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Future-proof gas distribution networks

this report is a translation of the Dutch report
GT-170272 Toekomstbestendige gasdistributienetten

kiwa

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Preface

This report describes a study into the future-proofing of gas distribution networks in a CO_2-neutral and sustainable energy supply, which was carried out by Kiwa Technology on behalf of Netbeheer Nederland.
The research builds on the four scenarios (images of society) developed by CE Delft (independent research and consultancy firm) for the energy supply in 2050.

The research was partly realized thanks to the input of a support group with participants from all Dutch gas network operators. The participants in this group were:

- Frank van Alphen (Stedin)
- Michiel van Dam (Enexis)
- Henk Engberts (Coteq)
- Nick van der Hout (Westland Infra)
- Johan Jonkman (Rendo)
- Jelle Lieffering (GTS)
- Pascal in Morsche (Liander)
- Carel Lauwereijs (Enduris)

The support group has made a major contribution to the research by guiding progress, actively participating in the discussions and by providing information and input.
DNV-GL has performed a review on a draft version of the report.
The valuable comments and additions thus obtained have been incorporated into this final version.

Abbrevations and terms

CCS	Carbon Capture and Storage (capture and storage of CO_2).
WEQ House equivalent	Unit from the report "Net voor de Toekomst" (Networks for the Future), prepared by CE Delft, where a WEQ is equated with a residence or 150 m² utility building.

Terms

Biomethane	(specific for this report) Partially purified or processed sustainable gas based on biomass, possibly of a broader quality than the currently applicable MR Gas quality (see for example the table in Annex IV, columns "Cleaned biogas (fermentation)" and "Methanizing gas").
Fuel cell	Device that directly converts the chemical energy of a reaction into electrical energy.
Requirement for precautionary measure	Indication in the operating equipment registration system of the regional network operator for an operating equipment, which indicates that with a KLIC notification for the operating equipment additional precautionary measures are required that promote safety.
Green gas	Sustainably produced gas from biomass that has been upgraded, so that it has the same gas quality as natural gas and meets the MR Gas quality.
KLIC Report	Report in the cable and pipe information system of the Land Registry, in which an excavation activity is announced. As a result, the supply of cable and pipeline data is initiated by the network manager to the digger.
Low temperature heat supply	Heat supply (such as central heating boiler), with which houses and commercial buildings are heated.
MR Gas Quality	Ministerial Regulation of the Minister of Economic Affairs of 11 July 2014, no. WJZ / 13196684, laying down rules for gas quality (Regeling gaskwaliteit) applicable from 1-4-2016.
Permeation	The intrusion of substances. With plastic gas pipes, gases such as water (vapor), nitrogen and oxygen (the most important components from the air) can permeate through the wall from outside to inside and vice versa.

Ignition energy
The minimum amount of energy required to ignite a gas / air mixture. This is a function of the type of gas (composition), the gas / air ratio, the temperature and the pressure.

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1 Summary

Consequences of the energy transition for the gas distribution networks
In order to achieve the objectives of the Paris climate agreement, the Netherlands wants to reduce carbon dioxide emissions in the built environment to 0% by 2050. Fossil energy sources give way to sustainable energy.
This transition has far-reaching consequences, including for network operators. With the phasing out of natural gas, the important question arises as to whether there is still a future for the existing gas network. This question is topical for the regional network operators because choices must now be made for maintaining the gas network for the long term.
Studies such as "Networks for the Future" predict that a sustainable energy supply will sooner come within reach with the use of sustainable gases, such as hydrogen and biomethane. Where gas networks are suitable, the choice can be made to opt for a solution with sustainable gas, temporarily or not. The question then is what sustainable gases they are and how network operators can anticipate this gas transition.
That is why Netbeheer Nederland has asked Kiwa to investigate what it takes to make the existing gas distribution networks future-proof.

Logic of releasing Groningen gas as the standard for gas quality
Today, less than 1% sustainable gas is added to the natural gas network. This "green gas" of biological origin has almost the same quality as regular (Groningen) natural gas. A valid question is whether the same natural gas quality should be maintained in the future. The switch to high calorific natural gas, the international standard, is not appropriate for the built environment. The climate objectives exclude the use of any kind of natural gas in the future. Logically, the gas quality in the future will therefore have to be in line with that of sustainable gases.
The study "Networks for the Future" is based on two types of sustainable gases. The first is biomethane, a term that covers an entire collection of biologically produced gas. Just as with natural gas, the main component is methane, but with a greater variety of different gas components.
The second is hydrogen, which can be produced using renewable electricity. Hydrogen is currently in the spotlight as an emission-free energy carrier for mobility, energy storage, industrial use and possibly also for the built environment.
The switch to new quality standards for these sustainable gases prevents unnecessary costs and loss of efficiency that would result from processing the sustainable gases to the quality requirements of natural gas.

Using more than 50 years of experience with natural gas distribution
In close collaboration with experts from the regional network operators, we investigated what is involved in switching from natural gas to these sustainable gases. In addition to ensuring safe, reliable and affordable transport, this also includes measuring and settling. The research also included the quality of the gas delivered, as well as the consequences for the customer. There is currently no large-scale experience with hydrogen and biomethane in the built environment. A lot of knowledge is available from practical tests, laboratory tests and technical manuals. For this report, all this knowledge was brought together for the first time and structurally applied to the situation of the Dutch gas distribution network. The following research questions were then answered:

- to what extent is the current gas distribution network resistant to sustainable gases?

- what adjustments are needed to make the existing gas networks suitable?

- what costs are involved in the changeover?

As a guideline, as many connections as possible were sought with the materials, standards and customs that currently apply to natural gas. These have again been critically assessed from the point of view of a safe distribution of hydrogen and biomethane.
The results provide insight into potential risks and control measures. This inventory forms a solid basis for a future implementation agenda to make existing gas distribution networks future-proof.

Existing networks are suitable for the distribution of sustainable gases
The most important conclusion from this research is that the existing gas network can be used with the right measures to distribute sustainable gases such as (100%) hydrogen and biomethane.
Where distribution of sustainable gases is desired, the gas network of the future can largely remain the same as the current natural gas network.
The most important adjustment for the network operators concerns the measurement and settlement of the amount of energy supplied. A further condition is that the devices are made suitable for 100% hydrogen and biomethane for the end user.

Safe and reliable use of hydrogen and biomethane in the built environment
In order to use these sustainable gases at least as safely and reliably as compared to natural gas, an overview of points for attention and potential control measures has been drawn up. According to the expectations of consulted experts, this makes safe and reliable distribution possible.
However, a quantitative assessment of the risks and the effectiveness of the measures to be taken is still lacking.
A minimum required precautionary measure is to give hydrogen and biomethane a recognizable odor, preferably with the aid of a sulfur-free odorant.
Another important point of attention is the safety measures to be applied in the event of undesired outflow of gas, such as excavation damage. The safety aspect also deserves extra attention when using hydrogen indoors.

Costs of network modifications estimated at a maximum of 700 million euros
The future use of new gases in the built environment still has various uncertainties. The costs for the network modifications depend on which parts of the current gas network will remain necessary.
With the help of the four scenarios from the study "Networks for the Future", an indication is given of the costs that the adjustments of the gas distribution networks entail, excluding the adjustments for end users.
The total costs for switching and adapting the networks can amount to 700 million Euros. The network costs increase roughly by 10 to 50% per house per year.
The largest cost item that was included in the switch to hydrogen is the replacement of the gas meter and the renewal of the procedure for offsetting gas costs as a result of differences in gas composition. For biomethane there are additional costs involved to enable the handling of the varying calorific value. A significant periodic cost item is related to stricter supervision during excavation work.

Incidentally, these additional network operator costs are limited compared to the expected adaptation costs of devices for end users.

Operational perspective network operators
For a safe and reliable delivery of sustainable gases in the built environment, a careful expansion of experience is required. Given the pace of the energy transition, a deliberate trade-off between the learning pace and an acceptable level of risk during this learning process plays an important role.
The responsibilities during this gas transition lie with several parties. Collecting this experience together is therefore essential. This goes further than just gas network operators, but also affects other owners of underground infrastructure, suppliers of

end-user equipment, safety authorities, municipalities, etc. Assuming that the distribution of sustainable gases will be a public task of network operators in the future, such as now for natural gas , the advice for the next steps consists of:

- validate and elaborate findings from this report in practice and develop "best practices";
- investigate the implications of measuring and settling sustainable gases;
- organizing and drafting appropriate (international) norms and standards throughout the entire chain from production to use;
- setting up training courses and campaigns for public awareness.

Final remark
This inductive research provides an answer that is as complete and objective as possible to the question of how gas networks can be used for future-proof distribution of sustainable gases. Perhaps the most important factor in answering this question definitively lies in human behavior. Decades of experience with natural gas distribution show that issues such as safety perception, corporate culture and leadership are essential for a safe and reliable energy supply. This also applies to sustainable gases.

It is up to the regional network operators whether, and how, the gas network will be used for the transport of sustainable gases. In that sense, the answer to the research question is not a given fact, but a choice. As a start to this, this report (with the appendices) contains all available information in order to arrive at an opinion on the possibilities and limitations of hydrogen and biomethane in the built environment. The remaining part of this summary contains the most important insights per type of gas.

1.1 Hydrogen distribution

Difference between distribution of hydrogen and natural gas
Hydrogen is the smallest molecule and can be made in a sustainable way by converting electricity - from wind or sun - into hydrogen and oxygen. Hydrogen can be used as an emission-free energy carrier and storage medium. No CO_2 is released when converting hydrogen to electricity or heat. The report "Outlines for a hydrogen road map" contains recent insights into the use of hydrogen in energy supply in the Netherlands. Hydrogen can be transported through the existing gas network. However, hydrogen is a different gas than the known natural gas. For example, compared to natural gas, hydrogen has a lower ignition temperature, wider explosion limits and a higher rising force. When hydrogen is burned, the flame is poor to invisible and the burning speed is higher than with natural gas. In addition, hydrogen, just like natural gas, is not smellable by itself. For safe distribution, the network operators must take these characteristics into account.

Experiences from the petrochemical industry, through scientific research and practical tests
Hydrogen is transported and used on a large scale in the petrochemical industry. Extensive scientific literature is also available about the effects of hydrogen on materials. Partly based on various practical tests, a comprehensive overview of current knowledge and experience has been made for the regional gas networks. Much basic knowledge about material resistance of plastics, metals and rubbers is available in standard works and manuals that are used in industry.

The most important scientifically based studies into the effects of the transport and distribution of hydrogen on the existing gas network have been carried out in the European NaturalHy project. Later, the multi-year Dutch EDGaR (Energy Delta Gas Research) study was added. In addition to an extensive literature exploration, the remaining missing knowledge has been supplemented through experiments with gas distribution materials. Because during this literature review sufficient knowledge of the effects at 100% hydrogen was already available, EDGaR no longer carried out any tests with 100% hydrogen (but did so with syngas that contains up to 62% hydrogen,

see Chapter 5). In these studies, the researchers conducted laboratory tests on the resistance of metals, plastics and rubbers. This concerns effects on the quality and remaining service life, such as embrittlement, tensile strength, hardness and toughness of pipe materials and seals.

The most relevant practical experience in the field of hydrogen distribution in gas networks has been gained in a practical test on Ameland. Up to 20% hydrogen has been added to the natural gas in a specially designed test network and offered to a variety of household gas installations. The test network consisted of the usual constructions with old and new materials and connections.

A second field test was carried out in Denmark where the transport of 100% hydrogen through new and used PE and steel pipes has been tested for 10 years.

In addition, numerous sub-studies have been conducted internationally, the results of which correspond to the results from the above studies.

With this inventory an in-depth insight has been obtained into the material effects. Subsequently these have been related to the already known failure mechanisms, which allows making a statement about the suitability of the gas distribution networks.

The gas distribution network is resistant to hydrogen

The overall finding from this inventory is that the current gas distribution network will not be significantly affected by hydrogen. For all known materials, with steel, PE and PVC as the most important, no noticeable degradation is to be expected and observed both on the basis of the literature consulted and on the basis of the laboratory tests and practical tests carried out.

The use of the current gas network requires one important point of attention. This is due to the lower energy density of hydrogen. With a constant energy demand, a gas volume that is three times as large is being transported. The consequence of this is that capacity of the majority of the gas meters, which are based on volume measurement, will not be sufficient at peak moments. To measure the same (maximum) energy flow, a volume that is three times larger is needed. The extent to which this effect makes current gas meters unsuitable has not been investigated. The lower energy density also results in a higher flow rate. In addition, the transport capacity of the pipes remains the same as that of natural gas. The other effects are unknown or negligible.

Existing devices are not suitable just like that for 100% hydrogen

Virtually none of the existing devices at the end users' are suitable for use with 100% hydrogen. The combustion of hydrogen in existing central heating boilers may result in flame impact and damage to the burner. Also the security principle (ionization current) in the current devices is not applicable with 100% hydrogen. This also applies to most gas cooking appliances. An increased safety risk with cooking appliances is that combustion of hydrogen does not produce a visible flame.

The availability of hydrogen makes it possible to use fuel cells. Fuel cells convert hydrogen and oxygen into electricity and water with a high efficiency. Pure hydrogen is important for the service life of fuel cells. It is not yet known with what quality hydrogen can be supplied via the gas network and to what extent this constitutes a restriction for the use of fuel cells. Experience with natural gas and green gas has shown that inevitably there is some contamination due to moisture ingress, permeation of oxygen and nitrogen, and the presence of dirt in the pipes. Also, the fragrance currently used with natural gas and green gas, the sulfur-containing THT, in combination with fuel cells is discouraged.

Switching to hydrogen requires a revision of standards and methods

For the control of risks for natural gas and green gas, standards, work instructions and training for engineers and other experts have been developed over the years. This makes the natural gas network in the Netherlands one of the safest and most dependable in the world.

The other properties of hydrogen require a critical assessment and review to remain at least at the same level. There is still insufficient practical experience to quantify the risks associated with the distribution of 100% hydrogen. That is why a qualitative

approach has been chosen based on the bowtie methodology and expert interviews. This provides insight into the potential risks and points for attention during work, leaks and calamities. Associated control measures have been named. These must be validated and optimized in practice.

Based on the survey carried out by experts, it is not possible to determine whether the distribution and use of hydrogen in the built environment is inherently more dangerous or safer than natural gas. An important plus of hydrogen is that carbon monoxide poisoning will no longer occur. In addition, the volatility of hydrogen reduces the risk of fire or explosion. On the other hand, the wider explosion limits, the lower ignition temperature and the lower ignition energy risk have an increasing effect. In a practical study in the United Kingdom into hydrogen leakage in a test farm, it was found that it was not possible to produce an explosive mixture under normal conditions. In short, there are arguments that lead to an increased risk and others that point to a lower risk compared to natural gas. The question of what measures are needed to adequately control the risks of fire or explosion in the event of hydrogen leaks cannot yet be definitively answered.

Finally, there are two other phenomena that are often associated with hydrogen. These are the permeation of hydrogen through plastic pipes and hydrogen embrittlement of steel. Both effects are negligible under the circumstances that apply in distribution networks and do not result in a significant degradation or increase in the safety risk.

1.2 Distribution of biomethane

Diversity of gas components in biomethane
Biomethane is very similar to natural gas. The main component is methane, supplemented with varying concentrations of other types of components.

The quality of natural gas and green gas is laid down in the Ministerial Regulation on Gas Quality, which allows a limited variation in concentrations of the gas components. Biomethane is extracted from a wide variety of organic biomass streams and therefore provides a greater variety of gas compositions than permitted in the MR. The most commonly used production process consists of fermenting biomass such as organic waste, residual waste from the food industry and manure. In addition, there are developments to produce "syngas" by gasifying woody biomass and methanizing hydrogen. Ultimately, more than 13 different main components can occur in biomethane in different proportions. For this research, limit values per component have been established for biomethane based on the known production methods.

Research into the broadest possible limit values for biomethane
The current gas must meet the MR Gas quality. Since 2016, limit values have been included for gas components that can occur in biomethane. Biomethane that meets these quality requirements is called "green gas" and can be fed into the existing gas network. These requirements have been drawn up to guarantee safety and interchangeability with natural gas.

That exchangeability will no longer be necessary in the future, which means that it is possible to set broader limit values for biomethane. To determine these broader limit values, research was conducted into the influence of gas components on materials and the combustion behavior in end-user devices.

The most important insights for the gas distribution networks come from EDGaR, where extensive tests have been conducted into the resistance of materials. In addition, there is experience in various places in the Netherlands with the transport of cleaned up 'biogas', for which the quality requirements are less stringent than for green gas. The MR Gas quality does not apply to these local applications and separate safety instructions and work agreements have been drawn up. Overall, more knowledge and practical experience is available for biomethane about its use in the built environment than for hydrogen. On the other hand, the conclusions in the publications are less clear-cut. While no results were found with the use of hydrogen

that indicate a deterioration of materials, there are indications for biomethane that some components influence the lifespan of the gas distribution network.

Almost every form of biomethane is permissible for the existing gas distribution network

Biomethane is currently brought to the same quality as natural gas. According to the research, this will no longer be necessary in the future, provided that the gas measurement and the devices are made suitable for end users. The network manager can then allow almost any composition of biomethane in the existing infrastructure. PE and PVC in particular have good resistance to the gas components that may be present in biomethane. Maximum values continue to apply for some gas components. These are included in Table 5-4 of this report. These maximum values are necessary to prevent degradation of metal parts of the gas network and the POM material. POM is frequently used in connections, house pressure regulators and gas meters.

The adjustments at end users' are less radical than for hydrogen. Just as with hydrogen, correct measurement and settlement is a point of attention. With biomethane this is due to the greater bandwidth in energy content. The measuring principle of volume measurement in the existing gas meters does not take this into account, as a result of which the settlement becomes less accurate than the existing requirement (<0.5%). At present, there is no measuring principle with comparable costs available for correct individual settlement with end users. Apart from the development of suitable meters, this can be solved by allowing (per area) a limited variation in gas quality, or by introducing gas quality measurement at area level. The economically best option has not been investigated.

Safe and reliable use of biomethane in the built environment

Biomethane may contain a number of toxic components. No work must be carried out in an environment in which the concentration of these components is above the maximum permitted value. The lowest limit value for the occurrence of an explosive gas mixture can be used as a maximum, because in this situation no work may be carried out anyway because of the risk of fire and explosion. Experience with the local transport of cleaned up "biogas" shows that following this measure does not present any additional risks for biomethane compared to natural gas. The robustness of this method depends on correct compliance with the applicable procedures and work instructions, as well as the supervision thereof.

2 Introduction, objective and research design

2.1 Background

The Ministry of Economic Affairs states that the built environment must be CO_2 neutral by 2050. Local authorities and citizens' initiatives develop energy visions, within which natural gas-free neighborhoods form a spearhead. From a social point of view, this should not automatically lead to the removal of the gas network. Precisely existing gas distribution networks can be part of making the built environment and the energy transition more sustainable.

A gas distribution network that is suitable for sustainable gases in the future offers opportunities for a successful energy transition. In addition, a sustainably employable gas distribution network will most likely have a positive influence on the business case for replacement and construction investments, which now require decision-making from gas network operators. A good understanding of the possibilities for a flexible gas network for sustainable gases can prevent disinvestments.
Distribution of sustainable gases is therefore a serious alternative that fits in with the vision of all stakeholders, such as the national government, regional and local governments and network operators.

2.2 Problem definition

The current trend is to reduce the share of natural gas in the energy supply of the built environment. What this means for the function that the gas distribution networks will fulfill is unknown. However, reducing the use of natural gas does not necessarily mean that gas will disappear as an energy carrier.

Sustainable gases, such as hydrogen and biomethane, could become an important part of the future energy supply. What this energy supply will look like exactly is not yet known. A number of developments can already be identified. One development is, for example, the emergence of local energy cooperatives.

Factors that are important for achieving an optimal local energy supply are the current and future energy use, the presence of sustainable energy sources and the possibilities for local storage. The storage of electrical energy is still expensive, and the applicable capacities are too limited to realize the winter / summer cycle of energy demand at a socially acceptable price.

Another development is the increasing availability of energy conversion techniques. These make it possible to transform the surplus of sustainably generated electricity into a gaseous energy carrier, such as hydrogen and methane. These energy carriers can be made relatively easily and cheaply and are cheaper to store than electricity.

By extrapolating these developments to 2050, future images arise. Depending on the choices made by, for example, national and local politics, but also by locally established energy cooperatives, a certain interpretation will arise for this. The whole of these interpretations is shown in energy supply scenarios. With the help of these scenarios, a picture can be sketched of the future energy supply and the contribution of the (current) gas networks therein.

Most scenarios assume the use of sustainably generated energy. This energy is generated in various ways, whereby electricity is produced with the help of wind turbines and solar panels. Sustainable gas is produced from biomass and / or by

converting a surplus of sustainably produced electricity into hydrogen and / or methane.

The use of the current gas network is obvious for distributing these sustainably produced gases. The question is whether the current gas network can simply distribute these sustainably produced gases, or whether adjustments to the network may be necessary before these sustainable gases can be distributed. The costs of the adjustments that have to be made to make the current gas network suitable for the future will partly determine whether a certain scenario will become reality. Some adjustments to the gas network can perhaps make a positive contribution in several scenarios. It is therefore wise to clearly map these options.

CO_2 neutral in combination with gaseous energy

It was agreed in the Paris Climate Agreement to limit global warming to well below two degrees Celsius. This translates into a CO_2 reduction for the European Union of between 80 and 95% [1].

To achieve this, an energy transition is needed. Fossil fuels lead to CO_2 emissions. Of all fossil fuels, natural gas leads to the lowest CO_2 emissions per energy unit [2]. Natural gas, however, remains a fossil fuel with the associated CO_2 emissions. As a result of the earthquakes in the Groningen area, domestic production of natural gas is currently being reduced [3]. It is therefore not surprising that more and more authorities and municipalities are calling for "to get rid of gas" [4] [5] [6].

In the public debate it is sometimes forgotten that gaseous energy carriers are not by definition fossil; hydrogen or biomethane can be produced from sustainable sources. The Netherlands has a dense gas infrastructure. It is therefore an important question whether this infrastructure can be used for the distribution of sustainable gaseous energy. In this way, a CO_2 neutral energy supply can perhaps be achieved that will definitely still include the use of gas.

2.3 Objective

The aim of this research is to, in close consultation with the Dutch gas distribution sector, give direction to the implementation of a future-proof, sustainable gas supply. An inventory was made on the basis of already available knowledge about how the gas distribution networks can be made future-proof.
The following research questions have been formulated for this purpose:
1. To what extent is the current gas distribution network resistant to sustainable gases?
2. What adjustments are needed to make the gas distribution network future-proof?
3. What costs are involved in the changeover?

2.4 Research design

The current situation has been chosen as the starting point in this study. Natural gas is mainly transported to the end users via the existing gas distribution network, where the natural gas is used for heating and / or as process gas. Because the Netherlands also wants to meet the obligations of the Paris Climate Agreement, the government has indicated that from 2050 onwards, no net CO_2 emissions may take place in the built environment. To meet this requirement, the use of natural gas in the built environment must be reduced. To meet the energy requirement, alternative energy carriers must be used. How this adjustment will proceed exactly is unknown for the

time being. Gaseous fuels will probably play a role in the new situation. It is therefore obvious to use the current gas network for this. However, the question is whether the current gas network is suitable for this, or what possible adjustments have to be to make it suitable for this. In this study it has been assumed that the replacement of asbestos cement pipes will have been completed when the "new" gases are introduced. Therefore, in the context of this study, no research has been done into the effects of "new" gases on asbestos cement pipes.

