HyDelta 2

WP7 – Conversion of natural gas distribution networks to hydrogen

D7.1 – Inventory of relevant aspects for conversion of gas distribution networks to hydrogen

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Executive summary

A model conversion plan is being developed in work package 7 of HyDelta 2 "Conversion of a natural gas distribution network to hydrogen" for large-scale conversion of gas distribution networks to hydrogen. This is done considering distribution networks from practice as case studies. The conversion plans for these practical case studies will be drafted based on the existing knowledge in and experience with converting distribution networks to hydrogen. This report is an inventory of the knowledge and experience that will be used when drafting the plans for the case studies. This report also provides an overview of the relevant aspects to be considered when drawing up a model conversion plan.

Projects and studies

Based on literature, an overview of hydrogen projects and conversion studies has been made. The overview includes 11 projects (mainly field tests and pilots) and 8 studies. Out of these 19 projects and studies, 14 are from the Netherlands, 3 from Germany and 2 from the United Kingdom.

Regulation

Similar to the natural gas market, regulation will apply to the hydrogen market. This regulation is still under development. The European Commission intends to amend the Gas Regulation and the Gas Directive for this purpose. In the proposed new regulation, among other things, a hydrogen distribution network will require a separate network operator, separate from the network management of the natural gas distribution network. If the natural gas distribution network is to be used for hydrogen, those assets must be transferred to the operator of the hydrogen distribution network.

In the absence of a specific legal framework (the current framework prohibits network operators from playing a role in hydrogen pilots), ACM has drawn up a Temporary Framework for Hydrogen Pilots for the next 5 years. A pilot must relate to the built environment and have a specific learning objective. Grid operators are allowed to distribute hydrogen through the grid, but have no role in the production, trade and supply of hydrogen.

Materials, components and technical knowledge and skills

Based on the available literature, an overview of components and materials present in the current gas distribution network and end-use installations, indicating whether they are suitable for hydrogen, or whether they need to be replaced or require adjustments has been made. In this overview for some components it is indicated that the suitability for hydrogen is not yet sufficiently known and that further research is required. An inventory was also made of the required technical skills and knowledge for the conversion.

Supply areas for hydrogen

Before plans can be made for the actual conversion of gas distribution networks to hydrogen, municipalities will draw up plans in consultation with property owners, residents and network operators (DSO and TSO) to determine which customers will continue to be supplied with gas or which will switch to another form of heat supply. In the areas where the gas supply is maintained, a choice is made for the type of sustainable gas: green gas or hydrogen.

For the built environment, the most cost-effective sustainable heat supply can be determined per neighbourhood, such as green gas or hydrogen supply. A similar consideration can be made for business customers (business parks, horticulture greenhouses). In the case of hydrogen, the basic principle is that the existing gas network of DSOs and TSO is used, because this is cost-effective and

accelerates implementation. A distribution network of a DSO consisting of a medium and low pressure network behind a city gate station (GOS) comprises several tens of thousands of customers. A low-pressure system just behind a district station provides about 250 to 500 home connections. There are major differences between distribution networks of a DSO in urban areas, rural areas and business parks. If the hydrogen supply is provided from the regional transport pipeline network of a TSO (RTL), other distribution networks and industry connected to this RTL network must be taken into account.

Hydrogen supply

Five situations can be distinguished for hydrogen supply, of which 4 relate to the supply of (almost) pure hydrogen. Delivery from a GOS that is connected to the high-pressure transmission line (HTL) hydrogen backbone via a regional transmission line (RTL) seems to be the most attractive in the long term, considering cost effectiveness and security of supply. Hydrogen supply areas behind a GOS can have a size of several tens of thousands of customers. Smaller hydrogen projects with several tens to hundreds customers, which will probably be the first to be developed, can be supplied with hydrogen via tube trailers and/or hydrogen produced locally with electrolysers. These projects can be scaled up at a later stage and connected to a GOS that supplies hydrogen from the RTL network connected to the hydrogen backbone. This will improve security of supply and reduce the need to store hydrogen locally. Hydrogen distribution networks that are fed from the hydrogen backbone will be the first to arise in the vicinity of this backbone and where RTL pipelines are converted to hydrogen transport, for example for supplying hydrogen to industrial customers.

Step-by-step plans

In some of the conversion projects and studies that were analysed, a step-by-step plan has been developed for the conversion of natural gas distribution networks to hydrogen. These step-by-step plans relate to the preparation and the actual implementation. Although the step-by-step plans are quite different and therefore difficult to compare with each other, they offer different starting points for developing a model conversion plan in the remainder of the study.

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1. Introduction

Hydrogen can be supplied via a gas distribution network to homes, non-residential buildings and businesses. This study is based on the distribution of (almost) pure hydrogen. For the distribution of hydrogen, the existing natural gas distribution network can be used after it has been made suitable for this purpose. The installations and gas appliances at the customers must also be made suitable for the application of hydrogen. The possibility of mixing hydrogen with natural gas (in a transitional phase) falls outside the scope of this research.

The aim of this part of the project (work package 7) is to draw up a model conversion plan (D7.3) for large-scale conversion of gas distribution networks to hydrogen. This model plan will be based on a number of concrete cases (D7.2). Before the cases can be worked out, an analysis has been carried out in this report (D7.1) into a number of aspects that are relevant to a conversion plan. These aspects can be divided into three categories:

1. Regulations

   The European Commission and the Netherlands Authority for Consumers and Markets (ACM), the State Supervision of Mines (SodM) and the Ministry of Economic Affairs and Climate Policy (EZK) have drawn up new regulations for hydrogen. This concerns, among other things, the role of network operators and offering security of supply to customers. Which (regulatory) preconditions must be taken into account?

2. Technology

   In order to be able to distribute hydrogen, natural gas distribution networks need to be technically adapted. For this, a number of questions need to be answered, such as: which components need to be replaced? Can this take place prior to the conversion or best during the conversion. How big are the sections that are converted at a time? What adjustments are needed at the customer's end ('behind the meter') and how can this be coordinated? How can flushing and purging of the pipes take place safely? What is the staffing need and what expertise is required, especially at the network operator? Etc.

3. Market

   Which gas distribution networks will be converted to hydrogen? To be able to answer this question, it will be necessary to know which customers will be supplied with hydrogen in the future. Scenarios drawn up by the network operators assume that 20% to 60% of households will be supplied with sustainable gas [1]. Renewable gas is green gas (methane) [1] or hydrogen. In two scenarios, the renewable gas consists entirely of green gas and is supplied to 20% of households, in one scenario 40% of households are supplied with green gas and 20% by hydrogen, and in one scenario 60% of households are supplied with hydrogen. In addition to households, hydrogen can also be supplied via gas distribution networks to business customers (utility buildings, companies) and possibly to hydrogen filling stations.

   A gas distribution network can be supplied with hydrogen in various ways. What does this mean for the conversion plan? In the future, hydrogen can be supplied via a regional transport

[1] The Climate Agreement sets an ambition of 2 BCM (billion m^3) of green gas (methane). The national government intends to realize sales of 1.6 BCM of green gas in the built environment through a blending obligation. This obligation imposed on gas suppliers can also be fulfilled with green certificates in addition to physical delivery.

pipeline (RTL network) that is connected to a national hydrogen network (HTL network). Hydrogen can also be produced locally from renewable electricity using an electrolyser. In addition, it is conceivable that networks with local production will be interconnected and/or supplied in due course from the national hydrogen network [2].

This report forms the basis for drawing up a model conversion plan and provides an overview of the important aspects that are relevant to a conversion plan. Possible knowledge gaps are also indicated. This overview is based on information about existing hydrogen projects, case studies and literature.

Chapter 2 provides an overview of existing hydrogen projects and conversion studies, both in the Netherlands and in a few countries outside the Netherlands. Chapter 3 describes the regulatory preconditions that must be considered when converting a gas distribution network to hydrogen. Chapter 4 provides an overview of the technical aspects that play a role in the conversion of gas distribution networks to hydrogen. Chapter 5, based on the information from the projects and reviewed studies, discusses various options for hydrogen supply and delivery. Finally, chapter 6 provides an overview of a step-by-step plan for converting natural gas to hydrogen networks derived from a number of conversion studies.

