken. Again, the risk scales linearly with failure frequency. The largest contribution to the risk lies with the 100mbar PE pipelines. In the model, all services are made of PE, so this pressure and material combination makes a large contribution to the total risk. If, through inspections, the failure rate for spontaneous leaks can be reduced, the risk will be reduced by the same factor.

In addition, the effect of ventilation was calculated. The ventilation rate seems to affect mainly the effects of explosions. This effect is much greater with hydrogen. Doubling the ventilation rate lowers the total risk of hydrogen by a PLL of 0.51 per year, for natural gas only 0.08 per year. When the distribution of risk by cause of leakage is made, it is found that spontaneously formed leaks in particular have a lower contribution: from a PLL of 1.0 to 0.5 /year.

9.3 Risk in the case study

To gain a better understanding of the relative effects of leakages behind the meter and from the distribution network, a case study with a representative neighborhood was assessed. This neighborhood consists of 57 houses connected to a 100 mbar main by individual service pipelines. The 100 mbar network is fed by an 8-bar steel pipe running through the neighborhood. The 100 mbar network is modelled in a number of segments with different materials (PVC and PE) and diameters (110 and 160mm). The houses were modelled based on their area and consist of both detached houses and semi-detached houses. In addition, the risk due to leakages behind the meter was also determined for each of the houses.

The probability of leaks leading to accumulation of gas in a house is higher for leaks behind the meter. For hydrogen, most of the site-specific risk is found to be caused by leaks behind the meter (about 73%). The remainder is caused by the mains and service to which the house is connected, but nearby mains sections also pose some risk. In general, the contribution from the 100mbar pipe is greater than from the 8 bar pipe, depending of course on the distance between the homes and these pipes. The risks are greatest for semi-detached houses compared to detached houses. With hydrogen, as with the risks described above, the effect of explosions is greater than that of natural gas. However, the total risk is smaller on average per house in the neighborhood with hydrogen than the risk from natural gas when the contribution of CO poisoning is included, as shown in the overview below. Again, the total risk, even without additional measures, remains well below 1x10^{-6} in both cases and is therefore considered a relatively small risk.

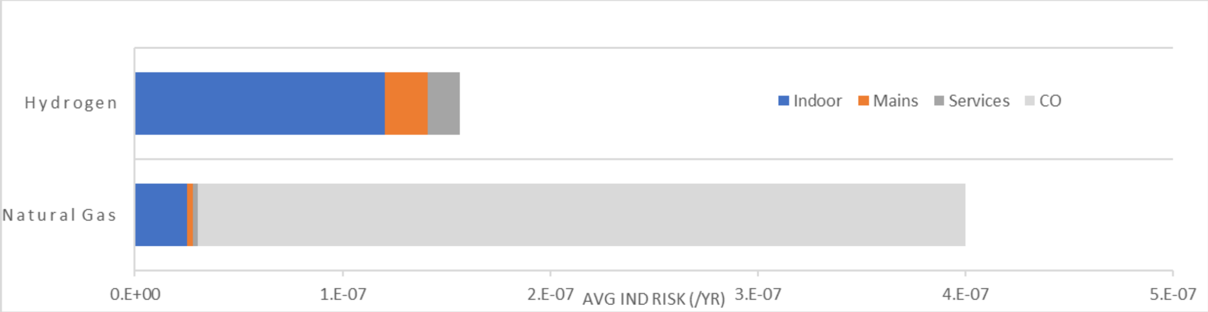


Figure 38 Average location-based risk per home in the case study for hydrogen and natural gas

In summary, it is concluded that the risks as calculated in the model are relatively small. In perspective, the number of fatal accidents in the Netherlands[9] in 2021 was around 6500. The largest proportion of these were caused by accidental falls (5430 corresponding to a risk per inhabitant of about $3x10^{-4}$/year) followed by transport accidents (608 corresponding to a risk of $3x10^{-5}$). The total of fatal accidents due to smoke, fire and flames[10] in 2017 was 43, corresponding to a risk of $2x10^{-6}$.

9.4 Effective mitigating measures

Without additional measures, the risk share due to explosions appears to be higher with hydrogen than with natural gas. This calculation assumes the same failure frequencies between natural gas and hydrogen based on historical failure data. The risk with hydrogen can be reduced by realizing the lower failure frequencies. It appears that especially spontaneous leaks in common parts of the grid (100 mbar) contribute to the overall risk. Interference damage is noticed earlier and therefore leads less often to accumulation of gas to dangerous concentrations in enclosed areas. In this regard, the greatest effect can be realized by mitigation measures that ensure less spontaneous failure of the pipelines and components, such as periodic leak searches or replacement of couplings that often lead to leaks.

