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An overview of the decarbonisation of the natural gas system with hydrogen

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Foreword


Source: DVGW

by: Prof. Dr. Gerald Linke (Chief Executive Officer of DVGW)

As a result of the national and European climate targets, the various sectors in Germany are in the midst of a comprehensive transformation process. Fossil fuels and raw materials, which still significantly characterise the energy and raw materials system today, are to be replaced by renewable energy and climate-friendly energy sources. Hydrogen will play a key role in this context, as it can be produced in a climate-friendly way, can be imported and stored on a large scale and can also be used in processes that are difficult or impossible to electrify. The use of hydrogen is not new. Both industry and the energy sector have been using hydrogen in chemical processes for many decades, operate private hydrogen networks and have often used hydrogen as a component of town gas in the past. They are therefore experienced in the safe handling of hydrogen.

Despite this experience, the transformation is sometimes viewed critically by the public. It is questioned whether the transport and utilisation of hydrogen will be possible in the future with today's natural gas pipelines and processes without compromising the current high level of safety. These safety concerns are mainly based on the different physical, chemical and combustion properties of hydrogen compared to natural gas. Various players in the gas industry and independent research institutes have initiated and carried out numerous research and demonstration projects in recent years in order to ensure the safe operation of the gas infrastructure with hydrogen through evidence-based further development of the technical standards and to be able to safely convert processes and systems to hydrogen.

This technical article is intended to make a scientifically sound contribution to objectifying the discussion on the safe use of hydrogen by presenting the current status of the regulatory work and the changeover in the area of application, in each case with the underlying research work.

It is shown that the utilisation of the existing gas infrastructure for hydrogen offers a technically sustainable and safe option and thus a resource-saving transformation of the energy system is possible, taking into account local conditions and user requirements. Hydrogen must also be considered as a realistic economic solution to replace fossil fuels and drive forward the energy transition across all sectors.

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Executive Summary

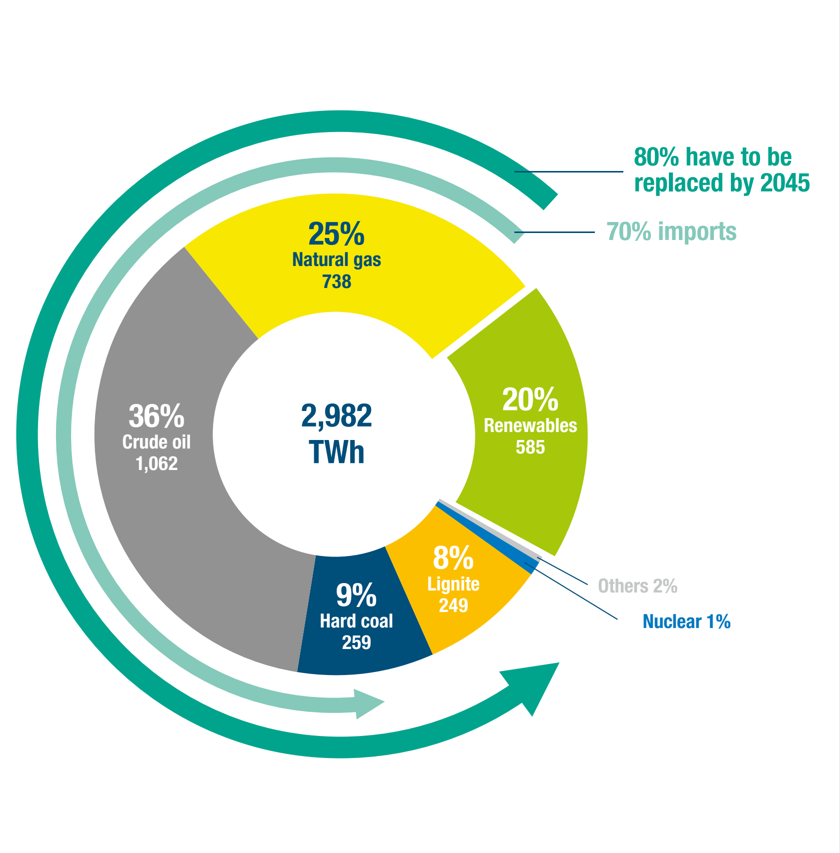
The gas infrastructure in Germany is facing a significant transformation, because hydrogen is becoming increasingly important as a sustainable energy source. Long-term studies and technical analyses have shown that existing steel and plastic pipelines are suitable for the safe transport of hydrogen. Nevertheless, the transition to hydrogen requires specific adaptations to ensure the safety and efficiency of the infrastructure. Various research projects have also confirmed that the steel materials used in the gas infrastructure are fully suitable for hydrogen. The findings form the basis of the DVGW standards and thus enable the safe utilisation of existing gas networks for hydrogen transport under normal operating conditions. At operating pressures (MOP) greater than 16 bar, a fracture mechanics assessment is required in accordance with DVGW Code of Practice G 464. Between 12 and 16 bar, fracture mechanics analyses are only necessary for pipe diameters greater than DN 200. In distribution networks with a pressure of less than 12 bar, no relevant influences from hydrogen are to be expected and fracture mechanics considerations can be omitted.