2. Hydrogen projects and conversion studies

Table 1 provides an overview of existing projects and known studies, based on available literature and other sources. Projects are pilot, trial or demo projects in which hydrogen has been physically supplied, often experimentally. Studies concern developed plans and conducted studies to convert a gas distribution network to hydrogen.[2]

Eight projects have been identified in the Netherlands where distribution or use hydrogen on a small scale is being considered. These projects currently concern a maximum of a few dozen dwellings. For some projects there are plans to expand to several hundred dwellings. The studies concern the conversion of gas distribution networks with hundreds to several thousand connections. This not only concerns dwellings, but also large-scale consumers (including so-called cluster 6 companies). The case studies by Alliander (Haarlem, IJmuiden, Drachten and Heerenveen) – based on learning experiences in the Lochem pilot – and the studies by Stedin (Stad aan 't Haringvliet, Gouda and Noord-Beveland) provide the most information about the challenges and possible solutions for converting gas distribution networks to hydrogen (see following sections). The study for Stad aan 't Haringvliet was carried out in preparation for the actual realization of the conversion.

Some publications have been found on projects and studies in Germany and the United Kingdom. A Hydrogen Network Plan has been drawn for the United Kingdom, including making natural gas distribution networks suitable for hydrogen [3]. The H21 study from Leeds provides information on retrofitting the gas distribution network. Most projects in Germany (more than 60 receive funding from the Bundesministerium für Wirtschaft und Klimaschutz) relate to large-scale hydrogen production, transport and industrial application. The LHyVE project in Leipzig is an exception to this and is also considering distribution of hydrogen to the built environment.

In the smaller pilot and demo projects, hydrogen is supplied from gas cylinders, tube trailers or produced with a local electrolyser. When using electrolysers, storage of hydrogen is required to maintain the supply/demand balance. When hydrogen is supplied to thousands of end users, the required hydrogen storage becomes very large. That is why the studies into the conversion of larger parts of the distribution network are based on connection, via the RTL network, to the national hydrogen network and the large-scale underground hydrogen storage connected to it.

[2] Studies precede projects. If there is an intention to actually distribute and supply hydrogen, then we speak of a project. We call it a study if there is no concrete intention to supply the distribution network with hydrogen.

Table 1 – Projects and case studies hydrogen distribution

Name	Location	Country	Type	Grid operator	Hydrogen supply	Hydrogen use	Reference
Entrance	Groningen	NL	Project		Local electrolyser	CV-boilers	[4]
Hydrogen district Wagenborgen	Wagenborgen	NL	Project	Enexis	Tube trailer (phase 1) Local electrolyser (phase 2)	Hybrid WP in 33 dwellings	[5]
Hydrogen pilot Hoogeveen	Hoogeveen	NL	Project	Cogas/Rendo	Tube trailer/local electrolyser	80-100 dwellings, then over 400	[6]
Temporary conversion Uithoorn	Uithoorn	NL	Project	Stedin	Gas bottles	14 dwellings	[7]
Hydrogen pilot Lochem	Lochem	NL	Project	Alliander	Tube trailer	10 monumental dwellings	[8]
Hydrogen pilot The Green Village	Delft	NL	Project	Alliander/Enexis/Stedin	Gas bottles	Project dependent	[9]
Hydrogen pilot P2G	Rotterdam	NL	Project	Stedin	Local electrolyser	Built environment	[10]
Hydrogen conversion	Stad aan 't Haringvliet	NL	Project	Stedin	Local electrolyser	600 dwellings	[11]
Analysis on splitting up the gas network	Gouda	NL	Study	Stedin	National hydrogen transport network	Urban area	[12]
	Noord-Beveland					Rural area	
H2.0	Haarlem	NL	Study	Alliander	National hydrogen transport network	Built environment, old town district	[13] [14]
	IJmuiden					Harbour district	
	Drachten					Built environment	
Theoretical study	Heerenveen	NL	Study	Alliander/Gasunie	National hydrogen transport network	5 industrial customers	[14]
LHyVE	Leipzig	DE	Study		National hydrogen transport network	Among others, built environment	[15]
H2HoWi	Holzwickede	DE	Project	Westnetz	Tube trailer	4 commercial buildings	[16]
H2Direkt	Hohenwart	DE	Project	Thüga	Tube trailer with green hydrogen	10 dwellings and a commercial building	[17]
H21	Leeds	UK	Study		Blue H2 via HTL/RTL network	Built environment	[18]
H100 Five	Buckhaven en Denbeath (Schotland)	UK	Project	SGN	Local electrolyser	300 dwellings	[19]

3. Regulations in relation to market design

3.1 Introduction market design

Market design is [20]:

> "(…) the set of rules and laws that describe which companies are allowed to operate on the market (entry regulation) and under what conditions (regulation of conduct), and also what options consumers have. Good market design is aimed at organizing markets in such a way that they can function optimally for the society."

By organizing a market, the government can adjust its development or functioning so that the public interests involved are sufficiently safeguarded [21]. For energy, the relevant public interests are affordability, reliability, sustainability, safety and spatial compatibility [22].

The market design for natural gas has evolved over the years. Since the turn of the century, under the influence of EU policy, efforts have been made to restructure and liberalize the gas market. This takes shape through a layered regulatory framework that regulates the gas market. The regulatory framework consists of:

- European legislation, in particular the Gas Directive, Gas Regulation, Security of Gas Supply Regulation and network codes.
- National legislation, in particular the Gas Act.
- National subordinate regulation, in particular Governmental Degrees (Algemene Maatregelen van Bestuur) based on the Gas Act, Ministerial Regulations and tariff structures and conditions set by ACM.

The regulatory framework includes, among other things, the elements shown in Table 2.

Table 2 – Elements of the current market design for natural gas

Element	Explanation
Demarcation segments	Different infrastructure segments are defined, such as transmission system, distribution system, storage facility and LNG facility.
Unbundling	Rules apply regarding the unbundling of various activities, such as the unbundling of network management on the one hand and production and supply on the other.
Third-party access	Market parties must be able to gain access to important infrastructure, such as transmission systems, distribution systems, storage facilities and LNG terminals, under non-discriminatory conditions.
Network tariffs	The network tariffs for access to the networks are regulated by an independent regulator.
Wholesale market	Rules on the operation of the wholesale market (entry-exit zones, balancing, capacity allocation, congestion management) are laid down in the regulatory framework.
Retail market and consumer protection	The starting point is that the retail market is a free market in which suppliers determine their prices and consumers choose their supplier. Under certain conditions, retail price regulation is also permitted for vulnerable and energy-poor households. In addition, various measures to protect consumers have been included in the regulatory framework. This concerns, for example,

	the right to switch suppliers, the right to a smart meter, the right to dispute settlement out of court or the right to price comparison.
Security of supply	Roles and responsibilities of parties with regard to security of supply are defined in the Security of Gas Supply Regulation. The policy is aimed at ensuring the supply to small consumers. There is a European infrastructure standard (N-1 transmission network criterion) and delivery standard (also delivery on cold days or in case of major interruption). Member States should draw up preventive action plans and contingency plans to ensure security of supply. In the event of an emergency, other Member States should provide support. Recently, an obligation to fill gas storage facilities has also been included in the Security of Gas Supply Regulation.

A similar regulatory framework for hydrogen is still lacking, but is under development. In December 2021, the European Commission proposed to amend the Gas Regulation and Gas Directive to make hydrogen infrastructure and hydrogen markets part of the regulatory framework (hereinafter: Decarbonisation Package) [23]. Although negotiations on the package are still ongoing, it is expected that the Decarbonisation Package will be broadly adopted [24]. Parts of the package may, of course, change as a result of the negotiations. The rules are expected to enter into force around 2025.[3]

The plans for the conversion of distribution networks will therefore in all likelihood have to be in line with this regulatory framework. In this chapter, we therefore discuss the market organisation as included in the Decarbonisation Package. In addition, we describe the obligations this entails for parties when converting the gas distribution network. In doing so, we will also address the question of whether it is necessary to establish additional rules when converting gas distribution networks in order to safeguard public interests.

In the period up to approximately 2025, there will be no specific rules for hydrogen. Although it is not expected that large-scale conversion of natural gas distribution networks to hydrogen will take place in the period up to 2025, pilots are expected to take place. In the absence of a specific legal framework, ACM itself has set certain requirements for hydrogen pilots in the built environment (hereinafter: Temporary framework hydrogen pilots) [25]. We also address these requirements.

3.2 Decarbonisation package

The proposed Decarbonisation Package makes hydrogen infrastructure and markets part of the regulatory framework for gas. The proposed market organisation for hydrogen therefore contains largely the same elements as for natural gas. However, there are a number of important differences per element. For some components, this will be subject to more flexibility during a transition period until 2031 to take into account the development phase of the hydrogen infrastructure and market. Table 3 provides an overview of this.