The research has been set up in such a way that from the perspective of the regional network operator it looks at the changes that are deemed necessary for a successful transition to take place. However, there is a dependence on the end users. After all, the gas distribution network is only a part of the total chain. That is why we also looked at the implications and application possibilities of and for the end user. The knowledge of combustion appliances and gas indoor installations is used for this. Although the focus is on the impact for the regional network operator, where deemed necessary, the impact and the significance for everything behind the meter are included.

In this research, the available knowledge has been brought together as much as possible to identify the necessary changes in the gas network. Because it is unclear how the transition to a sustainable energy supply will proceed, use has been made of four possible scenarios, such as those presented in the report "Networks for the Future", which was commissioned by Netbeheer Nederland to CE Delft. By using these scenarios, it is possible to estimate which sustainable gases are preferred. Based on this, the most important materials that have been used in the current gas distribution network (see Annex I) indicate whether they are resistant to these sustainable gases. In addition, it is indicated which measures must be taken to guarantee safety. The standards, work regulations and experiences that apply to natural gas are taken as the basis for this. Moreover, attention has been given to the settlement. As already indicated above, the impact of the use of the "new" gases on the end users has also been investigated. Measures have been specified that enable safe and efficient use of these gases. Because all these measures will have financial consequences, this study has also focused on the costs and benefits of those measures.

This gives a first impression of the possible costs and revenues. This is a financial estimate based on only a general outline plan for the conversion of the current gas distribution network, with the sole purpose of indicating solutions. The estimated costs partly depend on the answer to the question to what extent initial controls should be of a lasting nature. This must be apparent from the evaluation of practical experiences.

Applied approach: using technology, it was investigated where the challenges / obstacles lie for the integration of sustainable gases. A large number of specific measures have been specified for this. A cost estimate has been made for the most important measures. This first financial estimate provides an indication of the financial impact, which gives a sense of the size of the actions the gas distribution sector is facing. Additional research will be necessary to get an idea of the exact costs. For the four scenarios, the additional costs for the transition to sustainable gases have been calculated using this first cost estimate.

2.5 Format report

Chapter 1 contains the management summary of this report.
Chapter 2 contains a more detailed summary.
Chapter 3 contains the introduction and the research objective.
In chapter 4 a description is given of the chosen scenarios, from which the blueprint of the associated gas distribution network is derived.
The conditions and points for attention for the use of hydrogen in the existing network

are further explored in Chapter 5. Where there are technical bottlenecks for applying the existing network, these bottlenecks and the possible solutions are mentioned.

Chapter 6 describes the conditions for the use of biomethane in various compositions in the existing network. Here too, the technical bottlenecks are indicated for applying the existing network with the possible solutions.

The costs for adapting the network are presented in Chapter 7 per type of area and the type of sustainable gas.

Finally, chapter 8 summarizes the research conclusions and presents the recommendations that emerged from the research.

3 Selected scenarios and associated gas networks

3.1 Methodology

This chapter introduces the future scenarios for the energy distribution network for the future. For each of these scenarios it was investigated what type of gas network or gas networks will be present.

The type of gas network is characterized by three dimensions. Those are:
- the type of network (which is determined by the type of gas being distributed);
- the area type in which the nets are located;
- the degree of penetration of these nets.

These dimensions are discussed in more detail below.

<u>Net types</u>

The CE report "Networks for the Future" [7] refers to the use of various energy carriers for low-temperature heat supply with associated grid types. Low temperature heat is understood to mean the heating of houses and utility buildings. This is comparable with, for example, a current central heating system. In the aforementioned report the following energy carriers are distinguished:
- Heat
  - residual heat
  - geothermal energy
  - Hot Cold Storage (WKO)
- solid biomass for boilers
- electricity (inter alia for driving a heat pump)
- biomethane (for HR boilers and hybrid heat pumps)
- hydrogen (for HR boilers and hybrid heat pumps)

The two latter energy carriers (biomethane and hydrogen) are gaseous. This will also require gas networks to transport these energy carriers to the end user.
In addition to the low-temperature heat supply, the network types of biomethane and hydrogen can also be used for part of the energy needs of the industry. In the "Networks for the Future" study, these gaseous energy carriers are therefore used to meet the need for high-temperature heat and as "feedstock" (production raw material). The existing gas network may also be used for gas transport for this category of end users. That is why this study pays attention to this.

<u>Region types</u>

We distinguish four area types:
- urban
- residential areas
- nationwide
- industry

There may be a differentiation in the network types for the different area types. We now have the same nets in every area type in the Netherlands (in outline). At present there is a natural gas supply (for low temperature heat) and an electricity supply almost everywhere. The electricity supply will probably be maintained everywhere, but the network type for low temperature heat may possibly differ between the aforementioned area types.

In addition to the three area types, gaseous energy carriers are used in industry. Because of its location on industrial sites, often on the outskirts of cities, this forms its own category.

<u>Net penetration</u>
The last dimension that is considered is that of net penetration. This concerns the extent to which the gas network knows how to penetrate the built environment. We distinguish 5 levels of network penetration where the equivalents of the current natural gas network are indicated in brackets for clarification:
- to the outskirts of the city (City Gate station)
- up to the edge of the residential area (District Station)
- up to the corner of the street (Low pressure main line)
- to the house (Connection line)
- to and into the house (Connection line and transit through façade into the house)

3.2 Selected scenarios "Networks for the Future"
In the report "Networks for the Future" [8] four scenarios have been worked out for the energy supply in 2050. These are:
- Regional Management
- National Management
- International
- Generic Control

For each of these scenarios, the remainder of this chapter indicates what kind of gas networks are expected to be needed for this.

3.2.1 Regional Management Scenario
In the Regional Management scenario, provinces and municipalities are largely in control and these regional and local authorities focus strongly on decentralized energy generation and use. Citizens, companies and local and regional authorities play an active role in providing energy solutions, for example collective and individual solar PV solutions, small-scale collective heat networks and onshore wind energy. There is no large-scale import of renewable or fossil energy from outside the Netherlands, but energy can be transported within the Netherlands. CCS (Carbon Capture and Storage) does not occur. For the low-temperature heat supply, as many sources as possible are used on a regional scale. All-electric solutions are the most common. The image of the Netherlands has changed drastically: many large wind turbines, maximization of solar PV on roofs, but also sun pastures and many storage systems.

The gas supply within the Regional Management scenario

Gas type and origin
In this scenario, hydrogen and biomethane occur as a gaseous energy carrier.

Hydrogen is made from renewable electricity with the help of electrolysis. Hydrogen electrolysis will be realized at various voltage levels and scales. The report "Networks for the Future" states that hydrogen will also be stored to cope with seasonal fluctuations in energy consumption. However, the scale of this storage is not explained further. Within the framework of this scenario, it is obvious that hydrogen storage will take place locally as much as possible.
Biomethane: both the production and use of biomethane is very local. There is no large-scale import of energy. Biomethane is made using fermentation plants.

Gas use

Figure 3-1 shows how within this scenario the low temperature heat supply is distributed across the Netherlands in the Regional Management scenario. The areas present correspond with districts and neighborhoods.

The use of hydrogen is shown in the areas with the colors red (use in high-efficiency boiler) and orange (use in a hybrid heat pump). In this scenario, hydrogen is not used for the low-temperature heat supply. Hydrogen is often used in industry (high-temperature heat and feedstock). Part of the hydrogen is also used to support the large heat plants to generate the required extra heat on cold days - by burning hydrogen.

With this, it is obvious that in this scenario, hydrogen pipelines will be created from the hydrogen production plants to the major customers. Whether this also creates a national transport network - comparable to the current GTS network - is as yet unclear. It is clear, however, that in this scenario there is no reason for regional hydrogen networks to individual houses.

The use of biomethane is shown in the areas with the colors blue (use in high-efficiency boiler) and light blue (use in hybrid heat pumps). This shows that the distribution of biomethane takes place very locally. Distribution only takes place in the areas where biomethane from fermentation is available. Biomethane is brought into the houses.
The various areas where biomethane is used are quite far apart. Although this is not explicitly mentioned in the scenario study, it is not obvious that these areas will be connected to each other in the form of a national biomethane network. Local solutions for buffering and delivery security are more in line with this scenario.
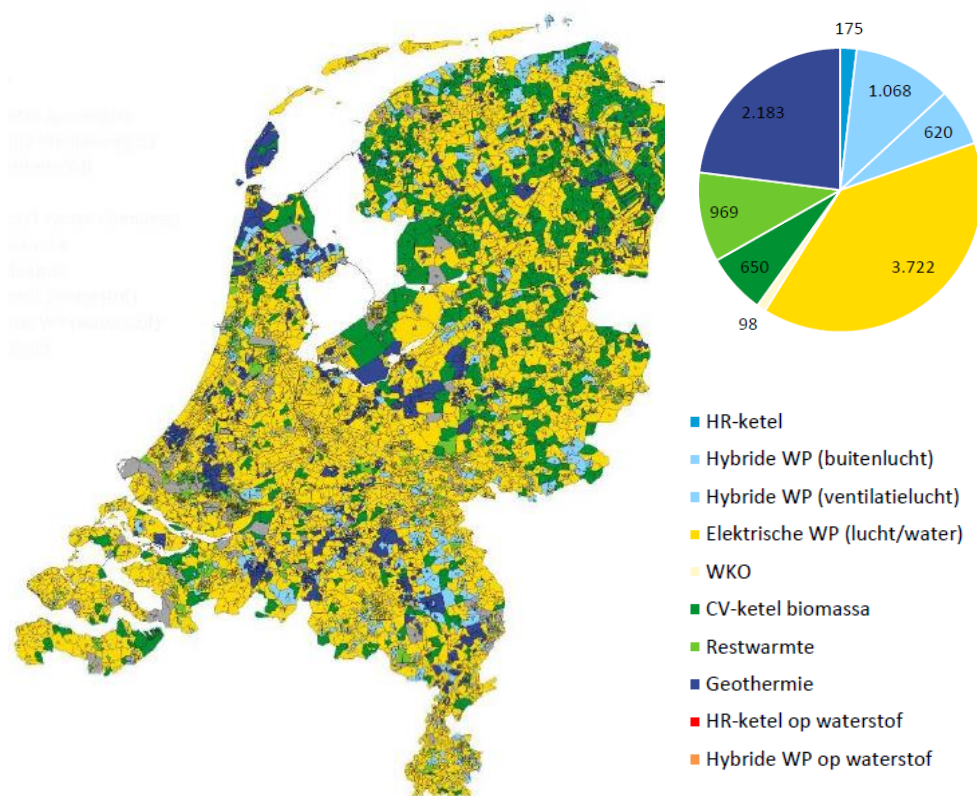
Figure 3-1. Image of Society Regional Management. Left: Map of the Netherlands with the low temperature heat supply. Above right: Heat connections (x1,000) per option. Bottom right: Legend (translation below) [8]

High Efficiency Boiler
Hybrid heat pump (outside air)
Hybrid heat pump (ventilation air)
Electrical heat pump (air/water)
WKO (Heat Cold Storage)
Central Heating boiler biomass
Residual heat
Geothermal heat
High Efficiency boiler on hydrogen
Hybrid WP on hydrogen

The above shows that within the Regional Management scenario there is room for the following types of gas networks: Area type Hydrogen network Biomethane network.

Table 3.1. Types of gas networks per area type per type of gas, Regional Management scenario.

Area type	Hydrogen network	Biomethane network
Urban	None	None
Residential areas	None	Sporadically, only where biomethane is available
Rural area	None	Sporadic, only where biomethane is available
Industry	In any case from source to (industrial) customer. National connection network is possible	No

3.2.2 National Management Scenario

The central government takes the lead in this vision of the future. The government organizes large projects, including in the field of offshore wind energy, such as energy islands in the North Sea or other major projects, to improve the integration of offshore wind energy. The Netherlands is energy self-sufficient in this vision of the future. Citizens and companies are aware that renewable energy is scarce in the Netherlands. As a result, the step towards setting up a highly circular industry, in which recycling plays a major role, is logical. The current oil refining and petrochemical industries have made way for an extensive recycling industry and a chemical industry based on renewable hydrogen and the production of plastic from methanol.

The gas supply within the National Management scenario

Gas type and origin
In this scenario, hydrogen and biomethane occur as an energy carrier.

Hydrogen is made from renewable electricity with the help of electrolysis. Hydrogen is converted centrally and on a large scale from sustainable electricity. This renewable energy comes mainly from large-scale offshore wind farms. Seasonal storage can be situated in the form of salt caverns in the north and east of the Netherlands. *Biomethane* has a limited role in this scenario: only 12% of the primary energy demand for low temperature heating is filled with biomethane.

Gas use
The low temperature heat supply is organized nationally. Figure 3-2 shows how the low-temperature heat supply is distributed across the Netherlands.

Hydrogen is represented in the areas with the colors red (use in high-efficiency boiler) and orange (use in hybrid heat pump). Hydrogen-powered HR (high efficiency) boilers are often used in large cities. In addition, hydrogen is used in a large number of (provincial) cities and villages in a hybrid heat pump. A gas network will not continue to exist everywhere, but in many places it will. In this scenario, it is anticipated that a large proportion of all houses will be connected to the hydrogen network. Hydrogen will also be used for mobility. Hydrogen will also meet an important need for feedstock for the industry. The creation of a national hydrogen transport network is obvious in this scenario. Both in the vicinity of this national transport network and in the vicinity of the high-pressure distribution network, petrol stations for driving on hydrogen can be situated.

The use of *biomethane* is shown in the areas with the colors blue (use in high-efficiency boiler) and light blue (use in hybrid heat pump). This shows that the distribution of biomethane takes place very locally. Distribution only takes place in the areas where biomethane from fermentation is available. Biomethane is brought into

the houses. Biomethane will also be used for transportation. This will result in gas stations for biomethane, whereby the locations are chosen in such a way that they fit in as well as possible with the existing gas infrastructure.

The various areas where biomethane is available and used as a fuel for low-temperature heat are well spread. The use of a national transport network for biomethane is therefore unlikely.

Figure 3-2. Image of Society National Management. Left: map of the Netherlands with the low temperature heat supply. Above right: Heat connections (x1,000) per option. Bottom right: legend (translation below) [8]

High Efficiency Boiler
Hybrid heat pump (outside air)
Hybrid heat pump (ventilation air)
Electrical heat pump (air/water)
WKO (Heat Cold Storage)
Central Heating boiler biomass
Residual heat
Geothermal heat
High Efficiency boiler on hydrogen
Hybrid heat pump on hydrogen

It follows from the above that the following types of gas networks are provided for in the National Management scenario:

Table 3.2 Types of gas networks per area type per type of gas, National Management scenario.

Area Type	Hydrogen network	Biomethane network
Urban	Yes, from the national network to the house	None
Residential areas	Yes, from the national network to the house	Sporadically, only where biomethane is available
Rural area	None	Sporadic, only where biomethane is available
Industry	Yes	No

3.2.3 International Scenario

In the international future perspective, the Netherlands is not energy self-sufficient. The Netherlands imports (largely renewable) energy carriers such as biomass, biomethane and hydrogen on a large scale, but also derived products such as ammonia.

A striking result of this scenario is that solid fuels are returning to rural areas. This can then be solid biomass for pellet boilers or collective systems. Despite the limited share in the total low temperature supply of these solid fuels, this covers a large part of the rural areas. The proportion of biomethane in this scenario is greater than in the Regional and National Management scenarios. In addition, hydrogen also plays a major role in this vision for the future as a feed for HR boilers and hybrid heat pumps. In this scenario, hydrogen will mainly be used in urban areas, in the Noordoostpolder and in the Veluwe.

The gas supply within the International scenario

<u>Gas type and origin</u>
In this scenario, hydrogen and biomethane occur as energy carriers.

Hydrogen is mainly imported from abroad. In addition, hydrogen is produced on a large scale in the Netherlands from (imported) biomass. The origin of these imported energy and energy carriers is not defined in the report "Networks for the Future".
Biomethane is partly produced in the Netherlands and partly imported, because the available amount of biomethane from our own soil is limited.

<u>Gas use</u>
Figure 3-3 shows how the low-temperature heat supply is distributed across the Netherlands within this scenario.

The use of hydrogen is shown in the areas with the colors red (use in high-efficiency boiler) and orange (use in hybrid heat pump). A hydrogen-powered HR boiler is often used in large cities. In addition, hydrogen is used in a large number of (provincial) cities and villages with a hybrid heat pump. A gas network will not continue to exist everywhere, but in many places it will. These hydrogen networks are connected to each other by a national network.

The use of biomethane is shown in the areas with the colors blue (use in high-efficiency boiler) and light blue (use in hybrid heat pump). This shows that the distribution of biomethane takes place very locally. Distribution only takes place in the areas where biomethane from fermentation is available. Biomethane is used throughout the houses.

The various areas where biomethane is available and used are widely distributed. Because biomethane is also supplied from abroad, there will be a need for a national transport network, which connects the areas with each other.
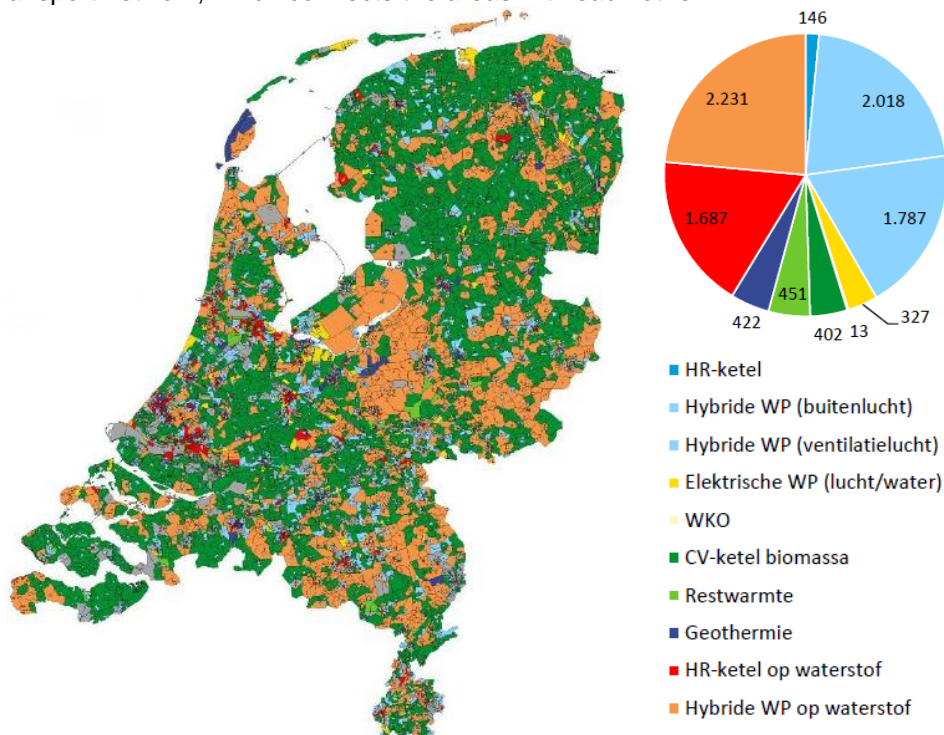
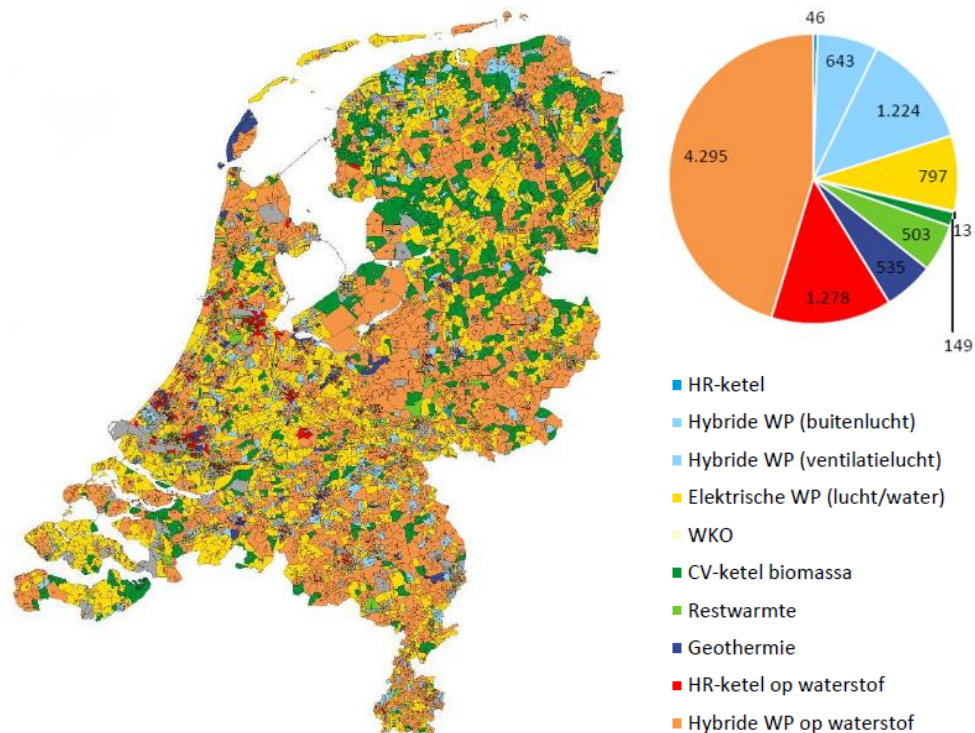*Figure 3.1. Societal image International. Left: map of the Netherlands with the low temperature heat supply. Above right: Heat connections (x1,000) per option. Bottom right: legend (translation below) [8].*

High Efficiency Boiler
Hybrid heat pump (outside air)
Hybrid heat pump (ventilation air)
Electrical heat pump (air/water)
WKO (Heat Cold Storage)
Central Heating boiler biomass
Residual heat
Geothermal heat
High Efficiency boiler on hydrogen
Hybrid heat pump on hydrogen

It follows from the above that the following gas networks are created in the International scenario:

Table 3.3. Types of gas networks per area type per type of gas, International Scenario.

Area Type	Hydrogen network	Biomethane network
Urban	Yes, from the national network to the house	Yes, from the national network to the house
Housing cores	Yes, from the national network to the house	Yes, from the national network to the house
Rural area	No	Sporadically, from a national network to the house
Industry	Yes	No

Both hydrogen networks and biomethane networks will occur in urban areas and in certain residential areas. However, only one type of network will be created per neighborhood. The hydrogen networks mainly occur in the largest cities in the Netherlands, and biomethane networks in the slightly smaller cities.

3.2.4 General Control Scenario
With this vision of the future, the energy transition is achieved through a more organic process without targeted government control. The government does manage through an emission tax and / or CO_2 tax, but does not provide any substantive guidance. The climate-neutral energy system, which ultimately forms itself, will have been established in smaller steps without major, shock-wise changes. It consists of a mix of decentralized, national and international energy sources.
In this scenario, unlike the other scenarios, CCS is used. Fossil fuels, including natural gas, are still used extensively in power plants and in industry.

The gas supply within the Generic Control scenario

<u>Gas type and origin</u>
In this scenario, hydrogen, biomethane and (fossil) natural gas occur as energy carriers.

Hydrogen plays a very small role in this scenario. The hydrogen that is used is mainly imported.
Biomethane is an important part of the energy supply and is for a small part produced in the Netherlands and for a large part imported. The exact origin of this biomethane is not defined in the report "Networks for the Future".

(Fossil) natural gas still plays a role as an important energy source for industry. Although this is not clearly stated in the report "Networks for the Future", it has been assumed for the purposes of this study that this concerns imported natural gas.

<u>Gas use</u>
With regard to gas distribution, the low temperature heat supply is largely comparable to the current situation, where natural gas has been replaced by biomethane. Figure 3-4 shows how the low temperature heat supply is distributed across the Netherlands.

Biomethane is shown in the areas with the colors blue (use in high-efficiency boiler) and light blue (use in hybrid heat pump). This shows that the distribution of biomethane takes place in large parts of the Netherlands. All cities and many residential areas use biomethane. Solid biomass is used in rural areas.