Studies by the plastic pipe industry for common pipe materials such as PE63, PE80, PE100, PE100-RC, PA-U12 and PVC have shown that these are generally suitable for the long-term distribution of hydrogen. The hydrogen suitability of ductile iron pipe systems has also been confirmed in further studies. Sufficient safety reserves were found for the fittings tested under pressurised hydrogen during operation. However, adjustments to a few parts of the gas infrastructure are necessary to ensure safe hydrogen operation. When handled properly and in compliance with technical standards, hydrogen is just as safe as natural gas.

The results of various research and implementation projects have already been extensively incorporated into the development of technical standards. The core standards for the gas infrastructure are already H_2-ready. This ensures technically safe operation with hydrogen. Further findings are continuously being incorporated into the technical standards.

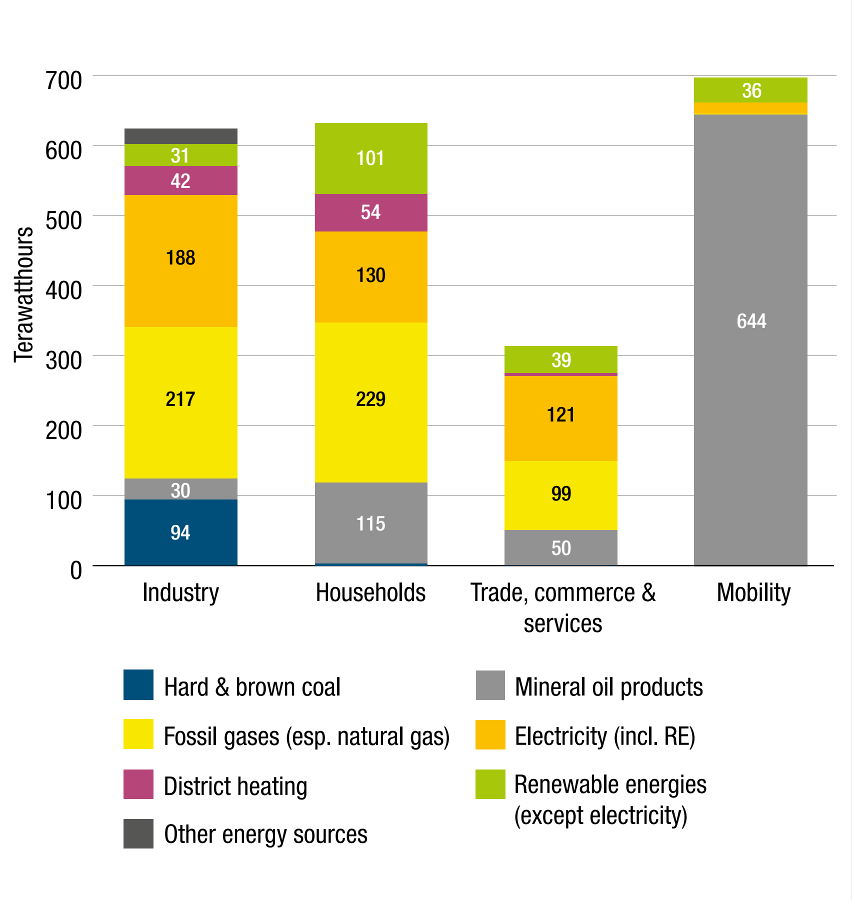
In the area of applications, a distinction must be made with regard to the assessment of the development status of hydrogen utilisation. Processes that already use fossil-based hydrogen today can be converted to climate-friendly hydrogen comparatively easily. When substituting natural gas with hydrogen, differences in combustion technology must be taken into account, which require individual adjustments in order to avoid a deterioration in safety, efficiency, emission values and, in many industrial processes, product quality. Nonpremixed burner systems, which are frequently used in industry, can often be converted to hydrogen with less effort than premixed burner systems, which are typical for household appliances and gas turbines, by taking appropriate measures.