From Table 3 we can distil three common threads:

1. The proposed Decarbonisation Package sets out a number of concrete requirements that the parties involved in the changeover must meet. For example, a hydrogen grid operator must be established, unbundled from production and supply and should be designated and

[3] The amended Gas Directive will have to be transposed into national legislation. The amended Gas Directive is expected to be converted into the Energy Act around 2025.

certified. There must be clarity on the tariffs and conditions for access to the network. For determination of the level of tariffs, the transfer of the assets from the natural gas distribution system operator to the hydrogen system operator is an important step.

2. The proposed Decarbonisation Package was drawn up on the basis of the assumption that hydrogen will mainly be used by industry and heavy transport. It therefore appears that the rules do not take into account the supply of hydrogen via a distribution network to small consumers. This can have the consequence that without additional (national) policy when switching from natural gas to hydrogen, customers experience less protection (such as consumer protection or security of supply policy) and thus constitute an obstacle to switching from natural gas to hydrogen. When supplying hydrogen via the national hydrogen network, it seems possible to align the protection of hydrogen consumers with natural gas consumers at national level with additional policies.
3. The proposed Decarbonisation Package is based on a geographically large market in which – in theory – sufficient competition is possible between producers, non-underground hydrogen storage and hydrogen terminals. In events when hydrogen is not supplied via the national hydrogen network but in a different way (e.g. options 1 t/m 3 shown in *Figure 1*) it is quite conceivable that the market organisation proposed in the proposed Decarbonisation Package will not fit well with the actual situation. Supplying hydrogen via a local electrolyser with storage may require regulation of the entire chain, such as with heat networks. However, it is questionable whether the proposed Decarbonisation Package will allow for this.

Table 3 – Requirements for conversion based on the proposed Decarbonisation Package

Element	Requirements for switching hydrogen distribution network
Demarcation segments	The package defines the different segments of the hydrogen chain, such as hydrogen network, hydrogen terminal, hydrogen storage and hydrogen interconnector. An important difference with natural gas is that for hydrogen no distinction is made between transmission system operators and distribution system operators, but in both cases there is a hydrogen system operator. The same rules therefore apply to a hydrogen distribution system operator as to a hydrogen transmission system operator. In the case of conversion, it is important to determine under which definition different activities of the hydrogen chain fall. For example, it seems that in addition to terminals where hydrogen ships dock, a small station for the discharge of tube trailers also falls under the definition of a hydrogen terminal. Hydrogen terminals are then subject to specific obligations based on the package.
Unbundling	In general, the same unbundling requirements apply to hydrogen system operators as to natural gas transmission system operators. The package allows three different unbundling methods (ownership unbundling, independent system operator and independent transmission system operator). These three methods ensure that hydrogen grid management is independent of hydrogen production or supply (vertical unbundling). In order to check whether a hydrogen system operator meets the requirements, the hydrogen system operator must be designated and then certified by the regulator. In addition, horizontal unbundling requirements apply. If a hydrogen system operator is part of a company that is also active in the transmission and distribution of natural gas, the hydrogen system operator must at least be an independent legal entity (separate B.V.) and have separate accounts for these different activities. In short,

	before a natural gas distribution network can be converted into a hydrogen distribution network, a separate B.V. must be set up within the network group, which is designated as a hydrogen network operator and certified by the ACM. Exceptions to the unbundling requirements are only allowed for "geographically defined networks" and "existing hydrogen networks". These exceptions seem more limited than, for example, for a closed distribution system for natural gas.
Third-party access	Hydrogen grid operators must grant access to their grid. From 2031, a system of regulated third-party access will apply, which means that the regulator approves or sets the tariffs and access conditions. In the period up to 2031, a Member State may opt for negotiated third-party access, whereby the network operator determines the tariffs and conditions in negotiations with connected parties. A choice for negotiated third-party access until 2031 could mean that customers switching from natural gas to hydrogen will experience less protection against the market power of the grid operator in the period before 2031. Regardless of whether there is regulated or negotiated third-party access, it is important that there is clarity about the tariffs and conditions for using the hydrogen network before switching from natural gas to hydrogen. In addition, a number of obligations apply to hydrogen network operators. For example, (i) a hydrogen system operator must grant non-discriminatory access, (ii) the hydrogen system operator must not withhold capacity (taking into account system integrity), (iii) there is a maximum duration of capacity contracts and (iv) the hydrogen network operator must implement congestion management procedures.
Network tariffs	In the case of regulated third-party access, the regulator sets or approves the tariffs. When regulating network tariffs, we can distinguish between the tariff structure and revenue regulation. The revenue regulation determines the amount of income that a hydrogen grid operator may obtain. The tariff structure determines how those revenues are allocated to tariffs for different categories of network users. When switching to hydrogen, it is important that there is clarity about the tariff structure. An important element for revenue regulation is that there is a transfer of value from the natural gas distribution system operator to the hydrogen network operator. In principle, the Decarbonisation Package requires that the value of the transferred assets be determined by the regulator. This means that the hydrogen network operator must pay the natural gas distribution system operator that value to obtain the assets. The hydrogen distribution system operator can then cover the costs through the tariffs. One option offered by the Decarbonisation Package is to temporarily charge part of the costs of the transferred assets to customers connected to the natural gas network. Specific conditions apply to this option.
Wholesale market	The Decarbonisation Package still leaves a lot open for the functioning of the wholesale market. Rules on balancing, congestion management or capacity allocation are likely to be incorporated into yet-to-be-developed network codes. When converting a distribution network from natural gas to hydrogen, it is important to determine how this interacts with the wholesale market. If the distribution network is connected to the national hydrogen grid, for example, rules on balancing are needed. For options where hydrogen is not supplied via the national hydrogen network, the functioning of the market is a point of attention. For example, it is conceivable that there is no competition between storages or between

	terminals for unloading tube trailers. Free market forces are these segments are probably not desirable in the absence of competition, but they are what the Decarbonisation Package is based on in principle.
Retail market and consumer protection	The Decarbonisation Package is based on the assumption that hydrogen will mainly be consumed by industry and heavy transport. It is not the European Commission's expectation that hydrogen consumption by small consumers in the built environment will play a major role. Therefore, the Decarbonisation Package contains fewer rules governing the protection of consumers in the retail market. For both hydrogen and natural gas, the starting point is that there is a free retail market in which consumers are free to choose their supplier and suppliers are free to set their prices. For natural gas, the package does include the possibility of exceptionally regulating the price for supply to vulnerable and energy-poor households. There is no similar possibility for hydrogen. A number of other articles on retail markets and consumer protection that apply to natural gas also do not apply to hydrogen. In fact, the protection of hydrogen small consumers on the basis of the package is equivalent to the protection of hydrogen large-scale consumers, while in the case of natural gas, small consumers experience more protection. It seems that the package does allow the Member State to implement a higher level of protection for small consumers on its own initiative.
Security of supply	The Security of Gas Supply Regulation does not apply to hydrogen. The consequence of this is that, on the basis of the Decarbonisation Package, the security of supply of hydrogen is not or hardly regulated. Such protection is desirable for the supply of hydrogen in the built environment and to small consumers.

3.3 Temporary framework for hydrogen pilots

In the period up to 2025, there is probably no regulatory framework that describes the market organisation for hydrogen.[4] Pilots will take place during this period, but safety and consumer protection are insufficiently protected on the basis of current legislation. ACM considers this undesirable and has therefore drawn up a Temporary Framework for Hydrogen Pilots. [25]. ACM indicates that it tolerates the role of grid operators in hydrogen pilots, provided that the pilot meets certain conditions. The conditions are divided into generic conditions, conditions regarding consumer protection and conditions related to safety.

Tolerating the role of network operators

The current legal framework prohibits grid operators from having a role in hydrogen pilots, because according to the law, grid operators must limit themselves to their statutory tasks for gas and electricity. Based on the current legislation, another company in the network group may be involved in hydrogen pilots (but not in production, trade or supply). ACM wants to give grid operators the space to learn through pilots and therefore tolerates the role of grid operators in hydrogen pilots.

This means that for pilots and until a specific legal framework has entered into force, it is not necessary to set up a separate hydrogen network operator within the network group in order to participate in pilots.

[4] It is possible that the market organization for hydrogen will be included in legislation before 2025.