Hydrogen is not used for low temperature heating. Hydrogen, on the other hand, is used in mobility and as feedstock for industry.

Natural gas is not used for the low temperature heat supply. Natural gas is mainly used in industry.
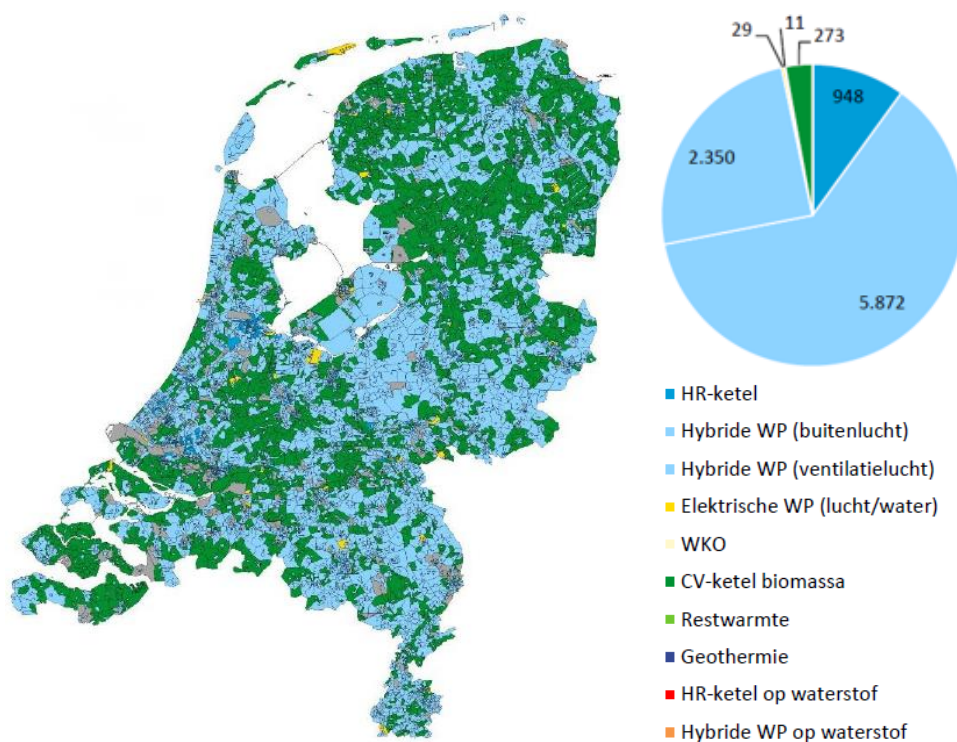
Figure 3.2. Image of Society Generic Control. Left: map of the Netherlands with the low temperature heat supply. Above right: Heat connections (x1,000) per option. Bottom right: legend (translation below) [8].

High Efficiency Boiler
Hybrid heat pump (outside air)
Hybrid heat pump (ventilation air)
Electrical heat pump (air/water)
WKO (Heat Cold Storage)
Central Heating boiler biomass
Residual heat
Geothermal heat
High Efficiency boiler on hydrogen
Hybrid heat pump on hydrogen

It follows from the above that within the Generic Control scenario the following types of gas distribution networks will occur:

Table 3.4. Types of gas networks per area type per type of gas, Generic Control scenario.

Area Type	Hydrogen network	Biomethane network	Natural gas
Urban	No	Yes, from the national network to the house	No
Residential Areas	No	Yes, from the national network to the house	No
Rural area	No	Yes, from the national network to the house	No
Industry	Yes, as feedstock	No	Yes, in combination with CCS

To supply both the natural gas industry and the low-temperature heat supply to houses and utilities with biomethane, it is likely that more than one national transmission network will be created.

How the hydrogen supply will be achieved in this scenario is still unclear. Whether this will be achieved via a national transport network or via tankers is therefore not yet known. A gas distribution network for hydrogen is not expected.

3.3 Overview of types of gas networks that arise within the four scenarios

Table 3-5 and Table 3-6 provide an overview of the types of hydrogen and biomethane networks that are present per area type within the four scenarios. This shows that in none of the four scenarios in the rural area do networks develop for low temperature hydrogen-based heat supply. The picture varies in the cities and residential areas.

Table 3.5. Networks for low temperature heat supply by means of hydrogen

Scenario	Cities	Residential areas	Rural areas
Regional Management	No	No	No
National Management	Yes, from the national network to the house	Yes, from the national network to the house	No
International	Yes, from the national network to the house	Yes, from the national network to the house	No
Generic Control	No	No	No

Biomethane networks occur for all area types in one or more scenarios.

Table 3.6. Networks for low temperature heat supply by means of biomethane

Scenario	Cities	Residential areas	Rural areas
Regional Management	No	Sporadically, only where biomethane is available	Sporadically, only where biomethane is available
National Management	No	Sporadically, only where biomethane is available	Sporadically, only where biomethane is available
International	Yes, from the national network to the house	Yes, from the national network to the house	Sporadically, from national network to the house
Generic Control	Yes, from the national network to the house	Yes, from the national network to the house	Yes, from the national network to the house

- Hydrogen application will not take place in rural areas. It is therefore not advisable to adjust the network there.
- A hydrogen infrastructure is possible in the other areas. Networks must be maintained here.
- Biomethane networks play a major role in the Generic Control scenario and to a lesser extent in the International scenario. In the other scenarios, the use of biomethane is limited and mainly takes place in those areas where biomethane is produced. Within the Regional Management scenario, there is a modest role for a local distribution network (biomethane) up to or in the houses. There is, however, a role for gas distribution (hydrogen and biomethane) from the production locations to the district heating plants and the buffers. The existing 8 bar gas network and of course the GTS (Gasunie Transport Services) transport network can serve as a connection from the production locations (hydrogen and biomethane) to industry, district heating plants and the buffers. Here adjustments will be needed at the gas receiving stations, where the gas must be brought from the 8 bar network to the higher pressure in the GTS network.
- Whether a gas network will be used for biomethane or for hydrogen is highly dependent on the local availability of these energy carriers.

Biomethane is the cheapest alternative in all scenarios, but availability is limited (to varying degrees). This means that the gas network will become superfluous in the areas where other energy carriers, such as district heating, geothermal energy and "all electric" are present. Due to the limited availability of biomethane, the cheapest energy carrier is then chosen here. The more expensive alternatives are not only more expensive in terms of production costs, but also in terms of transport costs. It can be expected that the sustainably produced electricity and geothermal or residual heat will be used as much as possible in the areas in the vicinity of the production location and that the (high pressure) gas distribution network will continue to exist in the other areas between the various regions.

For completeness, the total overview of the number of house equivalents per option and per scenario is shown in Figure 3-5.

Aantal WEQ per optie (miljoenen)

Legend:
- Hybride WP op waterstof
- HR-ketel op waterstof
- Geothermie
- Restwarmte
- CV-ketel op vaste biomassa
- Elektrische warmtepomp
- Hybride WP op groengas
- HR-ketel op groengas
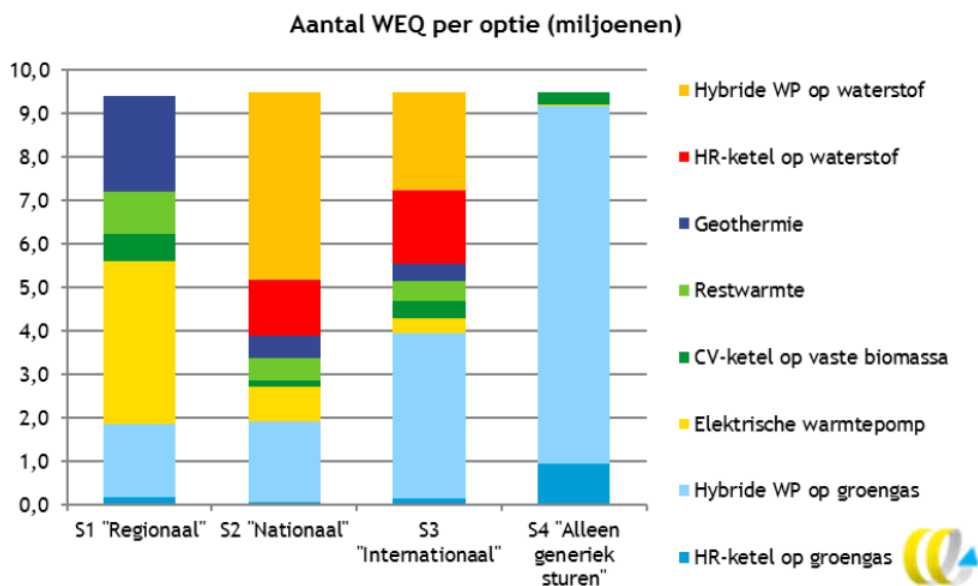
Figure 3.3. Overview of house equivalents per option per scenario [8]. Legend right, translation below:

Hybrid heat pump on hydrogen
High Efficiency boiler on hydrogen
Geothermal heat
Residual heat
Central Heating boiler biomass
Electrical heat pump (air/water)
Hybrid heat pump (Green gas)
High Efficiency Boiler (Green gas)

Gas distribution networks will still be there in 2050, but not for natural gas and not everywhere

The scenarios show that various energy carriers are provided. Those are:
- heat (from various sources)
- electricity
- biomethane
- hydrogen
- (fossil) natural gas (to industry, in combination with CCS)
- solid biomass

Three of the four scenarios provide for a substantial number of house equivalents, which meet their low temperature heat demand using condensing central heating appliances or hybrid heat pumps. For these areas, a gas distribution network will be present in the house (or be maintained).

In the new situation, hydrogen, biomethane and (fossil) natural gas could thus be transported through the existing gas networks. The situation will differ per region. Before new types of gas can be transported through the network, it must first be clear to what extent this is actually technically possible. It is important that at least the current safety level can be guaranteed for the future. This may require adjustments with regard to the construction, maintenance and use of the network.

4 Hydrogen

One of the network types that may play a role in the future is hydrogen networks. From the point of view of energy supply - like natural gas - hydrogen is a gaseous energy carrier. Incineration of this energy carrier, in contrast to natural gas, does not produce CO_2 emissions. This makes hydrogen one of the energy carriers that contributes to the government's objective of eliminating CO_2 emissions in the built environment. Hydrogen is not naturally available and will therefore have to be produced. A number of techniques are currently available for this. Possible production methods are the conversion of (sustainably generated) electricity by means of an electrolyser or the production from methane, whereby the CO_2 produced is captured (Carbon Capture and Storage, or CCS). Another possible variant is the conversion of hydrogen and CO2 into biomethane, which may require a local hydrogen network for the supply.

The hydrogen produced contains a number of other gaseous components in low concentration. The concentrations of these components, such as water, carbon monoxide, carbon dioxide, nitrogen and oxygen, depend on the production method and cleaning techniques chosen. It is therefore important to know the specific characteristics of these gases for both the network (integrity) and for the end user (application). The existing distribution infrastructure will have to be adapted on a number of points to make the gas network fully suitable for safe and efficient transport of hydrogen.

Where hydrogen is used in this study, 100% hydrogen is meant.

Chapter 7 contains an overview of the most important points for attention and the associated measures and costs.

Hydrogen is particularly suitable for use in fuel cells. These fuel cells are a promising link in the future energy supply of the built environment, because in combination with an electrically driven compression heat pump, they can realize low-temperature heating with a high efficiency.

4.1 Use of hydrogen

4.1.1 Use of hydrogen for conventional gas appliances

Hydrogen can be used as a fuel in gas burners. However, the combustion rate of hydrogen is considerably higher than that of methane, possibly resulting in flame impact and damage to the burner. This means that existing gas consumption devices cannot easily be made suitable for hydrogen (such as by adjusting the diameter of the injectors, or by a new adjustment of the gas / air ratio).

Current devices use the ionization current principle for flame protection. In the case of a hydrogen flame, this ionization current is practically absent and a different security principle (for example thermal) must be used. This means that the burner control of the appliance will have to be adjusted. Whether this is possible without further modifications to the device is still unknown. Hydrogen-modified burner controls are not yet commercially available.

Hydrogen flames are invisible, which makes the use of open flames (as in the current cookers) unattractive. As far as one wishes to continue cooking with gas, the appliances will have to be operated with closed burners (for example catalytic burners).

In short, the existing used equipment will have to be replaced or at least the equipment will have to be equipped with new burners and / or control.

4.1.2 Use of hydrogen for fuel cells

Fuel cells are used to produce electricity using hydrogen (and oxygen from the air). In combination with an electrically driven compression heat pump, efficient heating of houses and buildings can be realized [9].

A higher efficiency can be achieved via this route than with the conventional combustion of hydrogen. However, fuel cells place much higher demands on the purity of the hydrogen than conventional burners.

The cost of operating a fuel cell is largely determined by the life of the catalyst. This service life is in turn largely determined by the purity of the fuel. In Annex II an overview is given of the current (gas) quality requirements that are set for hydrogen. The PEMFC (Polymer-Electrolyte Membrane fuel cells) mentioned in this appendix are a type that is of particular interest for mobility applications.

SOFC (solid oxide fuel cells) are much less critical with regard to the quality of the hydrogen that is requested. SOFCs are primarily suitable for use in stationary configurations, such as in buildings. By transporting the hydrogen through the existing natural gas network, the hydrogen (certainly in the initial period) will be 'polluted' with natural gas components that adhere to the pipe wall of the gas network. Over time, these "old gas remains" will disappear, because the pipes will be flushed clean. Figure 4-1 shows the critical components for SOFCs and PEMFCs and compared them with possible components from the natural gas.

The components in the green circle are mentioned in the "Additional Conditions RNB Green Gas Invaders" [10] for the introduction of green gas into distribution networks, drawn up by the regional network operators (later replaced by the MR Gas quality). The components in the blue circle are the permitted components in PEM fuel cells for motor vehicles, the maximum concentrations of these components being given in ISO 14687-2 (2012) (see Annex II).

According to ASUE [11], the SOFC is much less critical for contaminations in hydrogen than a PEM fuel cell. SOFC fuel devices are already being used in combination with natural gas. In order to extract the hydrogen from the natural gas, a natural gas conversion takes place simultaneously in a cleaning step placed in front of the fuel cell, whereby hydrogen is split off and fed to the fuel cell. However, because these fuel cells, including a cleaning step, are put on the market, the requirements for the hydrogen "sec" are not known.

The natural gas supplied to such a fuel cell may not generally contain sulfur. According to DVGW, a sulfur-free odorant is currently used in 25% of German natural gas distribution networks.
Most substances that are absorbed in the natural gas network will disappear by themselves after switching to the distribution of hydrogen. However, the components O_2 and N_2 will not automatically disappear from the network due to permeation. The phenomenon of permeation is further explained in Annex VI.
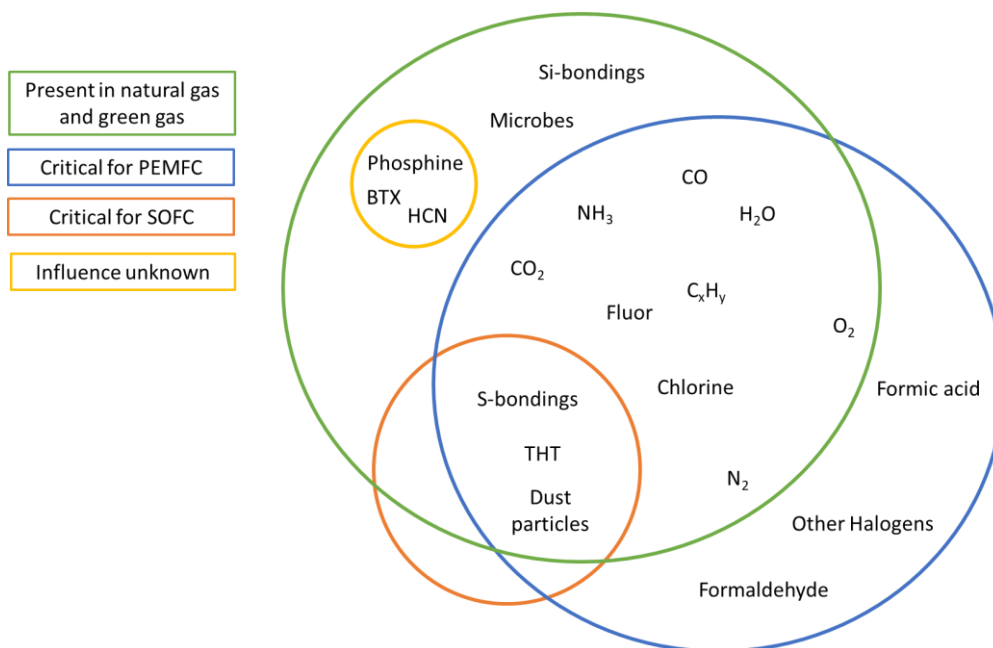
Figure 4-1. Overview of critical contaminants for SOFCs and PEMFCs.

4.1.2.1 Consequences for the gas network if fuel cells are the end application

The use of the existing gas network for hydrogen feed to fuel cells can lead to the limit values for certain gas components being exceeded. In particular, dust particles, nitrogen (N_2) and oxygen (O_2) pose a threat in the use of PEMFCs.

Even if very clean hydrogen gas is distributed with the existing gas distribution network, O_2 and N_2 will always be present. This is the result of permeation from the environment (air) via the wall of plastic pipes in the gas network. Depending on the gas flow rate (and thus the gas residence time in the pipe), the critical concentrations for PEMFCs can be exceeded within a few hours.

This means that for stationary PEMFCs, a cleaning step is required immediately in front of the fuel cell. For vehicles powered with PEMFCs, the gas will have to be cleaned upstream of the hydrogen filling station. The availability and affordability of such a technology to sufficiently clean contaminated hydrogen is a point of concern.

The presence of dust particles in the long pipes of the distribution network is almost inevitable. They are introduced during construction or during work but are relatively easy to capture with a filter.

The presence of sulfur, if - as with natural gas - THT (Tetrahydrothiophene) is used as an odorant, is a problem. However, there are also alternative sulfur-free odorants that can solve this problem. When introducing such a sulfur-free odorant, the fact is that the existing gas network is saturated with THT. This is now in balance with the THT (and other natural gas components) present in the natural gas but will slowly evaporate after switching to clean hydrogen. The sulfur components will eventually disappear. At this moment it is still unknown how long it takes to rinse a net clean. This certainly depends on the local circumstances, but a period of at least a few months must be taken into account in advance. If THT is used as an odorant, a cleaning step for the fuel cell will be considered when applying fuel cells.

4.2 Distribution of hydrogen

When distributing hydrogen, any consequences for the materials used in the network and the related safety aspects must be taken into account. This is discussed in more detail in the following sections.

4.2.1 Hydrogen influence on the materials in the gas network

For the description of the influence of hydrogen on the various materials, a distinction is made between plastics and metals. Both material groups have significantly different degradation mechanisms and are influenced in different ways by the hydrogen. The starting point for the analysis is that the hydrogen is clean and technically pure at the moment it is fed.

The results are outlined in this section. For a more detailed explanation, reference is made to Annex III.

4.2.1.1 Plastics

The most important plastics that occur in the gas distribution network are the three generations of PE, hard and impact-resistant PVC, the rubbers NBR and SBR and the plastic POM. This not only concerns pipe materials, but also rubbers, which are used for seals in connections and valves, as well as components for pressure regulators and gas meters.

Plastics can be attacked by reacting chemically with hydrogen or by changing their physical properties through, for example, absorption or swelling [12]. The sensitivity of the material to hydrogen depends on various factors, such as pressure, duration, temperature and gas composition. Many different tests have been reported [13] [14] [15] [16] [17] [18] [19] [20]. This information has been used to provide a targeted life expectancy.

For PE, up to 10 years of use as a hydrogen distribution material, no degradation has been established. It can therefore be expected from this material that no degradation by hydrogen will occur in the long term. This picture is somewhat less clear for PVC. No degradation has been demonstrated for both hard and impact-resistant PVC during a four-year study. The expectation of Kiwa Technology is that this will also apply for the long term. For the NBR rubbers and the older SBR rubber, no influence of hydrogen on the material properties has been established in the short term. A study by the American National Renewable Energy Laboratory [20] also considers these two types of rubber to be highly resistant to hydrogen.

No degradation was found for a two-year investigation (8 bar, 62% H_2) for the plastic POM, which is frequently used in couplings, gas meters and house pressure regulators. However, what exactly this means for long-term behavior is still unknown.

4.2.1.2 Metals

Hydrogen can degrade metals and degrade quality. Critical failure mechanisms are changes in tensile strength, fatigue and the occurrence of hydrogen emissions. Many different studies have also been conducted and reported on the behavior of the metals, that may be used in a gas distribution network, in combination with hydrogen. This information has been used to provide a life expectancy.

For various carbon steels used in gas distribution, it has been concluded that hydrogen emission will not occur if the hydrogen is transported under normal temperature. If the gas is law (that is, there is water in the pipe) can lead to hydrogen embrittlement under unfavorable conditions. However, the chance that normal corrosion will occur in such a situation is much greater.

Hydrogen has no significant influence on the tensile properties of the steels used. Although the flexibility and fracture toughness of the materials decrease, they are still considered to be more than adequate. If a small concentration of oxygen (a few hundred ppmv) is present in hydrogen, the fatigue of steel appears to be equal to the fatigue in natural gas.

The influence of hydrogen on cast iron is comparable to that of hydrogen on steel. For the commonly used stainless steel types (impulse line and flexible gas meter connection), usually AISI 316L or the Ti variant, it is reported that they are resistant to hydrogen under the prevailing conditions in the distribution network. Hydrogen embrittlement has not been observed [21].

All studies published to date have not shown any degradation of plastics and rubber gas distribution materials by hydrogen. The question with regard to the investigations is whether they have been carried out long enough to have sufficient power of expression over long-term behavior.

For steel, stainless steel and cast iron, which are used in gas distribution, it can be concluded that the most important failure mechanism (hydrogen embrittlement) will not occur in practice. The deterioration of some mechanical properties is small and can be considered unimportant.

Copper, brass and aluminum do not seem to be affected by hydrogen.

For the existing gas distribution networks it can therefore be stated that they are suitable for transporting hydrogen.

On the basis of the above findings, it is concluded that the currently applied construction and design techniques can also be used for the construction of new gas pipes.

4.2.1.3 Micro-organisms in hydrogen

Micro-organisms can occur in hydrogen. It is known that pipes can strongly promote bacterial growth and can stimulate microbiologically induced corrosion. At the relatively low pressures and relatively low temperatures (P_{max} <8 bar and T_{max} <18˚C) and under the dry conditions, which usually prevail in the gas distribution network, the chance of micro-organisms developing is very small.

4.2.2 Safety aspects in the distribution of hydrogen

4.2.2.1 Technical aspects of risk management

A so-called Generic Bowtie has been drawn up by the gas distribution sector, in which all safety risks of gas distribution have been identified [22].

The Bowtie method is a qualitative risk analysis method, with which a systematic picture can be obtained of the risks that are present in an organization and of the preventive and protective measures that can be applied to this. Risks, threats, preventive and protection measures are united in one model. The unwanted event is in the center. Left the causes, right the consequences.