In recent years, numerous projects under real conditions have demonstrated the safe use of hydrogen in household appliances, industrial processes and in combined heat and power generation. Extensive experience has been gathered for blending, retrofitting and new plants, which serve as best practice examples and provide the basis for a safe cross-sector hydrogen ramp-up. Based on such studies, 100 % hydrogen solutions are already commercially available for various systems and appliances. Due to the heterogeneity of the plants and processes, the solutions are generally not directly transferable, meaning that there is still a need for development, particularly in the implementation and scaling of industrial processes and large-scale turbines.



Source: AGEB

Figure 1: Primary energy consumption in Germany in 2023 (in TWh)



Source: [3]

Figure 2: Final energy consumption by energy source & sector in 2023

1 Introduction

Germany is undergoing a transformation process towards a climate-neutral energy supply, whereby molecular energy sources and electrical energy must be made available from renewable sources, depending on the application. The conversion of molecular energy into electrical energy and vice versa is a key aspect of the energy transition, as it enables the integration of renewable energies and the use of hydrogen as an energy storage medium. [1]

In recent years, primary energy consumption across all sectors in Germany has been made up of an average of around 80 % molecule-based energy sources and 20 % electrons (**Fig. 1**).

It is to be expected that the share of molecule-based energy sources in primary energy consumption will decrease in future and that the share of renewable energies will continue to increase. In addition, **Figure 2** shows the main molecule-based final energy consumption in various sectors.

Germany is heavily dependent on energy imports as it has no significant conventional energy resources apart from coal. Around 70 % of its energy requirements are covered by imports [4]. This dependence on imports harbours risks, as the 2022 energy crisis showed when gas supplies from Russia were greatly reduced. In terms of security of supply, hydrogen offers the opportunity to diversify the supplier countries and thus reduce dependency on individual energy exporting countries. [5]

Germany has set itself the goal of phasing out coal-fired power generation by 2038 at the latest [6]. The phase-out of nuclear energy was already completed in 2023 with the shutdown of the last reactors [7]. The consumption of oil is also to be greatly reduced in the coming decades in order to achieve the climate targets. These measures are part of the comprehensive strategy to achieve the national climate targets. [8]

Natural gas currently plays an important role as a bridging technology on the road to climate neutrality. It is used in power plants to generate electricity and heat and serves as a raw material in industry. The National Hydrogen Strategy shows that natural gas will increasingly be replaced by hydrogen in the future in order to further reduce CO_2 emissions. [9–11]

Combining hydrogen with renewable energies is a key to decarbonising the energy system. Surplus electricity from wind and solar plants can be used to electrolyse water to produce green hydrogen. This hydrogen can be stored in pressurised tanks, underground caverns or as liquid hydrogen and converted back into electricity when needed, ensuring a stable and sustainable energy supply. [12–13]

Figure 3 clearly shows the storage capacity of natural gas compared to electrons. Even if hydrogen only provides a third of the energy volume compared to natural gas with the same storage volumes, Figure 3 shows the potential of future hydrogen storage. The large-scale storage of hydrogen enables long-term energy storage and the use of hydrogen as a buffer for fluctuations in renewable energy generation.