Generic terms and conditions

ACM imposes the following generic conditions on hydrogen pilots [25]:

- The pilot concerns the application of hydrogen as a heat supply in the built environment.
- The role of the network operator is limited to the construction (or reuse of gas networks), the management and maintenance of the hydrogen network and associated tools. Network operators are allowed to distribute hydrogen over the grid, but have no role in the production, trade and supply of hydrogen.[5]
- The pilot contributes to a clear predetermined learning objective for the network operator that has been established with the agreement of all parties involved, whereby the network operator shares the results with the market during the pilot and afterwards.
- The size of the pilot is no larger than necessary to achieve the learning objective.
- The space offered is temporary, until the role of the network operator is regulated by law, the learning objective of the experiment has been achieved or the goal is not feasible in practice.
- The space offered is for a maximum period of five years from the moment of publication of these terms and conditions. Organisers of pilots can opt for a duration of more than five years. The pilot is then dependent on the completion of new laws and regulations within five years regarding the involvement of the network operator in pilots with hydrogen.

Consumer protection requirements (including security of supply)

ACM requires that consumer protection in hydrogen pilots is at least at the same level as in natural gas. This means, among other things, that potential customers in a hydrogen pilot must be well and fully informed and that a number of articles from the Gas Act and lower regulations based on it that regulate consumer protection for natural gas also apply to hydrogen pilots by analogy. This concerns rules relating to a complaints procedure with the network operator, a reporting point for defects, energy cost estimates and invoices, information in contracts and bills, a supply obligation at reasonable rates and conditions, the closing policy, consumer protection and a complaints procedure with the supplier. Finally, ACM sets a number of additional conditions for hydrogen pilots. The additional conditions relate to (i) the contract design and duration of the pilot, (ii) the security of supply, (iii) the conversion of the indoor installation and (iv) the costs and rates. In short, it follows from these additional requirements that participants in a pilot should not be disadvantaged by this. For example, it must be clear what the rights of the consumer are upon termination of the pilot, the same level of security of supply as with natural gas must be ensured, the indoor installation must be installed, checked and maintained by one of the pilot parties and the costs must be transparent and must not exceed natural gas supply.

Safety requirements

For the safety requirements, ACM refers to a temporary policy framework to be finalised by the Ministry of Economic Affairs [26] [27] [28].

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[5] Network companies (a company other than the network operator, within the network group) may have a minority interest in the production and supply of hydrogen, as long as there is no control over production and supply.

4. Materials and components and technical knowledge/skills for conversion

This chapter provides an overview of all existing components and materials in the current gas distribution network and gas installations. Furthermore, information is given whether these components can be used for the transport of hydrogen or whether adjustments or installation of new components are required. An inventory is also made of the necessary tools, personal protective equipment (PPE), technical skills and knowledge required for the conversion.

This chapter is divided into two parts. The first section focuses on the gas distribution network from the city gate station (GOS) to the customer's gas meter. The second section provides insight into components and installations behind the meter. It looks at three categories of end-users: households/dwellings, utility buildings and large-scale business consumers.

4.1 GOS up to and including the gas meter

4.1.1 Components in the grid from gas receiving station to the gas meter

The city gate station (GOS) forms the connection between the transmission network of the national network operator (Gasunie Transport Services) and the distribution network of the regional network operator. Here the gas pressure is reduced to approximately 8 bar. The gas is then supplied to the end users via various types of gas pressure control and measuring stations. There are also valves, connectors, domestic pressure regulators and other components in the gas distribution network.

Table 4 provides an overview of all components in the gas distribution network together with the status of hydrogen compatibility research.

Table 4 – Components in the gas distribution network and the current status of hydrogen research

Components	Status of research
City gate station (GOS)	No tests have been carried out so far to check the functionality of an existing GOS with hydrogen. Given the tests carried out at high-pressure delivery stations (HAS) and district stations (DS), there are no reasons to suspect that hydrogen would have a negative impact on pressure control and safety mechanisms. However, field trials are recommended to confirm this. The measuring equipment in a GOS will have to be replaced. Furthermore, it is advisable to inspect the gas filters more often after commissioning because more dust is expected to be transported with hydrogen due to the higher speed [29].
High pressure delivery station/ connection set (HAS)	There are two different studies in which a standard HAS was tested with hydrogen. The tested HAS with spring-loaded regulator in HyDelta 1 can be applied to hydrogen without modifications [30]. This only concerns technical functioning. The existing tested HAS in Uithoorn also worked well with hydrogen without modifications [7]. It is recommended to inspect the gas filters more often after switching because it is expected that more dust will be transported with hydrogen due to the higher speed [29].
Open end delivery (OEL)	The measuring equipment will have to be replaced depending on the measuring capacity and the measurement principle. The accuracy and reliability of the existing large-consumption gas

	meters with hydrogen has not yet been investigated. Normally, a rotor gas meter or turbine gas meter is used in OELs.
Gas supply station (AS)	So far, no tests have been carried out to check the functionality of an existing AS with hydrogen. Given the tests carried out on a HAS and a DS, there are no reasons to suspect that hydrogen has a negative impact on technical functionality. However, field trials are recommended to confirm this. Availability of certified components can help accelerate the transition to hydrogen.
Custody transfer station (OS)	No tests have been conducted so far to check the functionality of an existing OS with hydrogen. There are no reasons to suspect that hydrogen has a negative impact on technical functionality. However, field trials are recommended to confirm this. The measuring equipment in an OS will have to be replaced, depending on the measuring capacity and the measurement principle. It is recommended to inspect the gas filters more often after switching because it is expected that more dust will be transported with hydrogen due to the higher speed [29].
District station (DS)	Two DS's were tested – one with gas-controlled controller and a second with spring-loaded regulator [31] [30]. The tested district stations can be used for hydrogen without modifications. This only concerns technical functioning. It is recommended to inspect the gas filters more often after switching because it is expected that more dust will be transported with hydrogen due to the higher speed [29].
Low pressure meter setup (MOLD)	The measuring equipment will have to be replaced depending on the measuring capacity and the measurement principle. The accuracy and reliability of the existing gas meters (rotor gas or turbine gas meters) with hydrogen has not yet been investigated. At Entrance, G4 and G6 bellows meters were tested. It turned out that they can be used to measure hydrogen flows, but the detected deviations were greater than required by the Measuring Instrument Directive (MID). [6].
Domestic pressure regulators	The existing domestic gas pressure regulator proved to work well with hydrogen up to 10 Nm^3/h and no sound of resonance was detected [7]. As part of HyDelta 1, 40 domestic pressure regulators were tested with hydrogen. It was concluded that no safety risks are expected when using the pressure regulators with hydrogen. However, more malfunctions may occur due to the more sensitive intervention of the under-pressure shut-off valve. Also, closing pressures will be a few mbars higher with hydrogen. It is recommended to make the decision on replacing the domestic pressure regulator on the basis of the decision tree in Figure 6 in the report D1C.4 (from HyDelta 1) [32].
Gas meters	These should be replaced with ones that fit in the same physical space. With the same energy demand, approximately three times larger hydrogen volume is transported in the same pipeline. The existing bellows gas meters cannot be used with hydrogen because the increased volume flow is outside the range of the existing meters at peak times. There is little space in the meter cupboard to place a larger bellows meter. In addition, these gas meters have natural gas approval and the accuracy with hydrogen is not yet investigated. A few suppliers are developing hydrogen meters

	based on an ultrasonic and thermal mass flow measurement principle. It is expected that permitted hydrogen meters can be supplied by the suppliers in the short term (end of 2024). [33]. During the conversion in Uithoorn, the 'old' bellows meters remained. These did work, but the accuracy and reliability of the measurements was not investigated[7]. At Entrance, G4 and G6 bellows meters were tested. It turned out that they can be used to measure hydrogen flows, but the detected deviations were larger than required by the Measuring Instrument Directive (MID). A G6 ultrasonic meter was also tested at Entrance and it did not respond to the hydrogen flows offered.
Connection fittings/couplings (sleeve, weld, flange, thread, solder, clamping, compression connections)	During the conversion in Uithoorn, solder, compression, press and thread connections were checked for leak tightness. It turned out that all connections except three compression fittings were virtually leak-proof for hydrogen. It is recommended to check compression fittings carefully for sweating with hydrogen [7]. This can be done with the help of a hydrogen leak detector around the connections when the installation is pressurized with hydrogen. The welding and wire connections are suitable and leak-proof for both natural gas and hydrogen [34].
Seals	It appears from literature review that the soft materials used are suitable for hydrogen[35]. However, the leak tightness and permeation effect has not yet been fully investigated.
Fittings and gas saddles (branches and transitions such as tees, knees, bends)	Fittings made of PVC-U and PVC-Hi have been tested in the Kiwa lab and they meet the requirements set out in NEN7231. It is concluded that pvc-fittings in the gas distribution network are leak-proof for hydrogen [36].
Plastic transition piece	The plastic transition pieces, used as a connection between the PVC connection pipe and the copper inner pipe, were tested for leaks in DNV laboratory at 150 mbarg. They turned out to be leakproof [7].
Valves	The materials in the valves are compatible with hydrogen. However, the external and internal leak tightness of the valves with hydrogen has not yet been investigated. It is recommended to remove a few existing valves from the gas distribution network (possibly during gas remediation) and perform tests for external and internal leak tightness and functionality.
Gas stopper / gas safety shut-off device	A gas stopper, type G4, of the Pipelife product was tested at Kiwa at the request of Alliander. The gas stopper intervened at a gas flow rate of approximately 25 m3 per hour [37]. For the gas stoppers, a study is underway at Kiwa on behalf of Netbeheer Nederland in which three different gas stoppers are tested for 100% hydrogen. The results are expected before the end of 2022.