Control measures are indicated in the form of barriers. An example of a Bowtie is shown in Figure 4-2.
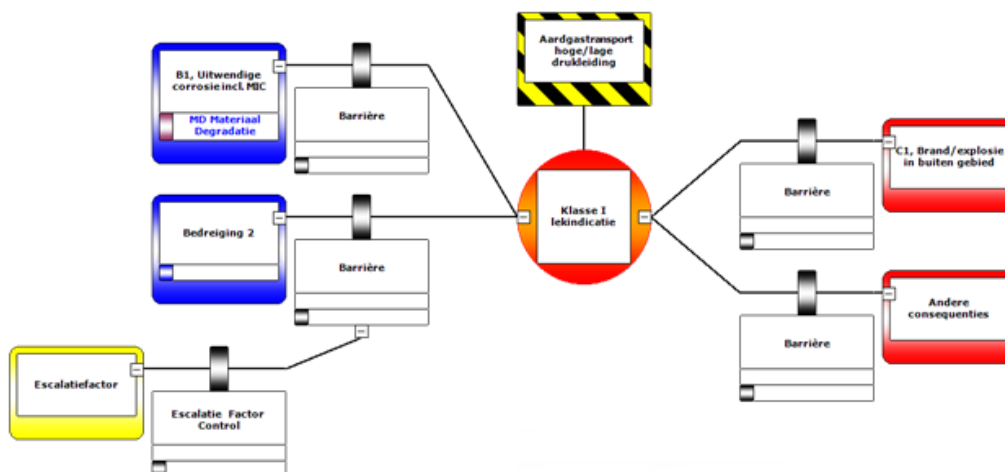
Figure 4-2. Example of a (partial) Bowtie [22]

The Generic Bowtie was used to assess specific risks of hydrogen distribution. For each barrier in natural gas distribution, it was checked whether this barrier is also sufficient for hydrogen.

Risk of insufficient gas smellability
One of the barriers present in the current natural gas system is the smell of natural gas due to the added THT. Hydrogen is - just like natural gas - an almost odorless substance. To be able to use a comparable barrier here too, a fragrance must also be added to hydrogen. This can be THT, but could also be another, for example, sulfur-free fragrance. This report assumes that hydrogen can only be distributed if it is odorized. The risks mentioned in this chapter are based on the use of odorized hydrogen gas.

Risk of excavation damage
In the distribution of hydrogen, the risks of excavation damage are a point of attention, due to the lower ignition energy of hydrogen (0.019 mJ), compared to 0.2 mJ for natural gas, which means that hydrogen can ignite even in the presence of a smaller ignition source (spark). In addition, the gas / air ratio, whereby hydrogen forms a combustible mixture, is different than for natural gas. For hydrogen, this concentration varies from 4 vol% to 74 vol%. This concentration varies for Dutch natural gas from 5.9 vol% to 15 vol%. A hydrogen / air mixture therefore has a wider explosion limit, so that the chance that - for example in the event of excavation damage - a gas cloud will ignite or explode is greater than in the case of a natural gas leak. Moreover, even with smaller quantities of gas / air mixture (than with natural gas) there is a risk of shock waves, with the corresponding risk of damage and injury. On the other hand, hydrogen evaporates much faster than natural gas (under comparable circumstances) (due to the large difference in specific mass), so that the ignitable gas cloud will be much smaller. Practical research in the United Kingdom [23] into the behavior of leaking hydrogen in buildings shows that under normal conditions it is difficult to create an ignitable hydrogen-air mixture. It is recommended to conduct further (practical) research into the way in which the risk of gas leaks changes when the transfer from natural gas to hydrogen takes place.
Incidentally, with a low concentration of hydrogen in air (below 10%), the required ignition energy is equal to that of natural gas. In a stoichiometric mixture (27% hydrogen in air), the ignition energy is a factor of 15 lower than with natural gas [24]. It is therefore conceivable that, if policy remains unchanged, a gas leak with hydrogen in the event of excavation damage escalates more often to an explosion / fire than is the case with natural gas. With natural gas, distribution pressures (≤ 100 mbar) almost never involve ignition. Further (practical) research must show whether and to

what extent additional measures are needed. Even with little damage, it is not good for the image of hydrogen (distribution) if excavation damage would lead to incidents more often.

To reduce this risk, work can first be done on reducing the number of excavation damage itself. This has already partly been done through an information campaign and through the mandatory reporting of digging activities and the exchange of map data (KLIC reports). This has had some effect in recent years, but a reduction to a fraction of the current number of excavation damage is unlikely. Insofar as these are measures that can also be applied to the current gas network, these are of course typical "no regret" measures. Given the different properties of hydrogen in comparison with methane, when introducing hydrogen distribution, the pipelines in question should be designated in the network operator's management system with a so-called "precautionary requirement", so that they receive extra attention during / after a KLIC report. This may include additional supervision or informing the party carrying out the excavation that this is a hydrogen pipe with other properties of the gas. Over time, the presence of the "precautionary measure requirement" indication in the management system can be reconsidered. It is also advisable to develop methods during this period to limit excavation damage in a cheaper and efficient way. For example, by using ground radar to detect pipes or by developing a pipe detector that can be mounted on the excavator and that intervenes if it comes too close to the pipe. Extra information to contractors about the specific characteristics of hydrogen and how to deal with it, through tool-box meetings, also seems to be a good measure to prevent incidents.

In order to substantially reduce the risk of gas outflow in the event of excavation damage, techniques must be applied which drastically limit the outflow of gas. A possible technical solution is the installation of excess flow valves (EFV) and / or a system with pressure measurement points and remote-controlled valves (whether automatic or not). Such a system is already being applied in some earthquake sensitive areas. In an adapted form, the same type of system can play a role in increasing the safety of the hydrogen network.

Risk of ignition during work
In principle, work on the gas network is carried out as much as possible without pressure. Depressurizing (and to a lesser extent when commissioning) pipes and installations can release gas, which must be blown off or flared off.
For flaring hydrogen, special burner constructions protected against flame impact must be used.
A point of further investigation is the necessity to first flush gas lines with an inert gas (for example nitrogen) during commissioning in order to prevent an impact-dangerous gas / air mixture exiting at the blow-off point. This precautionary measure is considered superfluous for the distribution of methane, but for hydrogen it deserves to be reconsidered (for example on the basis of practical tests). Compared to the regular construction and maintenance costs, any flushing with inert gas is a relatively limited cost item.

Risk of permeation
Hydrogen permeates a factor of 5 faster through plastic than methane (see Annex VI). The total amount lost in this way is small compared to losses due to "normal" leakage, but under special circumstances, permeation can pose a risk. This concerns permeation of a plastic gas pipe (mostly PE), laid in a long pipe sleeve. In the absence of ventilation, the annular space between the outside of the gas pipe and the inside of the casing is filled with a gas / air mixture that can ignite explosively if an ignition source is present. In the absence of ventilation, such a mixture can be created within a few days. After an even longer time, the upper explosion limit for hydrogen will be exceeded and the risk of explosion and impact will again be less high. The problem only arises with longer casing pipes (indication: length more than 5

meters), so not with normal wall ducts. Crawling spaces, where a similar permeation / ventilation situation prevails, are in principle sufficiently ventilated.

Whether this scenario is a problem in practice, against which measures must be taken (for example the mechanical ventilation of casing pipes), remains to be investigated.

Risk of connections

Leakage from connections (both outside and inside) and any further consequences are a risk for all piping systems that distribute combustible gas. In small slit-shaped leaks, the flow at distribution pressures is laminar. This means that the volume flow, at a given pressure, is inversely proportional to the dynamic viscosity of the gas. The viscosity of hydrogen is 0.88 10-6 Pa.s. That of methane is about 25% higher: 1.10 10-6 Pa.s.

The conclusion is that a possibly leaking compound in a hydrogen network is approximately 25% higher in terms of volume flow compared to the same leaking compound in a natural gas network. This difference is hardly significant from a safety point of view, the more so since the energy content of the leak is more than half the size. A point of attention remains the lower ignition energy and the greater concentration range of the combustible mixture. Provisionally, the expert opinion is that the effect of this on the risk is negligible [25]. Further research and practical simulations must provide a definitive answer.

4.2.2.2 Non-technical aspects of risk management

Technical measures and good work instructions will in principle bring the safety of hydrogen distribution to the same level as that of the current natural gas distribution. After all, in both cases it concerns the distribution of combustible gas in the built environment, whereby the first priority is to ensure that no gas leaks. There are no fundamental technical and physical reasons why it might be less successful with hydrogen than with natural gas.

Just as with natural gas, it is important that care is taken and that this care is safeguarded and monitored. Even in the period after the introduction, attention to this aspect should not be allowed to drop.

> With regard to the distribution of hydrogen, there are various points of attention with regard to safety.
> In particular, the lower ignition energy, the wider range of combustible gas / air mixtures and the higher combustion rate are properties that must be taken into account. With the introduction of hydrogen, extra attention to safety is therefore appropriate

4.2.3 Gas (energy) settlement

In this study it was assumed that when distributing hydrogen, agreements were made about gas quality with the supplier, so that the variations in gas composition will remain limited. Measuring the quantity of gas supplied is done for small consumers at a pressure equal to that of the indoor installation. Since hydrogen contains three times less energy per unit volume than methane, the volume flow will increase by more than a factor of three with the same power demand. A gas meter dimensioned for natural gas consumption in this situation would be operating beyond its measuring range, which would make it unsuitable for this increase in volume flow. It should be noted that in practice the gas meter for natural gas is often oversized. The theoretical effect of hydrogen on the size of the gas meter is shown in Table 4-1. Theoretically, the gas meter for hydrogen must be three categories larger than the gas meter for natural gas to be able to measure the same amount of energy. Whether this will be

necessary in practice depends mainly on the maximum energy demand and the volume to be measured. The maximum energy demand is mainly determined by the hot water supply. By designing this differently (for example by placing a boiler), the maximum energy demand and thus the volume to be measured can also remain limited. Another favorable factor is the fact that hydrogen-powered devices can achieve a yield that is approximately 7% higher (see section 4.3.5). This means that this also reduces the volume flow to be measured.

Table 4-1. The required capacity of gas meters (standard category) for hydrogen compared to natural gas / methane.

G-category (CH_4)	CH_4 max (m^3/h)	H_2 max (m^3/h)	G-Category (H_2)
1.6	2.5	8.3	6
2.5	4	13.3	10
4	6	20.0	16
6	10	33.3	25
10	16	53.3	40

Bellows-type meters need larger dimensions to handle the larger volume flow and, if they are needed, may no longer fit into the existing household meter cupboard. A possible solution for this is the installation of ultrasonic gas meters. With almost the same dimensions, this type of meter can measure a larger volume flow.

According to the meter manufacturer Landis & Gyr, there are no household ultrasonic gas meters larger than G6 on the market. The European standards committee CEN / TC 237 (Gas Meters) formed a study group in the autumn of 2017 that will take stock of the developments required for gas volume measurement of hydrogen in gas networks.

The space problem of Bellows-type meters has been identified as potential "Market Failure" within the H21 ("Leeds") project. Within this project there may be a budget for further development of these gas meters.

A no-regret option for the network manager to be able to realize the quantity measurement of hydrogen is to consult with meter suppliers to make the current household ultrasonic gas meters suitable for hydrogen.

Another option that can be used immediately is to reserve space for the larger Bellows-type meter when building or renovating a houses (as long as there are no compact ultrasonic meters on the market).

Finally: an interesting topic for consideration relates to the energy unit that the hydrogen gas meter must indicate. With hydrogen, there is a fixed relationship between the kWh and m^3 units. From a marketing point of view, the use of the kWh unit may be preferred.

4.3 Effects of and measures for the introduction of hydrogen in existing gas networks

4.3.1 Capacity of the gas distribution network

The capacity of the gas distribution network, with regard to the amount of energy transported, remains virtually the same at the transition from the current L gas to 100% hydrogen, with the same diameters and pressures.

Current regulations limit the permitted gas speed to 30 m / s in connection with possible noise nuisance. This limitation plays a role in particular with pipes in the vicinity of a gas station.

With the same energy transport, the gas velocity in a hydrogen pipe is 3x higher than in a natural gas / green gas pipe. However, the density of the gas is 10x less. It is therefore not clear from the outset whether noise pollution is noticeably increasing. Further research on this aspect is recommended.

4.3.2 Safety perception

For a successful implementation of a new product it is necessary to pay attention to the aspects that influence the acceptance of the new technologies and new measures. That is why in this chapter we describe necessary steps with regard to image and safety perception.

Measures for a successful implementation of the use of hydrogen
- An important means of informing and drawing attention to the population about hydrogen is an information campaign. In this way the different characteristics of hydrogen can be discussed at an early stage and attention can also be paid to aspects that are different in comparison with the existing natural gas infrastructure. The most important topics are the low ignition temperature, the invisible flame, the exclusion of CO poisoning, the costs (the price of a hydrogen appliance is probably in the same order of magnitude as the price of a natural gas appliance), the comfort experience (which is comparable to that of natural gas), the fact that hydrogen is a clean fuel and that hydrogen is odorless. The latter can incidentally be dissolved with fragrances. This topic is discussed in detail later in this chapter. Possible means for an information campaign are:
  o publications on a website
  o highlighting during presentations
  o press releases: targeted by connecting with current topics
  o use social media such as Facebook, LinkedIn and Twitter with high-quality content
  o commercials on TV

  With a coherent schedule, the components of the campaign can reinforce each other.
- Another measure to achieve a successful implementation of the use of hydrogen is to participate in and carry out pilot and demonstration projects. These projects can - if properly implemented - make a positive contribution to the public's perception of safety.

If this succeeds, the informed population will see hydrogen as a possible solution to achieve the climate goals in a safe manner and to transform society into a sustainable society.

Smellability of hydrogen
In the distribution of natural gas, a legally required alerting and specific odor is created by deliberately adding the THT (Tetrahydrothiophene) odor to the natural gas. The Dutch are generally aware of the risk of natural gas, which is characterized by this specific odor. A new specific and alerting odorant (for example sulfur-free odorant) can be used to provide hydrogen with another characteristic odor. This would allow the new odor to be associated with the specific properties of hydrogen. It is also possible to choose to odorize hydrogen with the known odorant THT, as long as hydrogen is not used in fuel cells (see section 4.1.2).

Leak detection
In the existing natural gas infrastructure, leak detection is an important means to guarantee safety by detecting and repairing risky leaks on time. With a hydrogen infrastructure, leak detection will also contribute to safety. Especially in the beginning, it is worth considering looking for a leak more often than is strictly necessary. In order to prevent this from being interpreted negatively, it must be clearly communicated that

the increased frequency to check for leaks is intended to create a higher degree of safety. This can increase the sense of security among citizens. If enough experience with the new infrastructure has been collected over time, the frequency of the leak can be reduced again.

4.3.3 Information provision for users
The use of hydrogen entails changes. It is essential that users know how to handle hydrogen.

The most important points of attention for the provision of information are:
- the specific physical properties of hydrogen:
  - lower ignition temperature
  - invisibility of the flame
  - higher burning rate
  - higher flame temperature
  - smell of hydrogen gas

- the necessary measures for the implementation of hydrogen distribution:
  - risk of ignition when working on the network
  - excavation damage
  - permeation in mantle tubes
  - connections (both in the main and connection pipes, as well as in the gas indoor installation)
  - effects after the gas meter

4.3.4 Adjusting regulations
The safety of the natural gas industry is guaranteed by a variety of standards and regulations. As hydrogen has properties other than natural gas, it is necessary that these standards and regulations are adjusted or replaced. This concerns, for example, the Natural Gas Safety Instruction (VIAG) and Dutch and / or European standards with regard to gas distribution and gas measurement. Important points for attention that need to be revised in these standards have already been mentioned under the heading 'information provision for users'. In addition, the current gas that is distributed meets the MR Gas quality. If hydrogen is being distributed, the MR Gas Quality will have to be renewed. Hydrogen distribution is not possible under the current MR Gas quality. The permitted variation in the composition of the hydrogen gas will be included in such a new MR.

4.3.5 Effects and safety aspects of hydrogen in appliances

Effects after the gas meter (fuel cells)
Hydrogen is suitable as fuel for fuel cells. A high conversion efficiency can be achieved with this form of cogeneration on a household scale.

Odorization of gas is an important safety measure if gas is distributed to or into the house. The current odorant THT contains sulfur and - if used in hydrogen distribution as an odorant - supplies the majority of the sulfur present in the hydrogen gas. The presence of sulfur in concentrations higher than 0.1 ppmv limits the life of the catalysts in fuel cells. The fuel cells, which are suitable for connection to the natural gas network, have a gas cleaner and a reformer to convert the natural gas to hydrogen. If the hydrogen in the network is sufficiently pure, these reprocessing components are unnecessary. This will make the fuel cell cheaper and it will require less maintenance.

However, sulfur-free odorant is also available. Abroad, such a switch has already

been implemented in a number of places. So we can learn from those experiences. The price of the odorant is not a high cost item, but the switch does entail relevant costs. In addition to the costs for technical adjustments, such as dosing and measuring the content, a public information campaign will also have to be held.

Effects after the gas meter (hydrogen burners)
The introduction of hydrogen to end users has, in addition to the aforementioned absence of local greenhouse gas emissions, a number of user benefits.
Gas appliances based on conventional incineration get a higher efficiency and (of course) emit no CO. Hydrogen also makes new device categories possible.

The theoretically feasible efficiency of condensing appliances is equal to the upper combustion value divided by the lower combustion value of the gas. The ratio between these two values is greater with hydrogen than with methane. The efficiency of a hydrogen gas device can therefore be higher.
A comparison between the combustion efficiency with methane and hydrogen is given in Table 4-2.

Table 4-2 Efficiency of condensing devices

Fuel		Methane	Hydrogen
Caloric Upper Value	MJ/m^3	39.8	12.74
Calorific Lower Value	MJ/m^3	35.9	10.78
Theoretically feasible return		111%	118%
Practical return (for methane: HR class)		107%	114%

It appears that a 7% efficiency improvement is achievable with a hydrogen device. This makes a substantial contribution to energy saving in the built environment. Hydrogen reacts more easily with oxygen than methane.

In the presence of a noble metal catalyst, it is possible to have hydrogen with oxygen react at ambient temperature (and this is also the case with very severe frosts). Catalytic devices, therefore, do not need spark ignition. A catalytic hob is safe because of this property, even after the gas pressure has dropped. Catalytic hot plates do not have to have conventional burners. In the past, prototypes have been developed for natural gas burners under a glass plate. This concept had the working title "gas under glass".

The absence of carbon atoms in hydrogen ensures that carbon monoxide accidents are a thing of the past. 45 poisoning accidents were registered in 2016, in which 2 people died and 140 people were injured. [26]

The NO_x emissions from burners depend, among other things, on the flame temperature. The higher the flame temperature, the more nitrogen oxides. The stoichiometric flame temperature of hydrogen / air is higher than that of methane / air. On the other hand, the stoichiometric combustion rate is also higher. For modern, fully pre-mixed burners, this can be compensated by a lower gas / air ratio. This is necessary anyway to prevent overheating of the burner deck. The conclusion is that NO_x emissions are a point of investigation, but an increase is neither obvious nor unavoidable.

Current gas appliances for heating and hot water preparation are not suitable for burning hydrogen. Lower concentrations of hydrogen (up to approximately 20%) do not cause any problems and for concentrations up to approximately 50%, it is probably possible to suffice with relatively limited adjustments, such as replacing injectors and firmware / control software. If there is 100% hydrogen, or percentages

that come close, a revision of the device concept is necessary. Burners and burner decks will have to be designed differently (smaller openings) to eliminate the risk of flame impact.
The current flame protection based on flame ionization does not work with hydrogen and will have to be replaced (for example with a thermal protection).

Hydrogen flames are virtually invisible. This has consequences for the safety of use of cooking appliances (and gas-fired fireplaces). Other appliance concepts are also needed for this and / or electric cooking appliances will have to be used.

Although the costs associated with the aforementioned adjustments are limited compared to the transition costs, the image aspects are probably considerable.

For the same capacity, approximately twice as much volume of combustion gases is produced (in the form of water vapor). Part of this water vapor condenses in the device (and contributes to a higher efficiency), but drainage systems and whether the device fans will have to be explained for the higher volume flow. Critical constructions in this context are the combined combustion gas exhaust systems in stacked buildings (CLV systems).

If hydrogen is only used for low-temperature heat and hot tap water, it can be considered to place appliances outside the house in an extension or boiler room. This prevents the need for pipes in the house. This may also be worth considering when using natural gas (in the current situation) and when using biomethane. The associated costs are, in the case of depreciation over 40 years, very limited (around € 50 / year).

> Current gas appliances for heating and hot water preparation are not suitable for burning 100% hydrogen. Hydrogen flames are virtually invisible. This has consequences for the safety of use of cooking appliances (and gas-fired fireplaces). Other appliance concepts are also needed for this and / or there must be a switch to electric cooking appliances.
> The absence of carbon atoms in hydrogen means that carbon monoxide accidents are a thing of the past.

Effects on connections in gas indoor installations
In the case of indoor gas installations, the connections are always a point of attention. At present, compression fittings are probably the most commonly used connections, but there are also many soldered connections and threaded connections.

All compounds can potentially leak. In practice with natural gas, the risk thereof is acceptable and accepted. As already mentioned above, the same slits and holes will leak a 25% higher volume flow of gas with hydrogen, at the same gas pressure, than with natural gas.
The question here is whether the same leaks with hydrogen, despite the lower energy content and the higher rising force (buoyancy), do not lead to more explosions because of the lower ignition energy and the wider explosion limits (this is essentially the same type of issue as with excavation damage but in a different environmental situation).

The H21 ("Leeds") study mentions the HyHouse project, in which some research has already been conducted with regard to the risk of hydrogen leakage in the gas indoor installation [25]. This concerned a practical study in an old farm.
The conclusion was that no flammable gas / air mixtures are produced that are more dangerous than with a comparable methane leak.

In the opinion of Kiwa Technology, this conclusion is not entirely justified, since the HyHouse study apparently did not speak of a normal living environment, with associated sources of ignition. In practice, an incident is always a combination of adverse circumstances. It is therefore not the question whether a gas mixture from a connection leak almost never ignites, but whether that "almost never" situation occurs unacceptably much more often with hydrogen than in current practice with methane. Unfortunately, this question cannot be answered with laboratory experiments. The recommendation is therefore - when introducing hydrogen on a larger scale - to closely monitor this aspect of the gas indoor installation. If there was a noticeable increase in the number of incidents with a leaking indoor installation, additional measures could be taken in the course of the transition. This may include, for example, the proactive replacement of specific types of inner pipes and connections.

5 Biomethane

5.1 Composition of biomethane

Biomethane can be extracted from very different organic sources and via specific biomass conversion processes. For example, it can be obtained from the fermentation of biomass or by methanizing syngas. As a result, biomethane can contain components other than traditionally distributed natural gas [27]. Liander (Dutch utility company) has supplied a list with the possible composition of reprocessed syngas and cleaned biogas [28]. Within this research, this list has been used to assess the effects of the components, which may be present in biomethane, on the materials in the distribution network. The findings are summarized in Table 5-4.

Gas composition
The origin of biomethane differs from that of fossil natural gas, so the composition of biomethane will be different. In addition, there are differences in the composition of biomethane as a result of differences in production methods. The following components may be present in biomethane produced by methanizing syngas: water, hydrogen, hydrogen sulfide, nitrogen, mercaptans, ammonia, hydrogen chloride, hydrogen cyanide, carbon monoxide, carbon dioxide, benzene, toluene and other hydrocarbons [28]. Biomethane produced from purified biogas can additionally contain sulfur, chlorine-containing components, fluorine-containing components, oxygen, phosphines and silicon-containing components [28]. The complete list of components is included in Annex IV.

The gas composition changes due to the presence of these components.
The question is whether the composition of biomethane has an impact on the integrity of the gas infrastructure, as well as on the safety of the end users and the engineers, who carry out maintenance work on the network.

Safety end users and technicians
In the event of a gas leak or the unburned release of biomethane in a house, the gas mixes with the ambient air. Oxygen and biomethane are mixed, which can result in an explosive gas mixture.
The lowest limit value for the occurrence of an explosive gas mixture[1] (LEL, Lower Explosion Limit) for natural gas (G gas) is 5.9 vol% gas in air [29]. From this concentration an explosive gas mixture is formed. According to the VIAG and the Occupational Health and Safety Act, work may not be carried out at a gas concentration of 10% LEL or higher (0.59 vol% G gas) [30].