Another measure studied is the effect of ventilation. For leaks both in the home and from the grid into the home, it is found that if the ventilation rate is increased, the risk with hydrogen is greatly reduced. On the other hand, it is also true that if the ventilation rate in the home is reduced, the risk is greatly increased. Thus, it is recommended that rooms in which hydrogen could accumulate be properly ventilated. In addition, residents and emergency services should be aware that if a smell of gas (odorized hydrogen) is detected, the gas supply should be shut off as soon as possible and the house ventilated. In this way, dangerous concentrations of hydrogen can be prevented from building up and eventually leading to dangerous explosions.

An initial estimate has been made to the impact of excess flow valves and gas sensors applied to the risk of hydrogen calculated in the case study. This is based on (as yet) unpublished initial calculations applicable to the UK situation. The approach shows that, depending on the assumptions in the model, excess flow valves can achieve a possible reduction in risk for hydrogen of about 20%. For gas sensors, this possible reduction is about 27%.

9.5 Recommendations

The results described in this report were obtained within the set of assumptions as described. In this simplified model of the distribution network and the built environment, several refinements of the model are possible. Based on the results, the following points to improve the model are recommended:

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[9] https://opendata.cbs.nl/statline/#/CBS/nl/dataset/7052_95/table?ts=1683028703713 (2021: €17.5 million inhabitants)

[10] https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81452NED/table?ts=1683029694112 (data for later years werenot found; 2014: 17.1 million inhabitants)

- **Greater variation in housing types.** The model mainly uses detached houses. In the case study some semi-detached houses have been simulated. The effect of explosions is calculated in the model for nearby homes. Therefore, the risk is higher in semi-detached houses. In a refined model a distribution of house types (detached / semi-detached / terraced / small apartments etc.) should be applied. This does lead to a (much) larger number of individual simulation runs required and thus longer computation time for the calculations. A first run of the model for leakages from the distribution network to detached houses with a crawl space was performed. This variation resulted in an increase in risk for both hydrogen (+28%) and natural gas (+40%). Further analysis and determination of the effect for leaks behind the meter is recommended.
- **Investigate leak size distributions**. One of the assumptions used, currently limiting the model, is that PVC pipes have the same leak size distribution as PE pipes. In practice, this could be different. Hard PVC has a more brittle nature and could potentially lead to more brittle fractures. This results in a different leak size distribution, thus affecting the calculated risk. Further investigation of the leak size distribution is recommended.
- **Effect of EFV and gas sensors (specific to the Dutch situation)**. In the version of the model used for this study it was not yet possible to model the effect of the EVF and gas sensors. Simultaneously to this study, the second phase of the H21 project was carried out in the UK. In this phase, the effects of the EFV, gas sensors and other mitigation measures were implemented in the model. The EFV limits the outflow of gas when exceeding a set flow rate (20 m^3/hr). The effect of the sensors is modelled by a higher probability of detection of a given concentration in the house (for example, if it occurs at night or because an audible alarm is more likely to be noticed by neighbors). Following alarms, it is assumed that the gas supply is shut off earlier and ventilation is increased, ultimately keeping concentrations in the home lower and reducing explosions. The results of H21 Phase 2, have not been published at the time of writing. In Chapter 8, an initial estimate of the impact of the EFV and gas sensor was made based on the results in the UK and applied to the risks of hydrogen in the case study. It is recommended to extend the model for the Netherlands to calculate the impact of these measures.

10 Bibliography

[1] KIWA, DNV, "Hydelta D1a_1 Uitkomsten onderzoeken Verenigd Koninkrijk Hy4Heat en H21 vertaald naar Nederlandse situatie," 2022.

[2] DNV, "H21, QRA model for hydrogen gas distribution networks," DNV report 10078380-2 Rev 0, 2020.

[3] DNV, "H21, Risk predictions for hydrogen gas distribution networks," DNV report 10078380-2 Rev 0, 2020.

[4] M. Acton, A. Halford and A. Phillips, "Quantification of the Risks Associated with a Hydrogen Gas Distribution Network," in *Hazards 30 (paper accepted)*, Manchester, November 2021.