4.1.2 Gas pipes and materials

The gas distribution network consists of approximately 82% low-pressure distribution networks (30 and 100 mbar) and 18% high-pressure distribution networks (1, 3, 4 or 8 bar). The gas from the distribution network is supplied to the final consumer's point of supply via connection pipes. Various piping materials used in the gas distribution network are:

- Plastics
    - Polyethylene (PE) - Connection pipes, high and low pressure distribution network
    - Impact-resistant polyvinyl chloride (impact-resistant PVC) - Connection pipes and low-pressure distribution network
    - Rigid polyvinyl chloride (rigid PVC) - Connection pipes and low pressure distribution network
- Metal
    - Steel – Connection pipelines, high and low pressure distribution network
    - Grey cast iron – High and low pressure distribution network
    - Ductile cast iron – High and low pressure distribution network
    - Copper - Connection pipes and inner pipes

From an inventory of literature and laboratory experiments and carried out practical tests, the study 'Future-proof gas distribution networks' concluded that all PE, PVC and steel materials in the existing gas distribution network are suitable for hydrogen [38]. It was also concluded on the basis of a literature review that soft materials - rubbers, plastics, lubricants (main component oil), epoxy resins and adhesives in gas distribution network are suitable for hydrogen [35]. However, it is recommended to take into account the possible higher permeation of hydrogen. The gas pipes in the distribution network do not need to be replaced for use with hydrogen. All grey cast iron and ductile cast iron pipes in the Netherlands will be replaced by the Network Operators anyway because of the safety of the gas network because cast iron is prone to breakage. In Lochem it was decided to replace all steel and hard PVC connection pipes for use with hydrogen due to high failure frequency values of these connection pipes.

4.1.3 Work procedure and supplies needed during maintenance and work

4.1.3.1 Work on gas stations

Work on gas stations includes activities such as:

- commissioning and decommissioning of stations
- settling pressure in the event that safety valves have been activated
- B-inspections
- C-inspections
- replacement of parts
- repair of a defective part

During the aforementioned activities, there are situations where gas will be released. Within the HyDelta 1 research programme, it was investigated whether the current management measures for work on natural gas stations should be adjusted in the event that they are used as hydrogen stations [39]. It was concluded that the measures described in G-51, G-52, G-53 and G-54 Safety Work Instructions[6] (VWI's) also should be followed for hydrogen with the only modification being the use of suitable hydrogen detection equipment and suitable antistatic clothing. Furthermore, it is recommended to use a vent/flare installation when depressurizing the gas control system. Gas outflows directly on the installation must be avoided. A hydrogen flame arrester must be used for

[6] A VWI is a safety-technical description of the performance of an activity. This must be used in addition to the existing assembly instructions.

flaring and venting. Make sure that there are no obstacles in the immediate vicinity of the outflow point of the flare or vent installation. It is estimated that a distance between outflow point and possible ignition sources should be used 2 to 3 times greater than with natural gas. This is indicative 7 meters. Field research is recommended to verify this distance.

4.1.3.2 Commissioning and decommissioning of hydrogen pipelines

When commissioning the pipelines (except during the conversion of networks from natural gas to hydrogen, because then it is safer to replace the natural gas directly with hydrogen), the hydrogen pipelines must be flushed with an inert gas (usually nitrogen). This is recommended to avoid the presence of a combustible mixture in the pipe. Research and field tests show that a minimum purge speed of 0.4 m/s is required. It is recommended to maintain a purge speed of 1.0 m/s [40]. When flushing hydrogen pipes with nitrogen, no hydrogen flame arrester needs to be used at the vent and flare installation because there is no risk of flame flashback [41].

Table 5 shows the required flow rate for purging different pipe diameters [40].

Table 5 – Required flow rate for purging

Pipe diameter	Minimum required purge speed [m/s]	Required flow rate at minimum required purge speed [$m^3{}_n$/h]	required flow rate at recommended purge speed van 1,0 m/s [m3n/h]
DN 32	0.4	2	3
DN 50	0.4	3	8
DN 80	0.4	8	19
DN 100	0.4	12	29
DN 150	0.4	26	64
DN 200	0.4	46	113
DN 250	0.5	89	177
DN 300	0.6	153	255
DN 400	0.8	362	452

When converting networks from natural gas to hydrogen, it is safer to displace natural gas directly with hydrogen. Flushing with nitrogen is not necessary [40]. It is recommended to use a purge speed of 1.0 m/s and a flaring installation [42]. However, one should be aware that the hydrogen flame is less visible. The use of a flame arrester is yet to be investigated.

When flushing hydrogen pipes with air, the following is recommended [41]:

- The chance of ignition and thereby flame flashback when venting is absent. This does not require the use of hydrogen flame arrester. However, this does not take into account the chance that dust (rust) will be taken from the pipe. This needs to be investigated.
- A hydrogen flame arrester must be used when flaring. One should be aware that the hydrogen flame is less visible.

4.1.3.3 Personal protective equipment (PPE) and tools

Personal protective equipment is held or worn by personnel during work on the gas distribution network. The behaviour of hydrogen is different from natural gas, so the question arises whether the currently used PPE and tools are also suitable for hydrogen, and which PPE and tools are additionally needed for hydrogen.

Gas measuring equipment

Within the Knowledge Centre for Gas Network Management, it was investigated whether the gas measuring equipment used is suitable for hydrogen. A few gas measuring devices from different suppliers that are in use by the network companies with natural gas have been tested at Kiwa with hydrogen. These gas measuring devices belong to three types – LEL meter, gas leak detector and gas concentration meter. It turned out that the gas measuring devices currently used for natural gas are not suitable for hydrogen [43]. It is recommended to use gas measuring devices suitable only for hydrogen. Kiwa is now investigating which devices are available in the market for use with hydrogen.

Protective clothing

When working on the natural gas distribution network, it is recommended to wear antistatic and flame retardant work clothing. It remains to be investigated whether the current protective clothing for natural gas is also suitable for hydrogen. Furthermore, it is also examined whether heat detection is desirable.

Below is a list of hydrogen specific devices and tools needed during work:

1. Vent/flare installation with hydrogen flame arrester
2. Hydrogen-capable gas measuring devices (LEL meter, gas leak detector and gas concentration meter)
3. Oxygen gas detector
4. Antistatic flame retardant workwear (suitability of current protective clothing for hydrogen is being investigated)
5. Nitrogen purging installation

4.2 Indoor installation: appliances and indoor piping

For conversion, the suitability of the current natural gas appliances and the indoor piping for hydrogen in the target region will also have to be assessed. Unsuitable elements will have to be replaced, for which the availability and delivery time of replacement elements is important for the planning and organization of the conversion. For both homes and utility buildings and commercial large-scale consumers, the most complete possible inventory of common appliances, piping and components has been made. This inventory can be used as a guide for the inventory of equipment parks in areas that are being transferred to hydrogen. However, as each supply area is unique, detailed accurate screening based on visits should be carried out so that non-common devices are also included in the fleet.

Annex 1 shows the availability of hydrogen replacement devices in the market. The suppliers have been approached to get an insight into the expected delivery time, but unfortunately no responses have been received yet.

4.2.1 Dwellings

Dwellings are considered to be the buildings that have the purpose of 'living'. This also includes specific forms of housing, multi-storey buildings such as high-rise buildings.