Biomethane may contain a number of toxic components. It is not allowed to work in an environment where the concentration of these components is above the maximum permitted value [31]. If the 10% LEL prescribed in the VIAG is taken as the maximum, the maximum permitted concentration of these gas components in biomethane can be calculated. This calculation is explained in Annex VII. To keep the whole practical, the results of this calculation have been rounded off and are shown in Table 5-1.

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[1] The lower explosion limit for biomethane is not precisely defined. For this, 5% was assumed in this study.

Table 5-1 Maximum permissible concentration of components in biomethane based on Time-weighted Average Limit values [32].

Component		Maximum permissible concentration [ppm]
Ammonia	NH_3	1,800
Benzene	C_6H_6	20
Phosphine	PH_3	10
Carbon dioxide	CO_2	500,000
Carbon monoxide	CO	2,300
Toluene	C_7H_8	3,600
Hydrogen chloride	HCl	500
Hydrogen cyanide	HCN	90
Hydrogen sulfide	H_2S	160

5.2 Influence of biomethane on the materials in the gas network

The resistance of a material to biomethane depends on the type of material, the gas component (s) present in the biomethane and the circumstances. As a result, the sensitivity of the gas distribution network for biomethane differs per situation. Nevertheless, the influence of some substances can be generalized. This concerns the components nitrogen, THT (mercaptans), oxygen, elemental sulfur and silicon-containing components. This is further explained below.

The resistance of the currently used gas distribution materials to biomethane is explained in the following sections and in Annex V per type of material.

5.2.1 Influence of specific components in the biomethane

Nitrogen

Nitrogen is an inert gas that does not react under normal conditions with materials from the gas distribution network. It is therefore often used as a reference gas in studies [16] [33]. Nitrogen has no discernible contribution to the aging and / or degradation of the gas network and is therefore not taken into account.

THT

THT is a mercaptan, which has been added to natural gas as an odorant for years. The content of mercaptans in biomethane is hardly increased compared to the current situation with natural gas distribution [28]. Therefore, no influence of mercaptans on material quality is expected.

Oxygen

Oxygen is an oxidizing substance. Plastics and some metals, such as steel, are generally sensitive to oxidation. This results in deterioration of material properties. Oxygen is common in the atmosphere. That is why plastic materials are designed and developed for resistance to this oxidizing substance, for example by adding antioxidants. Given the low concentration of oxygen present in biomethane, no influence of oxygen is expected. Steel gas pipes are usually protected against corrosion by applying a coating (paint) on the outside. Cathodic protection, in combination with a PE coating, is also applied to prevent corrosion from the outside. The inside of pipes is generally not protected. Due to the low oxygen content in the biomethane, the degree of internal corrosion caused by this is negligible [28].

Sulfur

Elemental sulfur can be formed in the presence of hydrogen sulfide and oxygen. Elemental sulfur can be formed in both a dry and moist environment. It is a solid and can therefore cause clogging of, for example, pressure regulators [31]. Elemental sulfur is an oxidizing agent. In the chemical reaction it is not able to donate

electronegative atoms (as is the case with many oxidizing substances), but it can absorb electrons [34]. As a result, elemental sulfur is not able to degrade plastics under normal circumstances [35]. However, sulfur is able to corrode metals.

Silicon
Silicon is hardly reactive and will have little influence on the degradation of metals and plastics. As a result, silicon-containing components have no influence on the integrity of the gas distribution network. Components containing silicon are converted to silicon dioxide (SiO_2) during combustion. Silicon dioxide is a solid that can deposit on parts of end-user equipment. Because no combustion of biomethane takes place in the gas distribution network, no SiO_2 is formed in the network [36].

5.2.2 *Resistance of the currently used gas distribution materials to biomethane*

For the description of the resistance of the current gas distribution materials to biomethane, a distinction is made - just as with hydrogen - in plastics and metals. It is also true for biomethane that both material groups have significantly different degradation mechanisms.

The results are outlined in this section. For a more detailed explanation, reference is made to Annex V.

PE and PVC in particular have good resistance to the gas components that may be present in biomethane. There is no significant influence of biomethane on the compounds.

Although NBR and POM have good resistance to most gas components, they may be sensitive to the acid gas components. It is therefore also recommended in this context to record the gas quality supplied by the injector. This allows to determine whether off-spec contaminants are present during the aforementioned gas quality checks. For example, because these - as indicated above - might affect the rubber seals of the PVC connections or POM.

The resistance of the different plastics is shown in Table 5-2.

It should be noted that concrete experiments are often described in the sources found. A statement can only be made for the circumstances associated with these experiments. Where relevant the circumstances are given in the table below.

Table 5-2. The resistance of PE, PVC, NBR and POM to components that may be present in biomethane.

		PE	PVC	NBR	POM
Ammonia	NH_3	up to 100 ppm	up to 100 ppm	up to 100 ppm	up to 100 ppm
Benzene	C_6H_6	Not liquid	Not liquid	Not liquid	
Chlorinated components			up to 1.000 mg/m^3 DCM	up to 1.000 mg/m^3 DCM	up to 1.000 mg/m^3 DCM
Fluorinated components					
Phosphine	PH_3				
Carbon dioxide	CO_2		up to 59 mol%	up to 59 mol%	up to 59 mol%
Carbon monoxide	CO				
Hydrocarbons		Not liquid	Not liquid	Not liquid	
Mercaptans					
Silicon-containing components					
Nitrogen	N_2				
Toluene	C_7H_8	Not liquid	Not liquid	Not liquid	
Water	H_2O				
Hydrochloric acid (Hydrogen chloride)	HCl				>3 ppm @82% R.H.[1]
Hydrogen cyanide	HCN				
Hydrogen	H_2		up to 20 mol%	up to 20 mol%	up to 62 mol%
Hydrogen sulfide	H_2S	up to 160 ppm	up to 160 ppm	up to 160 ppm	up to 160 ppm
Oxygen	O_2				
Sulfur	S_8 / S_n				

No / acceptable influence
Probably no influence
Unknown
Possibly harmful
Harmful

For metals (steel, copper and aluminum), the resistance to the gas components that can occur in biomethane is not clear.

The presence of water increases the corrosion rate of a number of gas mixtures. It is therefore strongly recommended to limit the presence of water in the gas distribution network.

If, due to the toxicity of hydrogen sulfide, the concentration is limited to a maximum of 160 ppm, the corrosion rates of steel and copper will therefore be limited. By ensuring that the oxygen concentration is also low (<3 vol%), the corrosion rate is reduced to acceptable values (pipe life> 50 years). Carbon dioxide influences the corrosion rate for steel in combination with oxygen and hydrogen sulfide. The exact limit of hydrogen sulfide is not known. It is known, however, that the corrosion rate of copper and steel is relatively low (<0.07 mm / year) up to a level of 34 ppm H_2S.
The influence of carbon monoxide is unknown. Steel and copper may be attacked in

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[1] R.H. = relative humidity

the presence of carbon monoxide and oxygen. Also for carbon monoxide, it applies that this substance is toxic. Here too it is desirable to limit the CO concentration for safety reasons.

With cast aluminum, no corrosion is observed with gas mixtures of 10 - 50 mol% CO_2 to 3 mol% O_2 and up to 160 ppm H_2S (at 30 mbar). Only in the absence of carbon dioxide does corrosion occur in the presence of water at 3 mol% O_2 and 160 ppm H_2S, as well as at 0.5 mol% O_2 and 34 ppm H_2S with corrosion rates of 0.31 and 0.19 mm / year, respectively. The results are summarized in Table 5-3.

Table 5-3 The resistance of steel, copper and aluminum to components that may be present in biomethane.

		Steel	Copper	Aluminum
Ammonia	NH_3		up to 50 ppm	No copper in alloy
Benzene	C_6H_6			
Chlorinated components		No ions	No ions	No ions
Fluorinated components		No ions	No ions	No ions
Phosphine	PH_3			
Carbon dioxide	CO_2	*	up to 50 mol%	up to 50 mol%
Carbon monoxide	CO	*	*	
Hydrocarbons				
Mercaptans				
Silicon-containing components				
Nitrogen	N_2			
Toluene	C_7H_8			
Water	H_2O	*	*	*
Hydrogen chloride	HCl			
Hydrogen cyanide	HCN			Provided pH>4
Hydrogen	H_2		up to 20 mol%	up to 20 mol%
Hydrogen sulfide	H2S	*	*	* Without CO2
Oxygen	O_2	*	*	* Without CO2
Sulfur	S_8			

No / acceptable influence
Probably no influence
Unknown
Possibly harmful
Harmful

*See Appendix V for more specifications

5.2.3 Micro-organisms

Various micro-organisms have been found in biomethane. These are by-products from, for example, digesters [31]. A number of microorganisms are known to affect the corrosion of metal by attacking the protective oxide skin or by producing harmful components [37]. In addition, micro-organisms can also attack plastics. In general, micro-organisms cannot develop in a relatively dry environment [38]. The gas distribution networks have a low water vapor pressure under normal conditions, so

that they can be characterized as dry. The fact that the micro-organisms do not grow in a dry environment does not mean that they will die. Possible traces of microorganisms can therefore also be present
To prevent the growth of microorganisms in the distribution network, the water content of the gas should preferably be kept as low as possible.

5.2.4 Maximum concentrations

The maximum permissible concentration of the harmful substances that may occur in biomethane is determined by the combination of the limits according to Table 5-1, Table 5-2, Table 5-3 and the values specified in the studies listed in Annex V called. The result is shown in Table 5-4.

These limit values apply to gas distribution. Certain specific gas applications (for example for mobility) may require further refinement.

Table 5-4 Maximum permissible concentration of a number of gas components in biomethane.

Gas component		Maximum concentration	Unit	Remark
Ammonia	NH_3	50	ppm	
Benzene	C_6H_6	20	ppm	
Chlorine / Fluorine containing components		1,000	mg/m^3	
Phosphine	PH_3	10	ppm	
Carbon dioxide	CO_2	500,000 (50)	ppm (%)	Not in combination with CO_2 and H_2O
Carbon monoxide	CO	2,300	ppm	
Toluene	C_7H_8	3,600	ppm	
Water	H_2O			Not in liquid form[1]
Hydrogen chloride	HCl	3	ppm	
Hydrogen cyanide	HCN	90	ppm	
Hydrogen sulfide	H_2S	160	ppm	
Oxygen	O_2	30,000 (3)	ppm (%)	Not in combination with CO_2 and H_2O

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[1] In combination with water, many metals are sensitive to corrosion. Lowering the water content to a dew point of -3°C, as mentioned in Annex IV, is acceptable. However, a dew point up to the current value of -10°C provides additional certainty from a material point of view.

The composition of biomethane differs from the composition of fossil natural gas. The list of components that can occur in biomethane is long. Some components are (at a certain concentration) toxic or have an influence on the life span of parts of the gas distribution network. That is why a network manager cannot just admit every composition of biomethane in the existing infrastructure. Table 5-4 gives an indication of the permitted gas concentrations.
Provided that the composition of the biomethane respects these indicative values, the gas network is suitable for transporting biomethane.

If the aforementioned conditions are met, the currently applied construction and design techniques can also be used for the installation of new gas pipelines.

5.3 Safety aspects in the distribution and use of biomethane

5.3.1 Effectiveness of the odorization
Experience has shown that biogas and green gas can contain contaminants, the odor of which can mask the alerting - and legally required - recognizable "gas" odor. Also in the future, as is currently the case for green gas, it will be the responsibility of the biomethane importers to ensure that these substances do not occur in the biomethane. It will also be the task of the network operator in the future to ensure that this is indeed the case and to intervene if necessary.

5.3.2 Measures for determining the gas quality
As indicated above, it is the responsibility of the injector to ensure that the biomethane feed-in meets the quality requirements that are imposed on it. The requirements for the gas composition of natural gas and green gas are currently laid down in the MR Gas Quality. The biomethane composition is not defined at this moment. It is obvious that the agreements on the new biomethane composition - similar to the current situation - will be laid down in a Ministerial Regulation, but this can also be an agreement between the injector and the network operator. The gas composition as stated in Annex IV can serve as first step.
When distributing biomethane, network operators will also have to ensure that the correct gas quality is fed. To this end, additional monitoring of gas quality must be carried out by the network operators. This extra monitoring entails costs in the form of more and more frequent analysis of gas samples or in the form of certified data exchange with the process monitoring equipment of the injectors.

5.3.3 Adjustments to devices
Two essentially different strategies are conceivable for the distribution of biomethane. One strategy could be that only biomethane is permitted within the current restricted band of the Wobbe index and supplemented with any additional restrictions related to the presence of other substances that influence the combustion properties (eg CO_2 and H_2). In that case no adjustments to the devices are necessary.

The other strategy involves broadening the Wobbe band and / or imposing fewer restrictions on CO_2 and H_2 levels. The advantage of this is a reduction in the costs of gas cleaning / conditioning at the manufacturers of biomethane. The disadvantage is then the necessity to replace the currently used equipment to a greater or lesser extent. Expanding the Wobbe band is technically possible without having to introduce substantially different device concepts. Depending on the permitted variation in gas quality, a concession may have to be made to the modularity of the devices. This, in turn, has consequences for the annual yield of the combustion plant.

5.3.4 Measures related to sulfur

In addition to the added THT as an odorant, biomethane can also contain other sulfur compounds. In particular, H2S should be considered. Less known is that elemental sulfur (in vapor form: at ambient temperature around 0.1 ppmv to 1 ppmv) may also be present in the gas. This vapor can precipitate as solid sulfur (S_8) and cause malfunctions in, for example, valves of gas pressure regulators. In the presence of O_2, H2S can decompose into sulfur and water ($H_2S + O_2 \rightarrow H_2O + 2S$). In fact, H2S acts as a kind of reservoir for the production of sulfur vapor in the gas [39].

The consequence of this is that more failures can occur in gas pressure control and safety installations and therefore more maintenance is required.

5.4 Settlement of biomethane (energy)

Depending on the breadth of the agreed quality bands and the accepted measurement uncertainty, additional measures may be necessary for a valid settlement of differences in gas quality. This may involve regional differences and differences over time.

If it only concerns a regional deviation (for example, one network that is fed by one biomethane producer), assuming that gas quality monitoring is already taking place, there are only limited extra costs in the form of an administrative justification.

If there are several injectors with varying flow rates and qualities, measurements must be taken at the level of district stations or at the level of the individual delivery points, depending on the desired accuracy.

With the current state of the art (gas chromatograph [GC]) the costs are approximately € 10,000 / year per measuring point. It is not realistic to measure the gas quality of all small-scale consumers with the current GC techniques, due to the logistical and financial consequences of maintenance and calibration. For this, either innovative, inexpensive measurement methods must be developed, or an approximate administrative financial settlement must be accepted.

If the quality measurement is carried out at the level of the district station, the costs are at least around € 10 / year per connection.

6 Costs

6.1 Approach

The transition to a sustainable energy supply is associated with higher costs. This chapter focuses on the costs that, in principle, will be incurred by the gas network operators, insofar as the gas networks must (and can) be made suitable for hydrogen and biomethane. To place these costs in the right perspective, the costs for the use and production of hydrogen and biomethane, which will be charged to other stakeholders, will also be discussed. Moreover, it can be expected that the costs that the network operators will have to incur will be included in their tariffs, so that everything will ultimately be paid by the end users.

The costs mentioned in this chapter are order-sized estimates based on the current state of the art. The costs are broken down into one-time costs and annually recurring extra costs (extra compared to maintaining the current gas supply with natural gas of Slochteren gas quality in a certain service area). The costs are further divided into a possible basic amount (scale independent) and an amount per connection in a service area. Strongly expected non-linear cost effects in terms of scale are explicitly stated.

The cost items are generically allocated to the following focus areas:
1. Transport and distribution safety
2. Security of delivery and service life
3. Input
4. Safety of delivery and end use
5. Adjustments installations at the end consumer

Not all conceivable measures are shown in the tables. A selection has been made based on necessity and estimated feasibility.

For each cost item it is also assessed to what extent the item is dependent on the penetration rate of the gas network in the various scenarios and supply areas. After all, a gas network up to or into the house requires certain measures that are superfluous for a gas network up to the edge of a residential area (with district heating).

Not all measures mentioned will always be applied. Some measures have a cheaper alternative. In certain cases, certain combinations of measures exclude other measures or make other measures superfluous. This is further specified in the explanatory text.

The additional costs associated with maintaining or adjusting the gas network (in whole or in part) are per scenario, based on the 'Net for the Future' CE report [7] (and the associated background report [8]) key figures are calculated (consumption per sector and consumption per house equivalent (WEQ)).

In the report "Networks for the Future" the costs for the various energy carriers are estimated. An explanation by CE Delft shows that the use of biomethane - if available - is the cheapest solution. After biomethane, hydrogen appears to be the best option. This appears to be less than "all electric". The latter option appears to have comparable costs compared to geothermal energy. The use of residual heat, which in terms of costs is again comparable to geothermal energy, will mainly take place in the areas where this residual heat will be present for a longer period of time.

6.2 Costs of measures for the transport of hydrogen

The table below provides an overview of the most important measures and the extra costs compared to natural gas distribution given the conclusion it is possible to use the existing gas infrastructure for supplying hydrogen to end users.

Table 6-1 Extra costs of the relevant measures when using the existing gas infrastructure for the transport of hydrogen.

++: larger extra cost item, +: limited extra cost item, 0: no measure and / or no extra costs

	Measure	One-time, basic	Once per WEQ	Recurring basis	Returning by WEQ
		k€	€/WEQ	k€/yr	€/(yr WEQ)
1	**Safety transport and distribution**				
1.1	Information and training of technicians	++	+	0	0
1.2	Adjusting work procedures for construction and maintenance	0	0	0	10
1.3	Adjustment of standards and regulations	++	0	0	0
1.4	Supervise during excavation work	0	0	0	+
1.5	Dynamic / automatic sectioning of the gas network	++	+	0	+
2	**Security of supply and maintenance**				
2.1	Tool and measuring instrument adjustments	0	+	0	0
3	**Feeding in network**				
3.1	Extra check for contamination (S, CO, N_2, O_2, etc.)	0	0	0	+(++)
4	**Safety of delivery and end use**				
4.1	Advertising / information campaign	++	+	0	0
4.2	Adjusting odorization	++	+	0	0
4.3	Extra check for odorization	0	0	+	+
4.4	Adjust standards for gas indoor installation (leak tightness)	++	0	0	0
4.5	Adjust work procedures for installation and maintenance of gas indoor installation	0	0	0	+
4.6	No open flame cookers	0	++	0	0
5	**Adjustments installations end users**				
5.1	Other gas meters (larger Bellows-type)	0	+	0	0
5.2	Other gas meters (ultrasonic)	0	+	0	0
5.3	Extra gas indoor installation check (one-time / yearly)	0	0	0	++
5.4	Other appliances (replacement / conversion of central heating appliance)	0	++	0	0

Explanation

1.1 The engineers originally trained for natural gas (own staff of network operators and contractors) will have to be retrained for work with hydrogen. To this end, one-off course material must be developed and the technicians in the region must receive additional training. The development costs of the course and the course material for the Netherlands (various educational levels) are estimated at € 200 k. Two course days of € 0.5 k / day (all costs) were reserved for each employee. A person can serve 1,000 WEQ with this knowledge.

1.2 When working on a hydrogen distribution network, additional measures and procedures are required to enable safe working. These measures make annual maintenance (repairs, replacements and adaptations of an existing network) 10% more expensive (compared to the current € 100 / (WEQ year)).

1.3 Norms and standards for hydrogen distribution networks are not yet available. A one-off extension / revision of existing standards (eg NEN7244 / NEN2650 / NEN1059) is required.

1.4 Excavation damage may lead to an increased risk if the current policy remains unchanged. Increased supervision during excavation work is considered necessary, at least initially. There are around 0.5 million KLIC reports per year. An unknown but probably large part concerns areas with gas distribution pipes. Per report 1 person / day at € 400 leads to a total cost item of € 200 million / year, if a 100% check would be required.

1.5 Excavation damage may lead to an increased risk if the current policy remains unchanged. One-off investment in sectioning the network can reduce the effect of excavation damage. This is an alternative to 1.4. Sectioning costs € 2,000 per automatically remotely operated valve and € 1,000 per Excess Flow Valve (EFV). Section length approx. 1 km. There is 0.02 km of pipeline per WEQ. The EFV / valve ratio is 4. A one-off investment (per region) is required for integration into business operations. Annual check on prevalence of valves (€ 100 / valve / year).

2.1 Extra purchase of, for example, a hydrogen alarm as a personal protective device. Extra equipment for flushing pipes with inert gas. Adjusting leak detection equipment. After the transition phase, this replaces the current equipment, so no permanent costs. Ca. € 1,000 / employee.

3.1 Extra control of contaminants in the gas is only necessary if sensitive fuel cells are set up as end use. Approximately € 25,000 for € 20 per feeding. Maintenance and capital charges double these annual costs. Costs are highly dependent on the currently unknown average size of a hydrogen feeder[1]. Assumption: There is one injector per 1,000 - 10,000 WEQ.

4.1 Advertising and information campaign must make the end user aware of the other properties of hydrogen, such as the possible different odor, the absence of CO poisoning, the possibly higher device efficiency, more condensation during combustion and the slightly different behavior in the event of leakage.

4.2 Important for fuel cells. It is assumed that the odorization is adjusted in the context of the preparation for a sulfur-free gas network. One-off conversion costs per odorization installation. For the Netherlands: 100 x 10 k € / 10 MWEQ.

4.3 Important in connection with the possibly increased risk perception of hydrogen and the greater number of feeding / odorization points. Intensification of samples. The costs now amount to approximately € 0.1 / (WEQ yr). Permanent minimum of 1 check per region / year + 1 per 1,000 WEQ / year.

4.5 Concerns the use of more expensive couplings and extra tightness tests when constructing the gas indoor installation. 10% cost increase on € 1,000 installation costs / WEQ per 40 years.

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[1] Report "Green Liaisons - Outlines of a Renewable Gases 2050 Roadmap" (De Gemeynt, April 2018) mentions a number of 3,350 installations with a total production of 38.4 PJ total (sum of renewable energy in the form of electricity, hydrogen and biomethane)

4.6   Conventional cooking appliances are being replaced at one time by catalytic burners under glass or electric hobs.

The table below shows the relevance of the measures in relation to the penetration rate of the hydrogen network present in the region.

Table 6-2. Measures for the distribution of hydrogen, subdivided by degree of penetration (X = applicable).

	Measure	Up to the city (City gate station)	Up to the neighbo rhood (DS)	Up to the corner of the street	Up to the property	In the house
1	**Transport and distribution safety**					
1.1	Information and training of technicians	X	X	X	X	X
1.2	Adjusting work procedures for construction and maintenance	X	X	X	X	X
1.3	Adjustment of standards and regulations	X	X	X	X	X
1.4	Supervision during excavation work		X	X	X	X
1.5	Dynamic / automatic sectioning of the gas network		X	X	X	X
2	**Security of supply and maintenance**					
2.1	Adjustments tools and measuring instruments	X	X	X	X	X
3	**Feeding into the network**					
3.1	Additional check for contamination (S, CO, etc.)		X	X	X	X
4	**Safety of delivery and end us**					
4.1	Advertising / information campaign		X	X	X	X
4.2	Adjusting odorization		X	X	X	X
4.3	Extra check for odorization		X	X	X	X
4.4	Adjusting standards for the gas indoor installation (leak tightness)					X
4.5	Adjust work procedures for installation and maintenance of gas indoor installation					X
4.6	No open flame appliances	X	X	X	X	X
5	**Adjustments installations end users**					
5.1	Other gas meters (larger bellows)				X	X
5.2	Other gas meters (ultrasonic)				X	X
5.3	Extra inspection gas indoor installation (one-off / yearly)					X
5.4	Other devices (replacement / conversion)	X	X	X	X	X

6.3 Costs of measures for the distribution of biomethane

The table below provides an overview of the most important measures and the extra costs compared to natural gas distribution because it is possible to continue using the existing gas infrastructure for the supply of biomethane to end users. This is based on a different gas composition compared to the MR Gas quality. If the composition of biomethane corresponds to the current MR Gas quality, these costs will lapse. Recurring costs relate to the higher replacement costs of the gas meter in connection with the internal calorific value correction.