- *Central heating boiler (combi)*: The combi central heating boiler is a combination of a hot water boiler and a central heating boiler. The combi boiler provides the entire house with hot water, both heating and tap water. For the most part, combi boilers are installed in homes. Adjustments to the boiler are necessary due to the differences in properties of hydrogen compared to natural gas, such as the combustion rate of the gas. Boiler manufacturers are developing H2-ready boilers that are suitable for natural gas and can be converted to 100%

hydrogen within an hour. The device is expected to be on the market in 2025. A manufacturer is also working on validation of a Super Efficiency Adsorption Boiler that can replace existing boilers and is suitable for natural gas, natural gas-hydrogen mixture and 100% hydrogen. More developments and suppliers are in Annex 1 – Availability of replacement devices**Error! Reference source not found.**.

- *Flue gas exhaust*: The flue gas extraction system ensures the removal of combustion gases from the combustion process in the boiler to the outside. All parts that come into contact with the flue gases and condensate of a 100% hydrogen boiler, the plastic pipe material and the sealing rings, must be resistant to this. Based on a limited theoretical analysis, the current material for drain pipes and sealing rings suitable for condensing additions appears to be 100% hydrogen [44]. This has also been observed by Entrance. At the moment it is not yet clear whether additional tests should take place on material that already has a quality mark for natural gas.
- *Cooker*: The cooking plate of gas cookers heats pans by burning gas. The biggest challenges for the development of variants suitable for 100% hydrogen are: visibility of the flame, material of the burner and the flame protection system [45]. It is expected that consumers in the Netherlands will switch to electric cooking.
- *Fireplace*: Gas fireplaces are, depending on their power, used exclusively for the atmosphere, or also partly for the heating of a home. Adjustments to the device are necessary due to the differences in properties of hydrogen compared to natural gas, such as the combustion rate of the gas. The visibility of the flame is also one of the biggest challenges.
- *Pipes, couplings and fittings (copper and multilayer pipe)*: Indoors, the gas flows through a combination of pipes, couplings and fittings. These usually meet the inspection requirements of the voluntary Gastec Qa quality certification. As soon as possible, the approached manufacturers want to have their products certified for Gastec Qa for hydrogen.
- *Other gas appliances (not included in this overview)*: Gas ovens are not included in the market inventory for appliances suitable for hydrogen in homes. It is known that only a few have entered the market in the Netherlands, but it is likely that these will not be found (anymore) in Dutch households. Outdoor gas fireplaces and gas barbecues will usually use a propane tank as fuel. These are therefore not included. As well as the gas heaters connected to the gas network, so-called exotics are on the market and therefore not considered in this study. These devices are mentioned in the overview table.

4.2.2 Utility buildings

Utility buildings are real estate that has no residential purpose. This can include industrial halls, buildings to work in such as offices and schools, but also buildings for commercial services such as shops and bakeries. Depending on the definition, the group of buildings classified as utility is larger or smaller. It should be borne in mind that there may be a larger selection of devices in the area to be converted than is included here.

- *Central heating boiler*: The central heating boiler provides buildings with hot water for heating. Adjustments to the boiler are necessary due to the differences in properties of hydrogen compared to natural gas, such as the combustion rate of the gas.
- Hot water boiler (tap water): Boilers provide utility buildings with heated tap water. Adjustments to the boiler are necessary due to the differences in properties of hydrogen compared to natural gas, such as the combustion rate of the gas.
- *Flue gas exhaust*: The flue gas extraction system ensures the removal of combustion gases from the combustion process in the boiler to the outside. All parts that come into contact with

the flue gases and condensate of a 100% hydrogen boiler, the plastic pipe material and the sealing rings, must be resistant to this. The expected flue gases of a 100% hydrogen boiler are steam and NO_x. The degree of condensate from combustion of hydrogen becomes higher than with combustion of natural gas.

- *Cooker*: The cooking plate of gas cookers heats pans by burning gas. The biggest challenges for the development of variants suitable for 100% hydrogen are: visibility of the flame, material of the burner and the flame protection system.
- *Gas oven*: In a gas oven, gas is burned to create heat, slightly moist, air for food preparation. Modifications to gas furnaces are necessary due to the differences in properties of hydrogen compared to natural gas, such as the combustion rate of the gas. Hydrogen-fired tunnel furnace is being developed and tested by AMF den Boer together with Kiwa.
- *Gas fryer*: In gas fryers, gas is burned to heat oil, used for frying food. Adjustments to gas fryers are necessary due to the differences in properties of hydrogen compared to natural gas, such as the combustion rate of the gas.

4.2.3 Large-scale business consumers

Large-scale business consumers include companies that are connected to the distribution network with a capacity greater than 40 m^3 per hour. This concerns greenhouse horticulture, paper and cardboard factories, chemical industry, industry with process heat demand, combustion plants and heat treatment processes, etc. It is not easy to make a list of all common devices. Examples of such devices at large-scale business consumers are: industrial burners, gas ovens, heat treatment devices, processes such as drying, melting, etc. Several pilots are running at various suppliers to make industrial burners suitable for hydrogen. Heattec has developed a test set-up consisting of a demand-driven hydrogen generator unit, a gas control unit, a Bentone hydrogen burner and an Osby Parca hot water boiler. This hydrogen burner concept can be applied to installations from 80 kW burner power. ICE-BT is also working on the development of an industrial burner for hydrogen.

A complete list of gas installations must be drawn up for each large-scale business consumer, after which the possibilities must be investigated to make these installations suitable for hydrogen. Below is an example of such an inventory for greenhouse horticulture.

Greenhouse horticulture is a part of the horticultural sector that uses greenhouses made of glass (or some plastics) for the cultivation of plants. In the greenhouses, the atmosphere can be controlled and the conditions can be made as favorable as possible for the growth of plants.

- *Heating boilers (also called: horticultural boilers)*: Heating boilers are used for heating the greenhouse. In terms of construction comparable to a central heating boiler, in terms of regulations, however, these appliances do not fall under the SRB (Gas Appliances Regulations) as it does for central heating boilers, for example.
- *Steam boilers*: These are used to "steam" the soil in the greenhouse to kill weeds (and possibly vermin).
- *CO_2 cannon*: In a CO_2 cannon, direct combustion of gas takes place. The combustion gases are blown into the greenhouse with a large fan. It is therefore a combination of CO_2 fertilization and heating of the greenhouse. Because hydrogen combustion does not produce CO_2, CO_2 must be supplied from another source or grown without CO_2.
- *CO_2 dosing plant*: These installations can extract flue gases from the exhaust system of an combustion plant (e.g. horticultural boiler) and blow them into the greenhouses, for the purpose of CO_2 fertilization. This system does not work when hydrogen is burned as CO_2 is not present in combustion gases.

- *Gas engines*: These are used as a cogeneration installation. The gas engine is coupled to a generator. The generator produces electricity for the greenhouses (especially lighting for the crops). The heat released in the gas engine is used to heat the greenhouse.

5. Supply and delivery options

The conversion of gas distribution networks to hydrogen will take place gradually. This is related to the availability of sustainable hydrogen, but also to the time needed to make decisions and realize conversion. In principle, three routes are possible for the distribution of hydrogen via gas distribution networks: [2]:

1. Bottom-up: local initiatives can lead to the conversion of (part of) the distribution networks. The supply of hydrogen takes place locally with tube trailers or an electrolyser with storage of hydrogen. A variant of this is the production of hydrogen at an industrial cluster. From here, (almost pure) hydrogen is supplied to a gas distribution network. These local grids can be connected to each other at a later date and/or connected to the national hydrogen grid.
2. Top-down: (almost pure) hydrogen is transported via a hydrogen transport network and supplied to a gas distribution network.
3. Blending of hydrogen into natural gas: This can take place in the regional gas transport network up to a maximum of 20% without having to convert the gas distribution network [46]. This route is outside the scope of this study. It is also a temporary solution because this route remains dependent on natural gas and does not lead to a climate-neutral energy supply. Partly for this reason, Stedin and Alliander do not see mixing as a desired route [12] [13].

5.1 Hydrogen delivery

Before plans can be made for the actual conversion of gas distribution networks to hydrogen, it will first be necessary to determine which customers will continue to be supplied with gas or switch to another form of heat supply. In the areas where the gas supply is maintained, a choice will have to be made about the type of sustainable gas: biogas (green gas) or hydrogen. To this end, municipalities, in consultation with property owners, residents and network operators, draw up a Heat Transition Vision in which it is indicated for each district how the homes and utility buildings will be supplied with heat in the future. Regional network operators have an advisory role in this. For this strategic choice, network operators have drawn up strategy plans (e.g.: [1] [3] [47]).

There are various approaches to determining which gas consumers can be supplied with hydrogen in the future.

Built environment

The Start Analysis [48] is a tool for municipalities, regional network operators and other parties in drawing up a Heat Transition Vision for the built environment. Using the VESTA-MAIS model, the Netherlands Environmental Assessment Agency (PBL) analysed the most, from a social perspective, cost-effective sustainable forms of heat supply at neighbourhood level. A neighbourhood has the size of a few dozen to more than a thousand housing equivalents[7]. Different strategies are distinguished (combinations of energy supply, use and building renovation), including the supply and use of biogas (green gas) and hydrogen.

Gas distribution networks

If the existing gas distribution networks are taken as a starting point, the supply areas are decisive. The gas distribution network is structured as follows:

- Gas is supplied from the regional gas transport network (RTL) via a city gate station (GOS). A gas distribution network is connected to the RTL network via various GOSs.

[7] Dwellings and utility buildings; Non-residential buildings are converted into residential equivalents

- The gas is first distributed in the supply area via an 8-bar network. Depending on the specific grid, 4, 2 and/or 1 bar network sections are connected to it.
- District stations are connected to these high-pressure (HD) networks that reduce the gas pressure to the low-pressure (LD) networks (100 or 30 mbar) that subsequently distribute the gas to the small consumers. Large consumers are connected to the HD network via a delivery station.
- The low-pressure networks are often ring-shaped (meshed network) and are supplied with gas via various district stations.

The largest unit is the supply area behind a city gate station (possibly fed from several GOSs), which can involve several tens of thousands of customers. This area is also called a pseudo-GOS area [2] [12]. The smallest unit is the supply area behind a district station with about 250 to 500 housing connections [2]. There are major differences in net topology, particularly between urban and rural areas.

Whether it is desirable and feasible to supply (part of) the gas distribution network with hydrogen depends on many factors. An area close to industry that has access to a hydrogen transport network may make the supply of hydrogen to customers of the distribution network attractive. If a hydrogen transport network is located at a relatively large distance from the gas distribution network, hydrogen supply is only possible from tube trailers or local production; probably a much more expensive option. The presence or absence of alternatives, such as a heat network or the possibility of supplying biogas (green gas), also determine whether or not hydrogen distribution in a supply area is attractive.

The gas distribution network that will be supplied with hydrogen can be 'cut off' from the other gas distribution network in which the supply of natural gas must be maintained. In many cases it may be necessary to lay additional pipes for this, for example to maintain the security of supply.

Different situations for hydrogen supply

If hydrogen is supplied to customers via existing gas distribution networks, the area classification of the gas networks is decisive [13]. Taking this into account, three different situations can be distinguished:

- Urban area, such as Gouda [12], Drachten and city centre of Haarlem [13].
- Rural area, such as Stad aan 't Haringvliet [11], Noord-Beveland [12].
- Business park, such as the IJmuiden port area [13] and large consumers Heerenveen [14].

Customers changes

Customers in an area can choose to dispense with a gas connection (e.g. by fully electrifying the heat demand). As a result, not all customers who currently have a natural gas connection will have to be connected to the hydrogen network in the future. New customers are also possible, such as hydrogen filling stations for trucks and ships [2] [13]. If these trucks and ships use hydrogen in battery electric fuel cells (BEFC), a purification step is required to remove the sulphur-containing odorant from the gas [13]. However, odorants can also be used where this is not necessary [38]. For the time being, Netbeheer Nederland assumes that filling stations for trucks and ships will be supplied with tube trailers and will not be connected to the hydrogen distribution network [47].

5.2 Hydrogen supply options

For the supply of hydrogen, most Dutch case studies (with the exception of Stad aan 't Haringvliet) are based on a top-down approach, i.e. hydrogen supply via the RTL network and a GOS. For hydrogen supply via the RTL network, the gas distribution company depends on Gasunie, the operator of the RTL network. If Gasunie converts an RTL pipeline from natural gas to hydrogen, this may mean that other GOSs are also supplied with hydrogen. These can also be GOSs from other regional grid operators. In addition, large industrial consumers may be connected to the RTL network. This increases the scale and complexity of the conversion. The meshing of the RTL network can partly be used by making a 'cut' in the RTL pipeline, whereby one side of the pipeline is connected to the national hydrogen network and the other remains connected to the natural gas HTL network [14].

Transition from small to larger scale

Because knowledge and experience with the conversion to hydrogen is initially limited and/or the supply of hydrogen is still relatively small, the hydrogen projects will be smaller in size in the initial situation and will not yet be fed from the national hydrogen network[8]. In this situation, hydrogen can be supplied via tube trailers and/or produced locally with electrolysers. The smallest scale[9] is a few tens to hundreds of small consumers connected to a low-pressure hydrogen network. These projects can be scaled up at a later stage, whereby the distribution network is supplied with local hydrogen production or from a GOS that is connected to the hydrogen transport network.

Figure 1 shows 5 possible start situations and 2 end situations. Options 1 and 2 (small-scale projects with a low-pressure hydrogen network) and 5 (blending) can be transformed into a final situation indicated by options 3 and 4 via one or more intermediate steps. Option 3 shows the situation of an electrolyser at a local wind or solar farm [11] or an electrolyser on an industrial site to which the gas network is connected [2]. Option 4 is the situation described in most case studies [12] [14] [13].

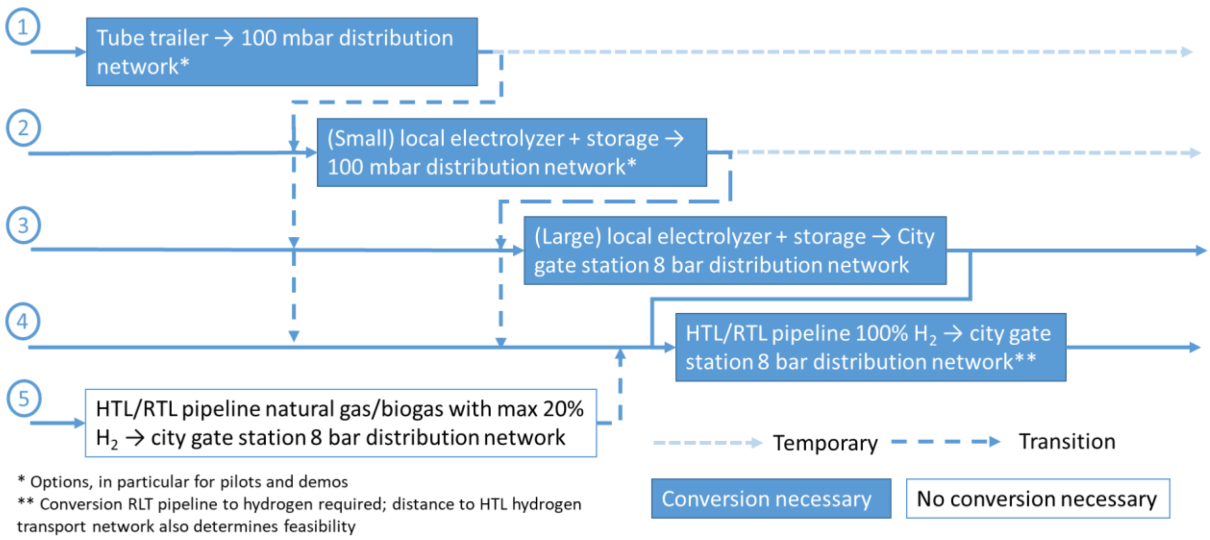

Figure 1 – Options for (temporary) supply of hydrogen

Feed-in of hydrogen

It is conceivable that local hydrogen production with an electrolyser is connected to a hydrogen network that, via RTL and GOS, is fed from a hydrogen transport network. When local hydrogen production exceeds local demand, this surplus from the gas distribution network (with possibly a

[8] It is possible that part of the national hydrogen grid will be put into operation before 2030. However, the possibility of supplying hydrogen to distribution networks also depends on the size of the (green) hydrogen production. In the first years, hydrogen will mainly be supplied to industry.
[9] Pilots with a few houses not included.

booster) can be fed into the RTL network. If this is not possible, the local hydrogen production will have to be switched off.

Security of supply

By making cuts in the RTL network and gas distribution networks, the meshed network (partly) disappears and thus the redundancy is reduced. As a result, the security of supply of hydrogen may decrease compared to the original natural gas supply, but that counts also for the remaining gas network in which natural gas is still distributed. By laying additional pipes, the meshed network can be (partially) restored [12]. It may also be necessary to install an additional district station [14]. Other options for improving security of supply are gas supply from tube trailers or local storage tanks.