Table 6-3. Extra costs for the relevant measures when using the existing gas infrastructure for the transport of biomethane.

++: larger extra cost item, +: limited extra cost item, 0: no measure and / or no extra costs

		One-time basic	Once per WEQ	Recurring basis	Returning by WEQ
		k€	€/WEQ	k€/yr	€/(yr WEQ)
1	**Transport and distribution safety**				
1.1	Information and training of technicians	++	+	0	0
1.2	Adjusting work procedures for construction and maintenance	0	0	0	+
1.3	Adjustment of standards and regulations	++	0	0	0
2	**Security of supply and maintenance**				
2.1	Adjustments tools and measuring instruments	0	+	0	0
2.2	Placement of siphons (controlling condensate in the network)	0	+	0	+
3	**Feeding into the network**				
3.1	Additional check for contamination (H_2S, CO, etc.)	0	0	0	+(++)
4	**Safety of delivery and end use**				
4.1	Advertising / information campaign	++	+	0	0
4.2	Adjusting odorization	++	+	0	0
4.3	Extra check for odorization	0	0	+	+
4.4	Optional placement of gas detectors	0	++	0	0
5	**Adjustments installations end-use**				
5.1	Other system of calorific value settlement	+(++)	+(++)	0	0(++)
5.3	Extra inspection gas indoor installation (one-off / yearly)	0	0	0	++
5.4	No open flame appliances	0	++	0	0
5.5	Other devices (replacement / conversion)	0	+(++)	0	0

Explanation

1.1   The engineers who were originally trained for natural gas (own staff of network managers and staff of contractors) will have to be retrained for work with biomethane. To this end, one-time course material must be developed and the technicians in the region must receive additional training. The development costs of the course and the course material for the Netherlands (various educational levels) are estimated at € 10 k / day. Two course days of € 0.5 k / day (all costs) are provided per employee. A person serves 1,000 WEQ with this knowledge.

1.2   Work on the distribution network requires additional measures and procedures on a limited scale to keep the risks at the current level (measures are envisaged with regard to H2S and microbiological contamination). These measures make annual maintenance (repairs, replacements and adjustments to an existing network) 2% more expensive (compared to the current € 100 / (WEQ year).

1.3   Standards and standards for specific biomethane distribution networks are not yet available. A one-time extension / revision of existing standards (eg NEN7244, NEN2650, NEN1059) is required. The gas distribution sector currently spends around € 1 million per year on maintaining system and component standards (NEN, CEN and ISO standards).

2.1   Extra purchase of, for example, an H_2S alarm as a personal protective device. Adjusting leak detection equipment. After the transition phase, this replaces the current equipment, so no permanent costs. Approximately € 500 / employee.

2.2   Placement costs € 1,000 per siphon. One siphon is needed per injector. Costs per WEQ therefore depend on the average size of an injector (1,000 to 10,000 / WEQ). Annual inspection required (€ 100 per turn).

3.1   Extra gas quality monitoring per injector. Capex: GC € 50 k over 10 years. Opex: € 5k. For installation 1,000 m3 / h = 10,000 WEQ. Costs strongly depend on the average scale of the future fermentation installations.

4.1   An information campaign has been included in this cost overview, particularly for the different types of smellability of biomethane and the increased risk of masked odor.

4.2   This item has been considered, but is considered superfluous, provided that the odorization of biomethane is sufficiently reliable.

4.3   For the conversion of existing odorization installations and the addition of this installation to the biomethane feed.

4.4   Extra checks for odorization are estimated at a maximum of a few checks per year at a few hundred euros per catchment area with a few thousand WEQs.

4.5   Placement costs around € 100 per (H_2S / CH_4) sensor. This control measure is optional. In principle, odorization of biomethane is a sufficient measure to achieve the current safety level.

5.1   Costs strongly depend on the desired accuracy and the permitted variation in calorific values. The method can vary from an administrative settlement based on input data to an actual measurement of calorific value per end user. The development and introduction of a new system requires considerable one-off costs. There is no affordable technology on the market for determining calorific value on the scale of one connection. The one-time costs of technology development are not included in the table.

5.2   (item only applies to hydrogen)

5.3   In order to control the possible additional risks of biomethane leakage, a regular inspection of the gas indoor installation can be introduced when introducing biomethane. This is set at 1 check per year. If the results show that safety with current practice (only inspection at the initiative of the house owner) is sufficiently guaranteed, this additional inspection can be canceled in the long term.

5.4   Due to the possible risk of incidental release of H_2S and microbiological contamination indoors, it is possible to consider replacing open flame appliances with other types of (cooking) appliances.

5.5   The costs for adapting the devices strongly depend on the permitted variation in the Wobbe index. The stated maximum amount concerns the replacement of injectors and the adjustment of the burner pressure. Extremely wide permitted bandwidth requires replacement of the device (€ 1,000 / WEQ).

Table 6-4. Measures for the distribution of biomethane, subdivided by penetration rate (X = applicable).

	Measure	Up to the city (City gate station)	Up to the neighbo rhood (DS)	Up to the corner of the street	Up to the property	In the house
1	**Transport and distribution safety**					
1.1	Information and training of technicians	X	X	X	X	X
1.2	Adjusting work procedures for construction and maintenance	X	X	X	X	X
1.3	Adjustment of standards and regulations	X	X	X	X	X
2	**Security of supply and maintenance**					
2.1	Adjustments tools and measuring instruments	X	X	X	X	X
2.2	Placement of siphons (controlling condensate in the network)		X	X	X	X
3	**Feeding into the network**					
3.1	Additional check for contamination (H_2S, CO, etc.)	X	X	X	X	X
4	**Safety of delivery and end use**					
4.1	Advertising / information campaign	X	X	X	X	X
4.2	Adjusting odorization		X	X	X	X
4.3	Extra check for odorization				X	X
4.4	Optional placement of gas detectors					X
5	**Adjustments installations end users**					
5.1	Other system of calorific value settlement.	X	X	X	X	X
5.4	No open flame appliances					X
5.5	Other devices (replacement / conversion)	X	X	X	?	?

6.4 Conclusion with regard to the cost estimate

The current costs for maintaining the gas network are € 100 - € 150 / year per WEQ. Many of the measures considered have one-time costs. If these are averaged over the duration of a 'future-proof' network, these are, as far as gas distribution is concerned, costs in the order of a few euros per WEQ / year. Perhaps the largest cost item is the replacement of the gas meter and the development and implementation of a possible different settlement procedure. The costs of measuring variations in the calorific value at the level of an individual house are high and uncertain. It is therefore expected that this method of settlement will not be applied.

The one-time costs associated with the (premature) replacement of gas appliances at the end user are much higher than any additional gas network maintenance costs (calculated back dozens of Euros per WEQ / yr)l However these costs are also

involved in the transition to heat or "all -electric".

Of the recurring costs, the items related to possible inspections are the highest. Extra inspection during excavation work is expensive. A 100% check makes gas (hydrogen) delivery 20 € / WEQ / year more expensive. The alternative of sectioning the gas network is not much cheaper and is not fully tested. Whether these measures are necessary in the long term is uncertain and depends on practical experience.

An annual inspection of the gas indoor installation and / or of gas sensors in the house is costly (order of € 100 / WEQ / year). The usefulness and necessity of this is also debatable. These costs are not part of the maintenance costs of the gas network.

The overall conclusion is that the costs for maintaining the gas network will increase by less than 50%. Depending on the usefulness of practical experience and the need for inspections, the best guess is that the additional maintenance costs will ultimately be around 5% of the current costs (5 to 10 € / WEQ / year)

6.5 Development of the scenarios

6.5.1 Approach
The Sankey diagrams in the CE report "Networks for the Future" ([8], p. 75 et seq.) form the basis for determining the costs for making the gas distribution network more sustainable.
The gas distribution networks are mainly important for the supply of low temperature heat. In the sustainable scenario they can supply hydrogen and biomethane to houses/residential and utility buildings, where this is subsequently converted into the low temperature heat for heating and hot tap water preparation.

It is assumed that in all four scenarios this concerns 9 million house equivalents (9 MWEQ) and that the size of the networks is proportional to the relative share of hydrogen or biomethane in the total energy flow to low temperature heat. Any supplied electricity is weighted with a COP = 4.

In case of low-temperature heat being supplied by means of biomethane or hydrogen this will happen to each individual house. Therefore, all associated measures and costs were included in determining the costs. The basic costs are charged once and added to the costs per WEQ, times the number of WEQ.
With hydrogen, intensive monitoring of excavation work during the introduction period and the use of innovative techniques to prevent excavation damage have been chosen in the long term. This eliminates segmentation of the network.

The costs for replacing devices are not included, because the same costs are also incurred for the rollout of other types of networks (heat or electrical). The settlement of biomethane is based on a medium level: one-time € 30 / WEQ and € 3 / WEQ annually.

6.5.2 Overview of results (4 scenarios)
The system described above for determining the costs for distributing low-temperature heat leads to the overview given in Table 6-5. The table is composed of the energy consumption per scenario and the number of house equivalents associated with each scenario. The costs have been calculated using this data, as well as the cost data from Table 6-1 up to and including Table 6-4.

Table 6-5. Total overview of costs for implementing the relevant measures per scenario. The costs reflect the size of the networks and not so much the intrinsic differences between hydrogen and biomethane.

		1. Regional	2. National	3. International	4. Generic Control;
Hydrogen	PJ	19.0	203.2	158.1	0.0
Geothermal / residual heat	PJ	80.3	5.5	4.7	0.0
Biomass	PJ	52.6	11.1	29.0	20.0
Biomethane	PJ	67.9	64.9	137.7	344.0
Electricity generation	PJ	77.3	54.0	44.8	43.9
CHP (large-scale)	PJ	78.3	49.1	42.1	0.2
Total LTW		607.3	549.8	550.8	539.8
Total	Mweq	9.0	9.0	9.0	9.0
Hydrogen	Mweq	0.3	3.3	2.6	0.0
Biomethane	Mweq	1.0	1.1	2.3	5.7
Network costs hydrogen (NL one-time)	M€	59	678	527	0
Biomethane network costs (NL one-time)	M€	38	40	81	202
Network costs hydrogen (NL annual)	M€/yr	36	422	328	0
Biomethane network costs (NL annual)	M€/yr	125	132	279	711

6.5.3 Summary consideration

The transition to a sustainable energy supply requires adjustments to transport and distribution networks as well as adjustments to the end user.
The adjustments at the end user (per WEQ) often appear to cost one or two orders of magnitude more than the adjustments to the gas network (per WEQ).
It is outside the scope of this report to make a comparison with the possible adjustment costs (expansion costs) of electricity or heat networks, but the authors have the impression that these costs for Electricity and Heat per WEQ will probably be higher. It must be borne in mind here that after the gas connection has been removed, considerable technical adjustments to the house are still necessary. The associated costs are at least of the same order of magnitude like the replacement or modification of gas appliances.

The main cost difference between the gas networks for hydrogen and for biomethane is the cost of replacing the gas meter. In the case of hydrogen there can also be circumstances where a different gas meter is required. The existing gas meter can be used for biomethane if at least the quality band of the distributed gas remains sufficiently limited.

Further investigation is needed to see whether the same ultrasonic gas meter can be used for both hydrogen and biomethane, possibly only with a small adjustment in software (and with a sealed switch).

If variations in the calorific value of biomethane are allowed, the extra costs for the biomethane measurement depend on the desired accuracy, the permitted bandwidth and the degree of variation in time and place. At the moment there is no technology available that can determine the gas quality at the individual end user at acceptable costs and with the current accuracy (<0.5%). It is possible that cheap sensors will be developed for this in the future [40].

The main obstacle to the reuse of gas networks is therefore not the technical limitations of the network or the financial consequences, but the availability of the alternative gaseous energy carriers hydrogen and biomethane.

An important advantage of gas as an energy carrier is the possibility of storing energy cheaply and saving it without loss. These cost benefits are not included in the overview.

The safe operation and maintenance of the networks that transport hydrogen and biomethane to the end user requires limited adjustments to procedures and instruments.
The costs of these adjustments are low compared to the costs of replacing devices at the end user.

7 Conclusions and recommendations

7.1 Conclusions

The existing gas distribution networks are suitable for transporting biomethane or 100% hydrogen. Modern materials such as impact-resistant PVC, PE and cathodically protected steel are also suitable for the use of these sustainable gases. When allowing both hydrogen and biomethane into the gas networks, the sustainable gas must be dry.

The maximum values for biomethane are already shown in Table 5-4.

These maximum values also apply to the hydrogen to be distributed. However, it is expected that hydrogen will easily meet this requirement in practice.

The resulting table for both sustainable gases is repeated below for completeness (Table 7-1).

Gas component		Maximum concentration	Unit	Note
Ammonia	NH_3	50	ppm	
Benzene	C_6H_6	20	ppm	
Chlorine / Fluorine containing components		1,000	mg/m^3	
Phosphine	PH_3	10	ppm	
Carbon dioxide	CO_2	500,000 (50)	ppm (%)	Not in combination with CO_2 and H_2O
Carbon monoxide	CO	2,300	ppm	
Toluene	C_7H_8	3,600	ppm	
Water	H_2O			Not in liquid form[1]
Hydrogen chloride	HCl	3	ppm	
Hydrogen cyanide	HCN	900	ppm	
Hydrogen sulfide	H_2S	160	ppm	
Oxygen	O_2	30,000 (3)	ppm (%)	Not in combination with CO_2 and H_2O

Table 7-1 Maximum value per gas component for biomethane and hydrogen (based on acceptable values for the toxicity and resistance of the gas distribution materials).

The stated concentrations do not yet take into account any restrictions imposed by consumer devices, such as a maximum value for silicon compounds.

The metal gas networks, but also the material POM, which is frequently used in connections, domestic pressure regulators and gas meters, are not suitable for transporting raw biogas.

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[1] In combination with water, many metals are sensitive to corrosion. Lowering the water content to a dew point of -3 ˚C, as mentioned in Annex IV, is acceptable. However, a dew point up to the current value of -10 ˚C provides additional safety from a material point of view.

An adjustment of the currently applied construction and design techniques is not necessary. These can also be used for the installation of new biomethane and hydrogen gas pipes.

The safe operation and maintenance of the networks that transport hydrogen (100%) or biomethane to the end user requires limited adjustments to procedures and measuring instruments.

During the introduction of these sustainable gases, extra attention will have to be paid to safety due to the different characteristics. After experience has been gained with this, the necessity of the extra measures can be reconsidered.

The costs of the measures that must be taken by the network operator are relatively low compared to the costs of replacing devices at the end user.

The gas meter must be taken into account when introducing 100% hydrogen distribution. This is because a gas volume that is almost 3x as large must be supplied per house for the same energy demand. If the current gas meter is already operating at the maximum load, it will have to be replaced by a larger one.

Alternatively, it is also possible to opt for ultrasonic meters.

The lower energy content of hydrogen compared to natural gas means hydrogen will have to be transported at a higher velocity to fulfill the same energy demand. However, the pressure drop across the pipes remains the same due to the lower viscosity. As a result, the capacity of the network remains virtually unchanged. The current design standards for the network can therefore be maintained. Due to the higher flow velocity, the noise production can change. Whether this is going to be a problem is still unknown.

The costs for transporting biomethane differ little from the current distribution costs for fossil natural gas, as long as a limited bandwidth of the calorific value (in the same order of magnitude as is currently the case) is maintained. If a larger bandwidth is allowed, additional settlement procedures are required. The costs of this depend on the desired accuracy, the permitted bandwidth and the degree of variation in time and place. At the moment there is no technology available that can determine the gas quality at the individual end user at acceptable costs and with the current accuracy (<0.5%).

Three of the four scenarios provide for a substantial number of house equivalents, which meet their low temperature heat demand using condensing central heating appliances or hybrid heat pumps. For these end users, a gas distribution network will be present (or maintained) in the house.

In the Regional Management scenario, a local role is reserved for a local biomethane distribution network up to or in the house.

The existing 8 bar gas network, as well as of course the GTS transport network, can serve as a connection from the production sites (hydrogen and biomethane) to the district heating plants and the buffers. This requires adjustments to the gas receiving stations, where the gas must be brought from the 8 bar network to the higher pressure in the GTS network. The associated costs are incidentally low compared to the re-laying of pipes.

Whether a local gas network will be used for biomethane or for hydrogen is highly dependent on the local availability of these energy carriers. Biomethane is the cheapest alternative in all scenarios, but availability is limited (in varying degrees).

In areas where gas cannot be supplied due to a national shortage of gaseous energy carriers or because these are not available locally, the next best alternatives such as

"all electric" or geothermal energy will be used, making the existing gas network (locally) superfluous. The more expensive alternatives are not only more expensive in terms of production costs, but also in terms of transport costs. It can be expected that sustainably produced electricity and geothermal or residual heat will be used as much as possible in the areas in the vicinity of the production and that the (high pressure) gas distribution network will continue to exist in the other areas between regions.

The costs for the necessary measures for gas distribution itself when switching from natural gas to hydrogen (100%) and biomethane (and which are therefore initially made by the network manager) are relatively low compared to the costs that are directly charged. of the end user (such as the purchase of new devices).

7.2 Recommendations

- In regions where there are no concrete plans for a general switch to "all-electric" or a heat network, whereby the gas network becomes superfluous, it is advisable to maintain the existing gas network for the time being.

- Continue gas network expansion and replacements with the currently used materials (impact-resistant PVC, PE100 and steel). The choice of piping material does not depend so much on the quality of the sustainable gas, but rather on the local circumstances (existing materials) and the (logistical) preference of the network manager. If the water content of the sustainable gas is increased, plastic pipes are preferred because of the possible corrosion of metal pipes.

- When replacing the gas meter, aim for an instrument that is also suitable, or can be made suitable for low costs, for 100% hydrogen.

- In the event of a widening of the permitted bandwidth of the energy value (Wobbe index) of biomethane, take into account the associated costs for settling the calorific value. These costs can be higher than the costs for the production of the biomethane. Therefore, be cautious about allowing an excessive bandwidth for the calorific value for biomethane.

- Assess all new materials and components for the gas network that come on the market also for their resistance to the combination of CO_2 / O_2 / H_2O in low concentrations, as well as the resistance to 100% H_2. This prevents these materials from having to be replaced at high costs before the end of their economic / technical life, when sustainable gases become available.

- Collect as much practical experience as possible about the ignition behavior and explosion safety of hydrogen, so that a substantiated risk assessment of digging activities and disruptions to gas indoor installations is possible as soon as hydrogen becomes available, so that the proportionality of any additional measures can be weighed. Monitor the practical experiences during the introduction of sustainable gases through temporarily more intensive inspection and control.

- Investigate the options of a sulfur-free odorant for hydrogen that does not interfere with the proper functioning of fuel cells. For the safety of hydrogen in the public gas supply, the smellability of the gas is essential.

- Investigate whether the higher speed of hydrogen gas in pipes has consequences for possible noise pollution. If the energy demand remains the same, the flow rate in the gas network becomes higher when switching from natural gas to hydrogen. This can cause extra noise nuisance, especially around stations (with the same dimensions). Experiences and information about this are still lacking. Therefore, gather experiences in practice or through laboratory tests.

- Investigate whether, and if so which adjustments to work instructions and standards must be made, in order to maintain the current high safety level of the (natural gas) network in the future with sustainable gases.

- When transitioning to sustainable gases, take into account adequate training of (technical) personnel and ensure a campaign for public awareness of the deviant behavior of sustainable gases.

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I Main materials present in the gas distribution network

Gas distribution				
	Connection lines	Main lines	Components outside (e.g. coupling, valve, filter, pressure regulator)	Components inside (eg coupling, gas meter, domestic pressure regulator)
PE (PE50, PE80 en PE100)	X	X	X	X
Hard PVC	X	X	X	
Impact resistant PVC	X	X	X	
NBR			X	X
SBR			X	X
POM			X	X
Asbestos cement		X		
Gerelined gray cast iron		X		
Gray cast iron		X	X	
Ductile iron		X	X	X
Copper / copper alloys	X	X		X
Carbon Steel (St 37/ 235)	X	X	X	X
Stainless steel (AISI 316 types			X	x
Aluminum alloys			X	X
Tin lead alloy				X
Hemp / lead string rope			X	X
Lead-strict line repair (Encapress, Polyfill[1])			X	
Loctite (Methacrylate Ester)			X	X

Table I-1. Materials used in the current gas distribution network

Sources:

[41] and [42]
Addition: Stedin, Liander, Rendo, Enduris

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[1] Acrylonitril based
Source: http://www.gastek.nl/werkzaamheden/polyfill/
(Last visited on January 10, 2018)

II Composition of hydrogen

The reference for the composition of hydrogen gas is often based on "technical hydrogen" as an example of what is feasible. In addition, standards have been established for the gas composition for PEMFC fuel cells (ISO 14687-2) and suppliers also state their own limit values.
Table II-1 provides an overview

	Technical hydrogen			Hydrogen for fuel cells	
standard/class	3.0	5.0	6.0	ISO 14687-2 (2012)	Requirement of fuel cell producer
H_2 content	≥99.9	≥99.999	≥99.9999	≥99.997	
N_2+Ar (ppmv)		≤3	≤0.5	≤100	≤100
H_2O (ppmv)	≤30	≤5	≤0.5	≤5	≤5
O_2 (ppmv)		≤2	≤0.5	≤5	≤5
$CxHy$[a] (ppmv)		≤0.5	≤0.1	≤2	≤2
CO_2 (ppmv)			≤0.1	≤2	≤1
CO (ppmv)			≤0.1	≤0.2	≤0,1
S[b] (ppbv)				≤4	≤1
NH_3 (ppbv)				≤0.1	≤1
Halogens (ppmv)				≤0.05	≤0.05
Formaldehyde (ppmv)				≤10	
CH_4+N_2+Ar (ppmv)				≤100	
Particles (mg/kg)				≤1	
not-H_2 (ppmv)				≤300	
applications (not exhaustive)	reducing gas (metallurgy)	Gas chromatography, gas detection, soldering	Semiconductor production, in calibration gases	PEMFC	PEMFC
source	Linde	Linde	Linde	US dept. of energy, 2016	Ballard Power Systems

a: excluding methane
b: addition of sulfur-containing components that usually occur in natural gas

Table II-1. Comparison between technical hydrogen and quality requirements for fuel cells

III Influence of hydrogen on the distribution network

Plastics

The most important plastics that occur in the gas distribution network are the three generations of PE, hard and impact-resistant PVC, the rubbers NBR and SBR and the plastic POM. This not only concerns pipe materials, but also rubbers that are used for seals in connections and valves, as well as for components of pressure regulators and gas meters.

Plastics can be affected by their chemical reaction with hydrogen or their physical properties changing due to, for example, absorption or swelling [12]. The sensitivity of the material to hydrogen depends on factors such as pressure, duration, temperature and gas composition. Many different tests have been reported.

Based on ISO / TR 7620 "Rubber materials - Chemical resistance" it is concluded that hydrogen has little or no influence on SBR and NBR [17] [18].

The resistance of MDPE, HDPE and PVC has also been assessed for pure hydrogen during relatively short-term test periods (± 60 days). The rapporteurs conclude from this that the materials are resistant. Little or no influence is found on the mechanical properties of the materials studied. The mass and volume measurements also show no change. The materials in this source are assessed as resistant to pure hydrogen [12].

In addition, the aging of PE80 and PE100 was investigated at a gas pressure of 100 bar and gas mixtures consisting of natural gas and hydrogen (up to 100% hydrogen) [13].

The conclusion from this study was that both PE types are resistant to hydrogen. The influence of hydrogen on the distribution network has been investigated in a project on Ameland. During 4 years, hard PVC, PVC / CPE, PVC / A, PE100, POM and the rubber materials NBR and SBR were exposed to a gas mixture of up to 20% hydrogen, supplemented with natural gas. No differences in material properties have been demonstrated during this period [15].

In another study, POM was exposed to 62% hydrogen at 8 bar for 600 days. No significant change in physical and mechanical parameters was observed after this period. POM has been assessed as resistant to hydrogen [16].

In another project, after 100 years of exposure to natural gas, PE100 pipes were removed from an existing gas network. The tubes were then exposed to 4 bar hydrogen for 10 years in a pilot project. No influence of hydrogen was found when analyzing the tubes. Based on this, it was concluded that hydrogen does not affect the aging of PE100 materials [14] [19].

Metals

Hydrogen can degrade metals and degrade in quality. Critical failure mechanisms that are considered here are change in tensile strength, fatigue and the occurrence of embrittlement. Many different tests have been reported for metals. This information has also been used to give an expectation.

Steel
Over the years, various types of steel have been used in pipes, fittings and other components, among others. Steels used are, for example, St 37/235, ASTM A106 gr. B, API 5L gr. B and stainless steel AISI 316 L and 316 TI [27] [43]. The ASTM A106 gr. B is almost the same as API 5L gr. B and is fairly similar to API 5L gr. X42 (X70) [44] [45]. The main difference between API 5L gr. B and API 5L gr. X42 is that B may have a lower yield point (B: 245 MPa and X42: 290 MPa). The minimum requirements that are set for the maximum elongation and tensile strength are the same. In addition, API 5L gr. Admit that the tube has a longitudinal seam. Because of the similarity with ASTM A106 gr. B steel is API 5L gr. X42 also assessed [45]. API 5L gr. X70 (X70) is a comparable but more modern type of steel.

Hydrogen embrittlement
The degradation of the mechanical properties and the associated breaking mechanisms can differ per material and per gas composition. The influence of hydrogen on these fracture mechanisms determines the applicability of hydrogen in the current gas network. The term hydrogen embrittlement as a fracture mechanism is frequently used in the literature. The sensitivity to hydrogen embrittlement is not clear. Some sources argue that particularly high-strength steels are sensitive to this form of embrittlement [27] [46] [47], while another source states that the strength of the steel grade has hardly any influence [48].
With hydrogen embrittlement, molecular hydrogen is converted at the metal surface into atomic hydrogen. The atomic hydrogen dissolves in the metal and diffuses through the metal. In the event of defects in the metal, atomic hydrogen can re-assemble and form molecular hydrogen. Molecular hydrogen is hardly able to diffuse through the metal and is therefore trapped. If this process continues, the pressure with these defects will increase. This causes an uneven distribution of stress in the material and ultimately leads to embrittlement of the metal [47] [49].

Hydrogen has a high dissociation energy (104 kcal / mol). So a lot of energy is needed to form atomic hydrogen. Therefore, this process only occurs at high temperatures or with electrical discharge [50]. Hydrogen embrittlement can occur during the production process of metal parts, because high temperatures are used to process the metal. In the distribution network, the temperatures are so low and electrical discharges are so limited that hydrogen embrittlement is not expected.

Atomic hydrogen can also be formed via electrochemical processes [51]. Specific conditions are required for an electrochemical process. For example, there must be a cathode, anode and electrolyte present. If one of these elements is missing, the process cannot proceed. Cathode and anode are always present in the line. Liquid water is usually the electrolyte. If water is missing, no electrochemical reaction will occur and therefore no atomic hydrogen will be formed. That is why it is important to only transport dry gas. In addition, several studies have already shown that the presence of water is also undesirable because it leads to corrosion of the metals [27] [31].

In the European project NATURALHY various metals have been investigated with regard to the applicability of the gas network for the transport of hydrogen. Different types of steel (X70 and X50, including welding) were investigated under different conditions (pressure, varying mechanical stresses [fatigue]). No hydrogen embrittlement was observed during these experiments. The experiments were carried out in such a way that they correspond to a useful life of 40 years in practice.
The compressors in the national transport network are driven by gas turbines. These gas turbines are fed with gas from the gas network. When the gas composition in the grid changes, also the fuel quality for the gas turbines. The temperature in the turbine can go up to a maximum of 1,200 ° C and the temperature of the exhaust gases is 450-500 ° C [52]. These are sufficiently high temperatures to dissociate any hydrogen present and cause hydrogen embrittlement in the combustion gas side of the compressor. The risk of hydrogen embrittlement appears

to depend on the temperature, pressure and material for each steel type and will have to be assessed per situation [51].

Mechanical properties
The influence of hydrogen on the mechanical properties of different types of steel has been investigated. The results of a tensile test in a hydrogen environment at 69 bar at room temperature were compared with results under standard conditions (air, 1 bar gas pressure and room temperature) [53]. With the uncut A106 gr. B, X42 and X70 samples, hardly any difference was observed in the tensile strength. However, the elongation at break is A106 gr. B steel 21% smaller. With notched A106 gr. B and X70 samples have hardly seen any differences in tensile strength. For both the notched and notched materials, the flexibility of the materials decreases as a result of the exposure to hydrogen [53] [54].

Table III-1. The influence of 69 bar hydrogen on the tensile properties of A106 gr.B, X42 and X70 steel. [53]

Steel	Mechanical properties	Air	69 bar H_2	difference [%]
A106 gr. B	Upper yield stress [MPa]	462	503	8.9
	Tensile strength [MPa]	559	576	3.0
	Elongation at break [%]	14	11	-21.4
X42	Upper yield stress [MPa]	366	331	-9.6
	Tensile strength [MPa]	511	483	-5.5
	Elongation at break [%]	21	20	-4.8
X70	Upper yield stress [MPa]	584	548	-6.2
	Tensile strength [MPa]	669	659	-1.5
	Elongation at break [%]	20	20	0.0

Fracture toughness
Fracture toughness is resistance to fracture growth [53] [55]. The gas composition, the applied voltage and the gas pressure determine the fracture toughness. In comparison with pure methane, the fracture toughness for X70 steel at 69 bar with both hydrogen and a mixture of hydrogen and methane (60/40%) decreases by approximately 50% to a value of 95 MPa m1 / 2. This value is still rated high by the researchers [53]. The material is therefore still considered suitable. These results are in agreement with the results from NATURALHY, in which a reduction of 30-50% with respect to natural gas was observed with a hydrogen pressure of 69 bar [13]. The fracture toughness of X42 steel decreases by 13-30% due to the influence of 20 bar of hydrogen [53].

Fatigue
Fatigue is the occurrence and cracking of a fracture under the influence of a cyclic load. In general, hydrogen accelerates the crack growth of the metal. This is partly dependent on the gas composition, in which, for example, oxygen and carbon monoxide counteract the increase in the cracking speed [53]. No fatigue increase was observed with a gas mixture of 75/25 (natural gas / H2) for X70 steel and 50/50 (natural gas / H2) for X52 steel. If the hydrogen content is increased, the crack growth rate increases. This effect can be counteracted by the addition of a small amount of oxygen. After adding 250-500 ppm oxygen to pure hydrogen, the fatigue is up metal the same size as natural gas [13]. Fatigue was not observed in the weld analysis of an X70 steel pipe [13] [19].

The maximum voltage intensity is calculated for an 8 bar gas network (7 MPa m½). This also takes into account periodic fluctuations in gas pressure and the influence of heavy traffic. From this it is concluded that the crack growth rate of X42 steel in a hydrogen environment according to BS7910 is acceptable [27] [56] [57] (crack growth

rate 0.01 µm / cycle). Based on the same calculation, the crack growth rate of X70 and X52 steel is also acceptable, regardless of the hydrogen concentration [13] [49].

Cast iron
There is little literature regarding the interaction of hydrogen with cast iron. Presumably the material behaves roughly like carbon steel. However, a study is known in which the influence of hydrogen on cast iron is simulated very quickly. The metal is contacted with charged hydrogen for 24 hours, causing hydrogen to accelerate to the metal surface. This process does not occur in practice. The conclusion is therefore that the tensile strength of cast iron hardly changes due to the exposure to hydrogen. The extension does decrease, the material becomes more brittle [58].
Many suppliers of repair and replacement technology for cast iron pipes guarantee the chemical resistance of their product to hydrogen [59].

Copper and aluminum
Copper is mainly used in connection pipes, while aluminum is used in house pressure regulators and gas meters. These materials are therefore used at relatively low pressure. During a pilot project, the materials were exposed to a hydrogen / methane mixture with a maximum of 20 vol% hydrogen for 4 years. After this period, the house pressure regulators and gas meters still functioned according to the standard, and visually no damage was observed. No leaks have been observed in the copper pipes and brass couplings due to hydrogen [15].

IV Compositions of sustainable gases in the future-proof gas network

This appendix contains the document submitted by Liander below (copied in full). (translated to English)

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Based on currently available knowledge, Liander, in collaboration with Kiwa, has drawn up the overview of gas compositions of sustainable gases below. This provides a picture of the gas compositions that can flow through our gas networks in the future. For gas and syngas in particular, several variants of gas quality are possible. It is less likely that the raw production quality (directly from digester / gasifier) will be transported over gas networks, therefore a more transportable quality (cleaned up) has been named for biogas and syngas.

The following sustainable gases have been named:
- Natural gas / green gas;
- LNG: although not included for the sake of completeness;
- Biogas (from fermentation);
- Raw biogas (directly from the digester);
- Cleaned biogas (transport quality);
- Syngas (from gasification);
- Raw syngas (directly from the gasifier);
- Methanising gas (initial cleaning and methanation);
- Hydrogen.

The table below shows the gas compositions of these sustainable gases:

Component	Unit	Aardgas / groengas	LNG	Ruw biogas (vergisting)	Geschoond biogas (vergisting)	Ruw syngas (vergassing)	Metha-nisering-gas	Waterstof Standard Industrial gas
Waterdauwpunt	°C @ barg	-10 C ° @ 8 barg		(nat)	-3 °C @ barg	6% water	?	-50 °C
Teerdaumpunt	°C @ barg					< 15		
Temperatuur	°C	5 – 20		0 – 50	40			
Methaan (CH_4)	mol %	70 – 100	81 – 98	40 – 68	40 – 68	15 – 30	20-55	0,001
Stikstof (N_2)	mol %	14,32	< 1	0 – 17	0 – 17	0 – 5	1-5	0,04
Zwavel (total)	mg/m^3(n)	16,5			250			
Anorganisch gebonden zwavel (H_2S)	mg/m^3(n)	0 – 5 (3 ppm)		10 - 4300 (2900 ppm)	240 (160ppm)	100-3000		
Mercaptanen	mg/m^3(n)			< 20 ppm		100		
Odorant (THT)	mg/m^3(n)	10 – 40 (nom. 18)						
Chloorhoudende componenten (uitgezonderd HCl)	mg/m^3(n)	< 5		0 – 735	0 – 735	Sporen		
Fluorhoudende componenten	mg/m^3(n)	< 5		0 – 256	0 – 256	Sporen		
Ammoniak (NH_3)	ppm	< 0,1		0 – 100	100	4000	0-500	
Waterstof chloride (HCl)	ppm	< 1,0		sporen	sporen	400		
Waterstof cyanide (HCN)	ppm	< 1,0		sporen	sporen	3000		
Koolstof monoxide (CO)	ppm	< 100				100.000-500.000	0-20.000	10
Koolstof dioxide (CO_2)	ppm	8900		240.000 – 520.000	240.000 – 520.000	100.000 – 3000.000	100.000-350.000	10
Aromatische koolwaterstoffen	ppm	500		sporen	sporen			
Benzeen	ppm			0 – 36	0 – 11,4	10.000 – 40.000		
Tolueen	ppm			0 – 290	0 – 76,2	1000 – 10.000		
Zuurstof (O_2)	ppm	< 100		0 – 26000	1 mol %	0		10
Waterstof (H_2)	vol %	< 0,5		0 – 190 mg/m^3	0,2	7 – 30	20-50	➢ 99,95 %
Ethaan (C_2H_6)	mol %	0,06 – 15	2 – 14	sporen	Sporen	0 – 4		
C_2H_y (behalve C_2H_6)	mol %			sporen	Sporen	1 – 25		
C_3H_y	mol %	0 – 10	0 – 4	sporen	Sporen	0 – 10		
C_4H_y	mol %	0 – 3,5	0 – 2	sporen	Sporen	0 – 4		
C_5H_y	mol %	0 – 0,6		sporen	Sporen	0 – 0,3		
C_xH_y	mol %	sporen		Sporen	Sporen	sporen		
Fosfine	mg/m^3(n)			< 0,7	< 0,7			
Silicium houdende componenten	mg/m^3(n)	< 0,1		< 20	< 20			
Metalen (koper, kwik)	ppm	Sporen	Sporen	Sporen	Sporen	Sporen		
Teer	mg/m^3(n)					200		
Naphtaleen	mg/m^3(n)					2,5		

V Influence of biomethane on the distribution network

Plastics

The material properties of plastics can be influenced by a gas component through a number of mechanisms.

First of all, the component can chemically attack the polymer. This leads to chemical degradation. This requires that the component be able to react with the polymer under the prevailing conditions.

In addition, a component can be absorbed by the plastic. This causes the material to swell. The degree of swelling is highly dependent on the affinity between the plastic and the gas component. If the volume of the plastic does not change by more than 3% after exposure to the component, it can be said that the material is resistant to the relevant gas component [12].

The gas component can withdraw certain substances, for example additives or polymer, from the polymer. This reduces the mass of the plastic. If the mass does not decrease by more than 0.5%, the material is assessed as resistant [12].

The above-mentioned processes have been taken into consideration for assessing the resistance of the plastics to the gas components.

Polyethylene (PE)

No damage to PE is expected from the components that are present in biomethane. This is partly based on experiments, in which the influence of specific levels of gas components has been investigated. It cannot be excluded that the PE is still resistant above these levels. This is explained further below.

In the context of the EDGaR project, the chemical resistance of HDPE 50, MDPE 80 and HDPE 100 for a number of biogas components has been investigated. During these tests, the materials were exposed to different gas mixtures for 600 days at a constant tensile stress of 20 MPa. After this period, the mechanical properties of the materials were assessed using a tensile test. Changes in physical parameters (such as mass and volume) were also analyzed. Based on these experiments, it can be stated that PE is resistant to [33]:
- Hydrogen sulfide (H_2S) up to 160 ppm;
- dichloromethane (DCM) up to 1,000 mg / m3; used in the EDGaR study as a reference for chlorinated and fluorinated components;
- Ammonia (NH_3) up to 100 ppm.

Higher concentrations of the components were not investigated during the experiments [28]. Possibly, for example, the ammonia content in methanized syngas is equal to 500 ppm.

Silicones (a form of silicon-containing components) have a negative influence on the weldability of PE. Organic silicones can occur in biomethane. Therefore, the weldability of PE was investigated in the context of the EDGaR project, after a PE tube had been in contact with organic silicones for 90 days. After this period, butt weld and electrofusion connections were made. The butt welds are made in accordance with NEN 7200 "Plastic pipes for the transport of gas, drinking water and waste water" [60]. The electro welds are made according to the manufacturer's instructions. The butt welds were then tested in accordance with NEN 7200 and the electro-welds in accordance with ISO 13953. The compounds tested met all the criteria. PE tubes are therefore weldable after contact with organic silicones.

Literature studies have also been carried out for EDGaR. Based on the results of these studies, it was assessed that PE is resistant to oxygen (O_2) and carbon dioxide (CO_2). It also follows from these studies that PE is sensitive to higher hydrocarbons (benzene, toluene, etc.). This is particularly the case for liquid hydrocarbons (gas condensate). The presence of liquid hydrocarbons must therefore be prevented [27]. It is unknown whether, and if so to what extent, this occurs in methanized syngas.

For a literature study for GERG, the resistance of PE was assessed for carbon monoxide (CO), hydrogen cyanide (HCN), hydrogen sulphide (H_2S), ammonia (NH_3), chlorinated and fluorinated components. Relatively short-term resistance tests under standard pressure according to (ISO / TR 10358 [18] and PPI TR-19 [61]) indicate that PE is resistant to CO, HCN, H_2S and NH_3 up to a temperature of 60 °C. However, the resistance to chlorine and fluorine-containing components is not clear. The chance of attack by these gas components is estimated to be low [31]. Based on tests according to ISO / TR 10358 [18], PPI TR-19 [61], PE is resistant to hydrogen chloride, phosphine and sulfur [12], although no lengthy experiments have been carried out to confirm this. However, the experiments were carried out at very high concentrations (often up to 100%) and high temperatures (60 °C). Because of the relatively low content of components in the biomethane, it is therefore assumed that PE is also resistant to these components in the long term.

Polyvinyl chloride (PVC)
No degradation of PVC is expected by the gas components that are present in biomethane. This is based on experiments in which the influence of specific levels of gas components has been investigated. It cannot be excluded that the PVC is still resistant above these levels. This is further explained below.

The EDGaR project has assessed the resistance of hard PVC and impact-resistant PVC (PVC-CPE and PVC-A). The samples were exposed to various biomethane components for 600 days, with the materials experiencing a constant tensile stress of 20 MPa. The degradation of the materials was assessed on the basis of physical and mechanical measurements. Based on these experiments, it has been established that PVC is resistant to [33]:
- Carbon dioxide (CO_2) up to 59 mol%;
- Hydrogen sulfide (H_2S) up to 160 ppm;
- dichloromethane (DCM) up to 1,000 mg / m^3; used in the EDGaR study as a reference for chlorinated and fluorinated components;
- Ammonia (NH_3) up to 100 ppm.

Higher concentrations of the components were not investigated during the experiments. For example, the content of ammonia in methanized syngas may be higher than 100 ppm [28].
From the literature studies that have been conducted in the context of the EDGaR research, it has been established on the basis of various sources that PVC is resistant to hydrocarbons, provided that these are not present in liquid form (gas condensate) for long periods of time [27] .

Based on tests in accordance with ISO / TR 10358 [18], PPI TR-19 [61], PVC has been assessed as resistant to ammonia, carbon monoxide, hydrogen chloride, hydrogen cyanide, phosphine, oxygen and sulfur up to a temperature of 60 °C [12]. This concerns relatively short-term experiments at standard pressure. The experiments were performed at very high concentrations (often up to 100%) and high temperatures (60 °C). Because of the relatively low content of said components in biomethane, it is therefore assumed that PVC is also resistant to these components in the long term.

Nitrile Butadiene Rubber (NBR)
NBR may not be resistant to acids and oxidizing substances. This makes the material potentially sensitive to hydrogen chloride and hydrogen cyanide. The degree of degradation in that case does depend on the concentration. The influence of phosphine is unknown. NBR is, with limitations, resistant to ammonia, hydrocarbons, chlorine and fluorine-containing components, hydrogen sulphide, oxygen and elemental sulfur. This is further explained below.

The resistance of NBR to various gas components was assessed in the context of the EDGaR project. The rubber was exposed to the various gases for 600 days. Based on the physical and mechanical properties, it has been assessed that NBR is resistant to:

- Propylene (C_3H_6) up to 2% by volume; used in the EDGaR study as a reference for hydrocarbons;
- Carbon dioxide (CO_2) up to 59%;
- Hydrogen sulfide (H_2S) up to 160 ppm;
- dichloromethane (DCM) up to 1,000 mg / m3; used in the EDGaR study as a reference for chlorinated and fluorinated components;
- Ammonia (NH_3) up to 100 ppm.

Higher concentrations of the components were not investigated during the experiments. Possibly the content of ammonia and propene in methanized syngas is higher than the investigated concentrations [28]. The effect of these higher concentrations on NBR is unknown.
The EDGaR literature studies have shown that NBR is not resistant to liquid hydrocarbons (gas condensate). NBR is resistant to carbon monoxide.
If sufficient antioxidants (a protective substance against degradation by oxygen) are present, the material is also resistant to oxygen [27]. Based on tests conducted in accordance with ISO / TR 7620 "Rubber Materials - Chemical Resistance" [17], it appears that NBR is resistant to ammonia, carbon dioxide, carbon monoxide, water and oxygen [12]. The experiments were carried out at high concentrations (up to 100%) and at high temperature (60 ° C) for relatively short periods. Because these components are present in the gas network at low levels and at low temperatures, it is assumed that NBR is resistant to these components.

Based on the same research [12], it has been established that NBR is poorly resistant to a combination of high concentrations of acids, such as hydrogen sulfide, and the presence of water. The volume of the rubber changes by more than 60% and the hardness changes by more than 30 IRHD. The experiments were carried out at high concentrations (up to saturation) in aqueous solutions and for a short period under standard pressure. These are circumstances that will not normally occur in the gas network. When using biomethane, however, it cannot be excluded that such a combination may occasionally occur. In that case, the NBR will be able to relegate and (partly) lose its function.

Polyoxymethylene (POM)
POM is not very resistant to hydrogen chloride (3 ppm) at high relative humidity (82%) [16]. In addition, the material may be sensitive to hydrogen cyanide. The effects of the concentrations present in biomethane are unknown. It has been established that degradation occurs at higher concentrations. The influence of carbon monoxide and phosphine is unknown. For the other components that may be present in biomethane, the material is, with limitations, resistant to ammonia, hydrocarbons, chlorinated and fluorinated hydrocarbons, carbon dioxide, hydrogen sulfide and elemental sulfur. This is further explained below.

As part of the EDGaR project, POM (homopolymer) has been exposed to various biogas components to assess the resistance of the material. The samples were

exposed to different gas mixtures for 600 days. Based on physical and mechanical properties, it has been established that POM is resistant to [16]:
- Carbon dioxide (CO_2) up to 59 mol%;
- Hydrogen sulfide (H_2S) up to 160 ppm;
- dichloromethane (DCM) up to 1,000 mg / m3; used in the EDGaR study as a reference for chlorinated and fluorinated components;
- Ammonia (NH_3) up to 100 ppm.

Higher concentrations of the components were not investigated during the experiments. For example, the content of ammonia in methanized syngas may be higher than 100 ppm [28]. The influence of this content higher than 100 ppm NH3 will have to be assessed separately.

POM is not resistant to 3 ppm of hydrogen chloride (hydrochloric acid) at a relative humidity of 82%. This resulted in a reduction in the tensile strength. Local attack in the form of pits was also observed [16]. From the EDGaR literature study it follows that POM is very resistant to hydrocarbons (both aliphatic and aromatic). However, POM is not resistant to strong bases, acids and oxidizing agents, such as, for example, hydrogen chloride, hydrogen cyanide and hydrogen sulfide [41], which is in accordance with the previously reported sensitivity to hydrochloric acid.

Metal

After excavation damage, external corrosion is the most common failure mechanism for metal pipes. Internal corrosion is strongly influenced by the gas composition. The presence of water is a precondition for corrosion. Corrosion can already take place at a relative humidity of 60-70%. Therefore, based on EDGaR research, it is recommended to keep the relative humidity below 70%. In addition, water can also enter the gas network via the pipe itself, for example due to leakage, drainage or permeation [27].