6. Step-by-step plan for conversion

In a number of conversion projects and studies, a step-by-step plan for the conversion has been developed. These are projects and studies by Alliander and Stedin and the H21 study from Leeds (UK). The information provided by the different projects and studies on conversion plans is very different and difficult to compare. The various step-by-step plans provide only limited insight into who is responsible for carrying out the various steps, such as making an inventory of technical adjustments among end users. Both the role division and the required coordination between the various responsibilities deserve attention.

Alliander, Haarlem, IJmuiden and Drachten [14]

Based on experiences with the pilot project in Lochem, Alliander has developed a conversion plan for Haarlem, IJmuiden and Drachten in which 8 steps are distinguished. The first 6 steps relate to preparation. The last two on the execution of the conversion. The boundary condition is to switch a grid section in one week.

- *Step 1 – Defining hydrogen areas*: Based on the Transition Vision Heat and the existing grid situation, the grid operator designates preferred areas for hydrogen distribution. The result is an Energy Mix Plan per area, with designated hydrogen areas.
- *Step 2 – Breakdown into manageable size*: The gas distribution network that will be supplied with hydrogen will be divided from the HD network (8, 4 or 3 bar distribution network) into sections of approximately 1000 to 3000 connections. The supply point of hydrogen is then determined and the order in which the various sub-areas are converted to hydrogen. Grid calculations are carried out for the hydrogen network (whereby 30 mbar networks are upgraded to 100 mbar) and network calculations for the surrounding areas that continue to be supplied with natural gas. The result is a division into hydrogen areas and insight into the required grid reinforcements.
- *Step 3 – Inventory of the construction of the gas network in sub-areas*: This step determines which adjustments to the gas distribution network are needed for the distribution of hydrogen. The necessary adjustments are documented and form input for the Technical Conversion Plan.
- *Step 4 – Inventory of customers*: In this step, it is investigated which technical adjustments are needed for future hydrogen customers. The necessary adjustments are documented and form input for the Technical Conversion Plan.
- *Step 5 – Technical Conversion Plan*: This plan, which brings together the results of the previous steps, provides an overall overview of the work to be carried out. This includes the construction of new hydrogen supply infrastructure, the sectioning of hydrogen areas (installing HD and LD grid separators), the necessary grid and customer adjustments and a description of switching operations in the HD network.
- *Step 6 – Planning:* The Implementation Plan describes how the Technical Conversion Plan is implemented. It states which materials and tools are needed, the capacity planning for Liander and contractors and a time schedule everywhere. This plan is divided into gas network, customer installation small consumption (homes) and customer installation large consumption. The precondition is that the conversion per subarea can be carried out in one week.
- *Step 7 – Conversion of gas network:* This includes the conversion work that is carried out well before the actual conversion to hydrogen.
- *Step 8 – Switching*: The supply of natural gas is interrupted, the conversion is carried out and the hydrogen supply begins.

Stedin, Uithoorn [7]

In 2020, the gas supply of 14 (vacant) homes was converted to hydrogen. It concerns conversion of 8-bar, 100-mbar and indoor pipes. The step-by-step plan does not provide insight into preparatory activities, such as inventory of grid construction and existing materials and components, but emphasizes the practical implementation:

- *Step 1 – Risk inventory*: inventory of, among other things, leak tightness and a leak tightness check with helium.
- *Step 2 – Preliminary tests and inspections*: Supply of hydrogen and test gases (nitrogen and helium) via a high-pressure connection set (HAS). All gas distribution and interior pipe connections have been checked and tested. At the indoor installation there is a flushing point placed near the gas meter that allows the indoor pipe to be depressurized and flushed with an inert gas. The houses are equipped with carbon monoxide detectors, of which it is known that these can also detect hydrogen. In a parallel process, in this phase the gas appliances are replaced by devices that are suitable for hydrogen.
- *Step 3 – Transferring distribution pipeline with temporary pipeline*: With a temporary pipeline next to the existing gas pipeline[10]. The house connections are transferred from the existing to the temporary pipeline. This maintains the supply of natural gas. The existing gas pipeline is then disconnected from the natural gas network and connected to the hydrogen supply. The house connections are transferred one by one from the temporary pipeline (natural gas) to the existing gas pipeline (hydrogen).
- *Step 4* – Project evaluation: All conversion work has been evaluated. The project has shown that the actual conversion of natural gas to hydrogen per home costs approximately 1 working day per installation employee. The total conversion of 14 homes took 7 working days, 3 days for the actual conversion and 4 days for testing in advance.

Stedin, Stad aan 't Haringvliet [11]

The starting point for the conversion plan of Stad aan 't Haringvliet is that the gas interruption of homes is only one day. The number of sections (with a gas bladder/gas stopper) is kept limited due to safety risks. The conversion plan includes 30 sections divided into 2 phases (180 and 342 connections). The conversion can be carried out in 30 days, whereby the conversion / replacement of appliances and associated control work of the meter setup and indoor installation can take place in 3½ hours by two technicians.

H21, Leeds [18]

Hydrogen in the Leeds project will be produced with a steam-methane-reforming (SMR) plant, equipped with CO_2 capture & storage (CCS), where the CO_2 is stored in an empty gas field in the North Sea. The SMR plant is connected to the Local Transmission System (similar to RTL network), where the feed-in to the distribution network takes place via district governors (similar to city gate stations).

The boundary conditions for the conversion are that (1) the interruption of the gas supply to homes may last between 1 and a maximum of 5 days and (2) the conversion will only take place outside the heating season (April-September). This means that the conversion of leeds' entire gas distribution network requires a period of 3 years. In this transition period, there are network sections in which hydrogen is distributed in addition to network sections that are still supplied with natural gas. The net

[10] A conversion method with a temporary pipeline has been chosen here. Two other methods are: using only the existing pipeline (less flexible than temporary pipeline) and a new pipeline (more expensive and existing pipeline is not reused).

part in which the conversion will be carried out for a given year is divided into net sections into conversion sections for a month and conversion sections for a week. These last sections have a size of approximately 2,500 homes.

In the preparation, the required grid reinforcement is determined using grid calculations and the 'zones of influence' from the feed-in points, whereby new hydrogen feed-in points on the 2 bar medium-pressure network are also possible. For the (temporary) separation of a grid section with hydrogen and a network part with natural gas, a 'double block and bleed valve configuration' is applied.

Two conversion strategies have been developed:

- *Incremental Conversion with Zone Isolations*: In this scenario, new hydrogen feed-in points are created and a series of successive zones are converted. In this scenario, the gas interruption of customers is the shortest and the conversion can be carried out with a relatively small group of people.
- *Minimal Network Interference*: The supply of hydrogen takes place at an existing natural gas supply point. The gas interruption of customers is relatively long and a larger number of people is needed for the implementation.

Annex 1 – Availability of replacement devices

Component	Replacement/ adjustment necessary	Replacement available

Central heating boiler (combi)	**Yes**	**Intergas, Remeha, Nefit Bosch and Cooll**
		Working prototype of a central heating combi unit has been developed. A preliminary version has been used on a modest scale (10 to 100s) in field tests. Expected hydrogen central heating units with CE marking (from 2023) [45]..
		
		Intergas: 100% hydrogen device (field tests: hydrogen Tiny House Hoogeveen, Wagenborgen)
		
		Nefit Bosch: H_2-ready device (field test UK). Late 2022 - early 2023 on the market.
		
		Remeha:
		- Natural gas-hydrogen appliance (suitable for fluctuating admixture with 0-20% hydrogen)
		- 100%-hydrogen appliance
		  ○ One type: mass production from 2023
		  ○ Multiple types (various capacities): production from 2024
		- H_2-ready appliance (field test hydrogen house, Stad aan 't Haringvliet)
		Cooll: Adsorption boiler suitable for natural gas, biogas, natural gas-hydrogen mixture and 100 % hydrogen.

Flue gas exhaust	Undecided, possibly not all suitable for H_2 Based on a limited theoretical analysis, the current material for drain pipes and sealing rings suitable for condensing additions appears to be 100% hydrogen [44]. At the moment it is not yet clear whether additional tests should take place on material that already has a quality certification for natural gas. The various standards committees are	**Muelink and Grol** Pp drainage material (polypropylene, under trade name: Burgerhout) has already been submitted for inspection at a 'Notified Body' [45]..

	still working on adapting the standards. For more information, see section 3.2 in [45].	
Cooking appliance	**Yes**	**Atag Keukentechniek** Intends to develop hydrogen-powered devices within a "visible horizon", approximately within 1-5 years (October 2021) [45]
Decorative fireplace	**Yes**	**Glen Dimplex Group** No clear starting points – electrical options possible

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