Unlike for plastics, the gas composition is very important for the resistance of the metal to corrosion. It is known from the professional literature that steel in combination with carbon dioxide forms a protective layer of iron carbonate ($FeCO_3$). This carbonate layer functions as a barrier, reducing the corrosion rate. Hydrogen sulphide prevents the formation of this protective layer, which increases the corrosion rate. Thus, it may be that the resistance of a metal to CO_2 is sufficient, but to CO_2 with a small amount of H_2S is insufficient. With this insight, the corrosion rate of various metals (steel, copper and aluminum) with different gas mixtures (CO_2, O_2 and H_2S) was investigated within the EDGaR study [27].

Steel

Hydrogen chloride and elemental sulfur in combination with water may be harmful to steel because they can cause pitting corrosion. A gas mixture of carbon dioxide, oxygen and hydrogen sulphide is very corrosive at certain levels (corrosion speed up to 1.13 mm / year in the presence of liquid water). A gas mixture of carbon dioxide, carbon monoxide and oxygen can be corrosive to steel. However, this is not supported experimentally. Ammonia, chlorine and fluorine-containing components and hydrogen cyanide are likely to have little influence on the corrosion rate of the steel, partly due to the low content of these substances in biomethane. For the hydrocarbons, it is expected that they have hardly any influence on the degradation of steel. This is further elaborated below.

There are many different types of steel, in which the material composition, the tube production, the age, etc. influence the material properties. For the sake of clarity, a selection is made in this consideration of samples that are often used in the distribution network. This selection consists of; ST 37/235, ASTM A106 gr. B, API 5L gr. B and - albeit to a lesser extent - stainless steel. Stainless steel is used within gas distribution only for measuring pipes with a small diameter in gas stations and as a flexible gas meter connection. Stainless steel of the type 316 L or 316 Ti is usually

used for this.

Carbon dioxide, oxygen and hydrogen sulfide
In the EDGaR study, the corrosion rate of steel (St 37/235) at different carbon dioxide, oxygen and hydrogen sulphide gas mixtures and under different conditions was determined. In all experiments, the steel sample was kept partly in liquid water and partly in the vapor phase. This allowed the influence of liquid water to be taken into consideration. It should be noted that the relative humidity of the gas phase was therefore 100%. The following emerged from the experiments [33].
In the presence of liquid water, a relatively high degree of corrosion occurs under the following conditions:
- A carbon dioxide / oxygen gas mixture of 50 mol% CO_2 and 3 mol% O_2, respectively, resulted in a corrosion rate of 1.13 mm / year at a pressure of 30 mbar;
- An oxygen / hydrogen sulfide gas mixture of 0.5 mol% O_2 and 34 ppm H_2S, respectively, resulted in a corrosion rate of 0.13 mm / year at a pressure of 30 mbar;
- A carbon dioxide / oxygen / hydrogen sulphide gas mixture of 10 mol% CO_2, 0.1 mol% O_2 and 34 ppm H_2S, respectively, resulted in a corrosion rate of 0.32 mm / year at a pressure of 30 mbar;

A relatively high degree of corrosion occurs in the gas phase under the following conditions:
- A carbon dioxide / oxygen / hydrogen sulfide gas mixture of 50 mol% CO_2, 0.01 mol% O_2 and 160 ppm H_2S, respectively, at a pressure of 8 bar resulted in a corrosion rate of 0.18 mm / year.

In the gas phase, an acceptable value of the corrosion rate for steel occurs under the following conditions:
- A carbon dioxide / oxygen / hydrogen sulphide gas mixture up to 50 mol% CO_2 and up to 160 ppm H_2S with less than 30 ppm O_2 or with 3 mol% O_2. The corrosion rate has a non-linear correlation with the oxygen content. There is a maximum between 30 ppm and 100 ppm O_2. The exact location and influence of this optimum has not been established experimentally. At a pressure of 30 mbar, this resulted in a corrosion rate of less than 0.07 mm / year.

The experiments were carried out at a temperature of 25 °C. The temperature is in practice lower than the test temperature. As a result, the corrosion speed is also lower in practice. In addition, some experiments were carried out at a relatively low pressure. With increasing pressure, the partial pressure (the pressure of one gas component relative to the absolute total gas pressure) of the gas components increases, which in turn increases the corrosion rate.

Carbon dioxide, oxygen and carbon monoxide
Carbon monoxide and carbon dioxide can result in stress corrosion in the presence of water. The influence of oxygen on this process is still unclear. For example, one source [62] reports that oxygen slows down corrosion, while another source [63] reports that oxygen accelerates corrosion. Due to this uncertainty, stress corrosion cannot be excluded [27].

Other gas components
Carbon steel is widely used for the transport of ammonia at very high concentrations. It is known that ammonia in combination with oxygen can result in stress corrosion, whereby carbon dioxide can influence the process. Due to the low content of oxygen and ammonia, a limited influence of these gas components on the corrosion rate is expected. However, this is not supported experimentally [33].

Hydrogen sulfide forms a corrosive medium with water. It can cause hydrogen embrittlement and stress corrosion. If the partial gas pressure remains below 3 mbar (333 ppm at 8 bar) and the pH remains above 3.5, then hardly any damage to steel is observed. A passive FeS layer is also formed by oxidation. This reduces the corrosion speed. Hydrogen cyanide, however, affects the passive oxide layer of FeS. This increases the corrosion rate with increasing H_2S concentration [31]. Due to the low content of H_2S, hardly any influence of these components on the total corrosion rate is expected. Hydrogen cyanide can result in stress corrosion in the presence of water. The influence of the HCN content in biomethane on the corrosion rate of the steel is unknown [31].

Chlorine ions and / or fluorine ions can strongly influence the corrosion of steel. This usually results in pitting corrosion. These elements do not affect corrosion if chlorine or fluorine is strongly bound to the hydrocarbons. If the chlorine and fluorine-containing components do not disintegrate into chlorine and fluorine ions in the presence of water, no adverse effects are expected. Hydrogen chloride is capable of separating chlorine ions and is therefore harmful in combination with water [27].

Steel is used extensively in practice in the use of hydrocarbons. Therefore, no impact on steel is expected for hydrocarbons [27].

Elemental sulfur is a strong oxidizer. In the presence of liquid water, it can cause very local corrosion (pitting corrosion) [31]. The influence of elemental sulfur has not been determined experimentally.

Cast iron
Within the EDGaR project, no research has been carried out on gray or ductile cast iron pipes. They are expected to corrode in the same way as steel [33].

Copper and copper alloys
At a content of 3% O_2 and 160 ppm H_2S at a relative humidity of 100%, the gas mixture is corrosive to copper (corrosion rate up to 0.19 mm / year). At lower levels of O_2 and / or H_2S, the corrosion rate is relatively low. The corrosion rate is also low at 50 ppm ammonia. In view of the low content of carbon monoxide and hydrogen cyanide in biomethane, the influence of these components on the corrosion rate will be limited. For hydrocarbons, it is expected that they have hardly any influence on the degradation of copper and copper alloys. This is discussed further below.

Carbon dioxide, oxygen and hydrogen sulfide
In the EDGaR project, the corrosion rate was determined for copper, various carbon dioxide, oxygen and hydrogen sulphide gas mixtures and under various conditions. In all experiments, the copper sample was kept partly in liquid water and partly in the gas phase. This allowed the influence of liquid water to be taken into consideration. It should be noted that the relative humidity of the gas phase was therefore 100%. The experiments showed the following [33].

A relatively high degree of corrosion occurs in the gas phase under the following conditions:
- An oxygen / hydrogen sulfide gas mixture of 3 mol% O_2 and 160 ppm H_2S, respectively, at a pressure of 30 mbar results in a corrosion rate of 0.08 mm / year. If 50 mol% CO_2 is mixed in, this results in a corrosion rate of 0.19 mm / year.

Copper is suitable in the gas phase under the following conditions:
- A carbon dioxide / oxygen / hydrogen sulphide gas mixture up to 50 mol% CO_2 and up to 160 ppm H_2S, if the O_2 concentration is lower than 3 mol% or a gas mixture up to 50 mol% CO_2 and up to 3 mol% O_2, provided the H_2S

concentration lower than 160 ppm. The exact location of this limit value for oxygen and hydrogen sulfide is not known. The corrosion rate at a pressure of 30 mbar is hereby less than 0.03 mm / year;

- A carbon dioxide / oxygen / hydrogen sulphide gas mixture of 50 mol% CO_2, 0.01 mol% O_2 and 160 ppm H_2S resulted at a pressure of 8 bar in a corrosion rate of 0.01 mm / year.
  The experiments were carried out at a temperature of 25 ° C. The temperature is in practice lower than this test temperature. As a result, the corrosion speed in the gas distribution network is slightly lower.

Ammonia
In the EDGaR project, no stress corrosion was observed for a copper alloy after 19 months of exposure to 50 ppm ammonia at a relative humidity of 50%. The applied voltage was above the voltage level that is present with normal installation of mechanical fittings [16]. It should be noted that ammonia is known for causing stress corrosion in copper [27] [31]. In addition, the ammonia concentration in biomethane can rise to 500 ppm [28]. It is therefore recommended to assess the influence of higher ammonia concentrations, in combination with oxygen, or to require a lower ammonia content in biomethane.

Other gas components
Copper and copper alloys are insensitive to dry carbon monoxide and to both dry and wet hydrogen cyanide. In the presence of water, carbon monoxide can result in corrosion. Experimental data regarding this corrosion are still lacking. The resistance to chlorine and fluorine-containing components is not clear [31]. If the chlorine and fluorine-containing components do not disintegrate into chlorine and fluorine ions in the presence of water, no adverse effects are expected. Hydrogen chloride is capable of separating chlorine ions and is therefore harmful in combination with water [27].

Copper is in practice frequently used without problems for the transport of hydrocarbons. Therefore, no influence on copper is expected for hydrocarbons [27]. Hydrogen sulfide in combination with elemental sulfur results in an increase in the corrosion rate. Elemental sulfur can cause local degradation, resulting in pit corrosion [31]. The influence of elemental sulfur has not been determined experimentally.

Aluminum
Aluminum is highly resistant to gas mixtures of oxygen and hydrogen sulphide, provided that carbon dioxide is present. In addition, with restrictions, no influence of ammonia, hydrocarbons, carbon monoxide, chlorine and fluorine-containing components and hydrogen cyanide. Hydrogen chloride is potentially harmful to aluminum. This is further explained below.

The research of EDGaR [33] shows that cast aluminum (such as is used with house pressure regulators, for example) is highly resistant to hydrogen sulphide in combination with carbon dioxide. The material has been tested with different carbon dioxide / oxygen / hydrogen sulfide gas mixtures under different conditions. The samples were partly exposed to water and vapor, where a relative humidity of 100% prevailed. No corrosion was observed with gas mixtures having a pressure of 30 mbar from 10-50 mol% CO_2 to 3 mol% O_2 and up to 160 ppm H_2S. Only in the absence of carbon dioxide did corrosion occur in the aqueous phase at 3 mol% O_2 and 160 ppm H_2S and at 0.5 mol% O_2 and 34 ppm H_2S with corrosion rates of 0.31 and 0.19 mm / year, respectively.

In addition, aluminum has also been found to be resistant to a gas mixture of carbon dioxide / oxygen / hydrogen sulphide with 50 mol% CO_2, 0.01 mol% O_2 and 160 ppm H_2S at a pressure of 8 bar. Negligible little corrosion was observed here.

It follows from the literature study by EDGaR that aluminum has a good resistance to ammonia and hydrocarbons [27]. A GERG study describes that, based on literature, carbon monoxide has no influence on aluminum. Hydrogen cyanide also has no influence on aluminum, provided that in combination with water this does not result in an acidification of the environment (pH <4). Aluminum has good resistance to ammonia, provided that no copper is used in the aluminum alloy (such as for example in the 2,000 and 7,000 series). The resistance to chlorine and fluorine-containing components is not clear [31].

If the chlorine and fluorine-containing components do not dissociate in the presence of water in chlorine and fluorine ions, no adverse effects are expected. Hydrogen chloride is capable of separating chlorine ions in aqueous environments. This often results in pitting corrosion. In addition, hydrogen chloride is a strong acid, which can result in general corrosion, because the oxide skin dissolves at a pH below 4 [27].

Remaining materials

Asbestos cement
Asbestos-cement pipes consist of various components. The tubes are made of asbestos, cement (calcium hydrogen silicate) and silica (very fine sand particles). Asbestos is thermally very stable and chemically resistant. No damage to the asbestos is expected. Colin Bowker describes a process in which water in combination with hydrogen sulfide results in the leaching of the calcium component. As a result, the binding force in the tube wall is lost, whereby the mechanical strength is lost [64]. Other acid components are also capable of leaching the calcium. This relates, for example, to hydrogen cyanide and hydrogen chloride. The condition is, however, that sufficient liquid water must be present, so that this leaching can take place. Under normal circumstances, such a situation in the gas network will not occur, so that the danger of gas leaching of cement from the gas is negligible.

VI Permeation

When examining the suitability of the current gas distribution network for the transport of hydrogen, it is not only necessary to ascertain whether the gas network is resistant to hydrogen, but also to examine the influence of the gas network on the quality of the hydrogen, which via the just being transported. We distinguish two processes in the latter aspect:

- Permeation of components from the environment of the line to the hydrogen gas;
- Evaporation of natural gas components that are adsorbed in / on the inner wall of the pipeline.

In addition, it is important to gain insight into the extent to which hydrogen permeates through the wall of a - in particular - plastic pipeline.

Permeation from the environment
All plastic pipes in the gas distribution network suffer from permeation. This concerns both certain components of the gas to be transported (permeation from inside to outside), and for components in the immediate vicinity of the gas pipes (permeation from outside to inside). The components present in the vicinity of the gas line, such as water (vapor), nitrogen and oxygen (the most important components from the air), can thereby permeate through the wall from outside to inside. The driving force behind permeation is the absolute pressure difference of the component to be considered. In the case of oxygen, the prevailing partial pressure on the outside of the pipe will be approximately 0.2 bar (a). When pure hydrogen is fed in, the partial pressure of oxygen on the inside of the pipe will be approximately 0 bar (a). Due to this pressure difference, some oxygen will always permeate through the tube wall. A similar process also takes place for water vapor and nitrogen. The consequence of this is that the pure hydrogen is gradually contaminated with oxygen, water vapor and nitrogen. Because the required purity of the hydrogen for the current generation of PEM fuel cells cannot be achieved as a result, the use of hydrogen that is supplied via a (partly) plastic gas distribution network in such fuel cells without an additional cleaning step in the vicinity of the fuel cell will not be achieved. to be possible.
The permeation of water vapor can be considerably greater for pipes that are below groundwater level (controlled drilling) than for pipes exposed to air and dry soil.

Evaporation of natural gas components
As indicated above, some applications, such as PEM fuel cells, require a high hydrogen purity. However, the question is whether this high purity can be guaranteed if we use the existing gas distribution network. During its use for the distribution of natural gas (and perhaps before that of city gas), certain gas components have adhered to the (metal or plastic) pipe wall through adsorption. In the case of plastics, some natural gas components may also be included in the pipe wall (absorption). If natural gas is switched to hydrogen, the existing balance between the concentrations of components in the gas and the concentrations in or on the pipe wall will be disturbed and a new balance will be established. During this process, the gas components that were previously adsorbed or absorbed will be released again. These can for example be higher hydrocarbons, but also THT. How fast this process of releasing this components expires is unknown. For THT it is known from practice that plastic pipes still smell of THT months after being removed from the network.

Now THT has a very low odor limit (order of magnitude of a few ppb), but the sulfur in the THT is harmful to PEM fuel cells. The significance of this for practice is that natural gas components, albeit in decreasing and low concentrations, are still to be found in the hydrogen during the first months after switching from natural gas to hydrogen.

Permeation of hydrogen

The permeation of a medium by a material is dependent on very diverse factors. These factors can be divided into three groups: the material, the medium and the circumstances. For example, the type of pipe material, the manufacturing method of the pipe, the wall thickness, the connection between the pipes, the gas composition, the temperature and the gas pressure determine the permeation of hydrogen [65] [66] [67] [68]. The actual permeation therefore differs per situation and research results vary with the circumstances in practice.

At greatly elevated pressure, the permeability to hydrogen of materials can change because the material structure changes as a result of the pressure. In LDPE, the permeation coefficient for hydrogen remains practically the same, even at a 100 atmospheric pressure [69]. The expectation is that this also applies to the MDPE and HDPE used in gas distribution. No effect on permeation has been observed for PE80 and PE100 if hydrogen is mixed with natural gas. The permeation coefficient of PE 80 and PE 100, measured after aging at 60 ° C, was found not to change [13]. For hydrogen it can therefore be said that changes in pressure and physical aging of the material are not expected to lead to a change in the permeation behavior of PE for hydrogen.

The permeation coefficient is strongly influenced by the ambient temperature and the crystallinity of the PE. For a certain type of HDPE, the permeation coefficient of hydrogen has been determined at a pressure of 17 bar at three different temperatures, see Table VI-1. The strong temperature dependence of the permeation coefficient is also described by J. Humpenoder. His study shows that the permeation of a gas proceeds according to an Arrhenius equation [70]. The permeation coefficient therefore differs per material and the results mentioned depend strongly on the temperature at which the analysis was carried out. This must be taken into account when comparing different studies.

Table VI-1. Permeation coefficient of HDPE at 17 bar hydrogen [65]

Temperature (°C)	Permeation coefficient $(cm^3*mm)/(m^2*atm*day)$
-15	31.9
25	156
68	761

The permeation coefficient of HDPE around room temperature is 108-156 $(cm^3 * mm)$ / $(m^2 * day * atm)$ for hydrogen and for methane 21-56 $(cm^3 * mm)$ / $(m^2 * day * atm)$ [65] [71] [72]. In practice, the permeation coefficient will be lower, because the soil temperature is lower. Under equal conditions, the permeation of hydrogen is therefore 3-5 times higher than for methane. However, the energy value of hydrogen is 3 times lower than that of G-gas, 12 MJ / Nm^3 and 35 MJ / Nm^3, respectively [73] [74]. Based on the permeability of HDPE, the loss in energy value due to leakage is therefore greater for hydrogen than for natural gas [75]. NATURALHY states that the permeation of hydrogen through PE tubes is 6 to 7 times higher than for methane, which roughly results in a doubling of the loss in energy value compared to natural gas [13]. DNV-GL states that the transport of hydrogen through polyethylene is approximately 5 times higher than for natural gas [74].
Fewer sources are available about the permeation of methane and hydrogen by PVC. For example, the permeation of water vapor is mentioned in [65], but not for hydrogen. From [76] and previously collected permeation coefficients for PVC, these for hydrogen at 20 ° C appear to vary between 100 - 115 $(cm^3 * mm)$ / $(m^2 * day * atm)$. For comparison: the permeation coefficient for methane mentioned in [76] is 1.9 $(cm^3 * mm)$ / $(m^2 * day * atm)$.

Estimation

To form an image of the influence of permeability on the total gas emission, an estimate has been made of this. Three calculations were made for this:

1. The permeation of hydrogen by HDPE.
    a. For a 110 mm SDR-11 tube.
    b. At the maximum gas pressure of the low-pressure distribution network (100 mbar) and the high-pressure distribution network (8 bar), as well as at a gas pressure of 200 mbar.
    c. The connections between the pipes are not included in the calculation. Because these are often welded, they are assimilated to the pipe material with regard to permeation.
    d. The permeation coefficient is assumed to be 156 (cm^3 * mm) / (m^2 * day * atm) [65]. This value is based on the highest measured permeation coefficient at 25°C.

2. The permeation of hydrogen through hard PVC without compounds.
    a. For a 110 mm SDR-41 tube.
    b. At the maximum gas pressure of the low-pressure distribution network (100 mbar) and at a gas pressure of 200 mbar.
    c. The connections between the pipes are not included in the calculation.
    d. The permeation coefficient is assumed to be 112 (cm^3 * mm) / (m^2 * day * atm) [76]. This value is based on the highest measured value of the permeation coefficient.

3. The permeation of hydrogen by PVC-HI including compounds.
    a. In NATURALHY the permeation for 110 mm tubes has been determined [13]
    b. For PVC-HI, the compounds are included in the analysis.
    c. The test temperature was 16°C and test pressure was 200 mbar.

The results of the calculation are shown in Table VI-2.

Table VI-2. Hydrogen permeation through 110 mm tubes of HDPE and PVC HI

m^3/(km.year)	100 mbar	200 mbar	8 bar
HDPE	1.9	2.1 (and 1.9*)	15.9
PVC without connections	5.6	6.1	-
PVC-HI incl. connections	-	(4.8*)	-

* values are from NATURALHY where other materials and test conditions have been applied

In Table VI-2 it can be seen with HDPE at 200 mbar that the calculation differs little from the measured value from NATURALHY. The difference is caused by testing under different circumstances.

It is striking that PVC with compounds has a lower hydrogen permeation compared to PVC without compounds. This difference is probably caused by the different test conditions. However, this gives a strong suspicion that PVC compounds have little influence on the total loss of hydrogen. This assumes that PVC connections are relatively leak-proof.

Every year an estimate is made of the methane emissions as a result of the gas distribution. This estimate is based on the leaks present in the distribution network and the permeation of methane through the tube wall. For PVC-HI and PE it is

assumed that 51 m^3 methane / (km.year) for the low pressure distribution network (up to and including 100 mbar) and 75 m^3 methane / (km.year) for pressures above 200 mbar are lost [42]. The permeation of hydrogen is far below these values and has a relatively small contribution to the total gas emission.

The transition from natural gas to hydrogen will also influence the loss of transported gas as a result of leaks. This depends on the properties of the gas. For example, the density of hydrogen is lower than the density of methane, 85.5 and 678.6 g / Nm^3, respectively. As a result, hydrogen leaks faster from openings than, for example, methane. Under equal conditions, a proportion of 2.8 times more hydrogen leaks than methane (in volume). The energetic value of hydrogen is 3 times lower compared to methane, 12 MJ / Nm^3 and 35 MJ / Nm^3, respectively [73] [74]. The loss in energy value due to leakage is therefore approximately the same for hydrogen as for methane [75] [77].

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VII Calculation of maximum acceptable concentration

In this appendix the underlying information is given, which has led to table 5-1 "Maximum permissible concentration of components in biomethane based on Time-weighted Average Limit values".
An example calculation is also performed for determining the maximum acceptable concentration of a gas component in biomethane.
This calculation is based on the following assumptions:

- The LEL (Lower Explosion Limit) of biomethane is (assumption) approximately 10% in air.
- The TGG8 limit value (Time-weighted Average Limit value for 8 hours; equivalent to the previously used MAC value) [32] of the gas component depends on the type of gas component.
- Work is being carried out in accordance with the current VIAG.

According to the VIAG, it is not permitted to work at a gas concentration above 10% LEL. In this case work may therefore be carried out up to a gas concentration of:

$$10\% \text{ (LEL)} * 10\% = 1\%$$

At this gas concentration, the gas component must not exceed the TGG8 value. Because the biomethane is diluted 100 times in this situation, the content of a certain component of the biomethane may therefore be 100 times higher. The maximum acceptable concentrations of the various components that can occur in biomethane calculated in this way are shown in Table VII-1.

Component		TGG8-valve mg/m^3 [32]	Calculated TGG8 [ppm$_v$]	Maximum acceptable concentration [ppm$_v$]
Ammonia	NH_3	14	18	1,800
Benzene	C_6H_6	0.7	0.2	20
Phosphine	PH_3	0.14	0.1	10
Carbon dioxide	CO_2	9,000	5,000	500,000
Carbon monoxide	CO	29	23	2,300
Toluene	C_7H_8	150	36	3,600
Hydrogen chloride	HCl	8	5	500
Hydrogen cyanide	HCN	1	0.9	90
Hydrogen sulfide	H_2S	2.3	1.6	160

Table VII-1. Maximum concentration of components in biomethane based on TGG8 limit values.

Based on health and safety considerations, it is advised to adhere to the maximum permitted concentrations of the components in the right-hand column of this table.