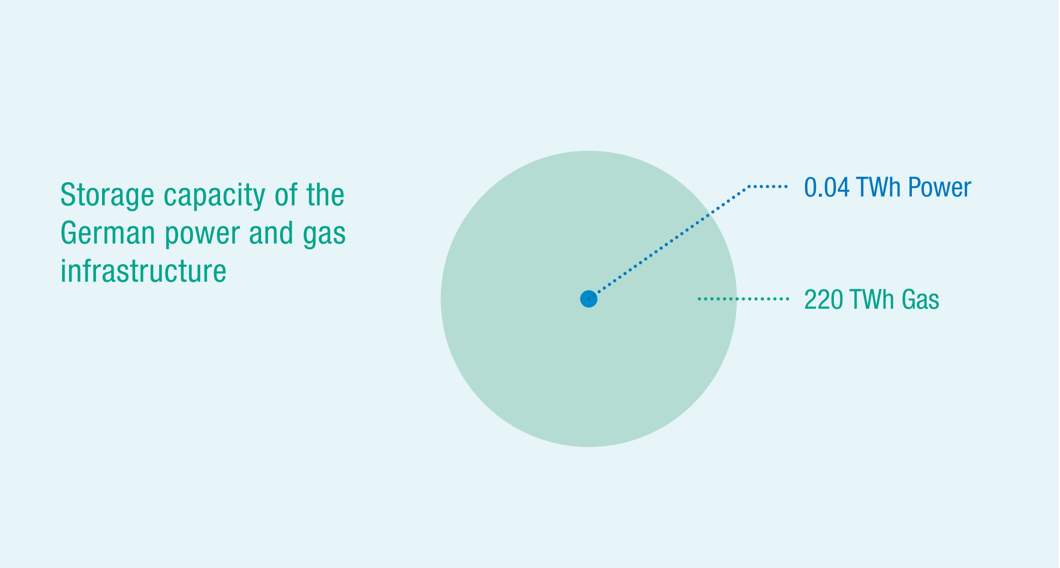
Hydrogen can also be transported and stored via the approximately 600,000 km long gas network and newly laid gas pipelines (see chapter 3.8). By using existing infrastructures, synergies can be utilised in a resource-saving and cost-efficient manner and the large quantities of energy required can be supplied as needed. In addition, transport via the gas pipeline network allows the energy supply to be made more flexible and stabilised, also with regard to import capability. [15, 16]

The decarbonisation of the natural gas system with hydrogen is a central component of the German energy transition. By utilising existing infrastructures, integrating renewable energies and the many possible applications of hydrogen, Germany can achieve its climate targets and shape a secure, sustainable energy future. This technical publication ″An overview of the decarbonisation of the natural gas system with hydrogen″ is intended to show in detail which topics need to be considered for the transport, distribution and use of hydrogen. In addition, the paper clearly shows where there are still technical challenges with regard to the use of hydrogen and which questions have already been answered in terms of safety and operation. Furthermore, the costs of converting the gas infrastructure to hydrogen are shown and it is explained to what extent the technical standards for hydrogen exist and where there is still a need for adaptation.

The aim is to evaluate the opportunity that hydrogen can play in defossilisation from a technical and scientific perspective and thus offer a contribution to a solution-oriented discussion.

2 Safety aspects along the hydrogen value chain based on experience with natural gas

The integrated safety concept of DVGW, which exists since 1990, has always been used to assess and reduce reportable and immediately reportable incidents in the gas supply. Based on the analysis of incidents, cause-orientated measures can be formulated which are incorporated into ▹



Source: [14]

Figure 3: Storage capacity in Germany

the standards. On this basis, specific technical and procedural improvements as well as further training and informational measures have been developed and introduced over decades, which ensure a sustainably high level of safety in the German gas supply. [17]

The experience gained from the operation of city gas and natural gas networks as well as from numerous specific research projects is transferred to hydrogen networks. This provides a stringent safety concept right from the start.

Immediately reportable incidents on operator pipelines

The DVGW has been recording (immediately reportable and reportable) incidents since 1981. Reportable incidents include an accidental release of gas and are recorded as part of an annual report. Immediately reportable incidents, on the other hand, are unintentional gas releases with personal injury, deflagration, explosion, fire, flying debris or other incidents with media impact. The trend in immediately reportable incidents of operator pipelines since 1981 is shown in **Figure** 4. The rate of immediately reportable incidents shows a continuous reduction over the last 20 years, particularly for the number of incidents related to the exposure. Mediaeffective incidents are not taken into account here because they only involve a gas leak with no further consequences. The exposure is calculated by adding the length of the pipeline of the current year to the length of the pipeline of all previous years. This would result in an exposure in Germany of around 14.6 million annual kilometres (km x a) in the period from 1981 to 2022. [18]

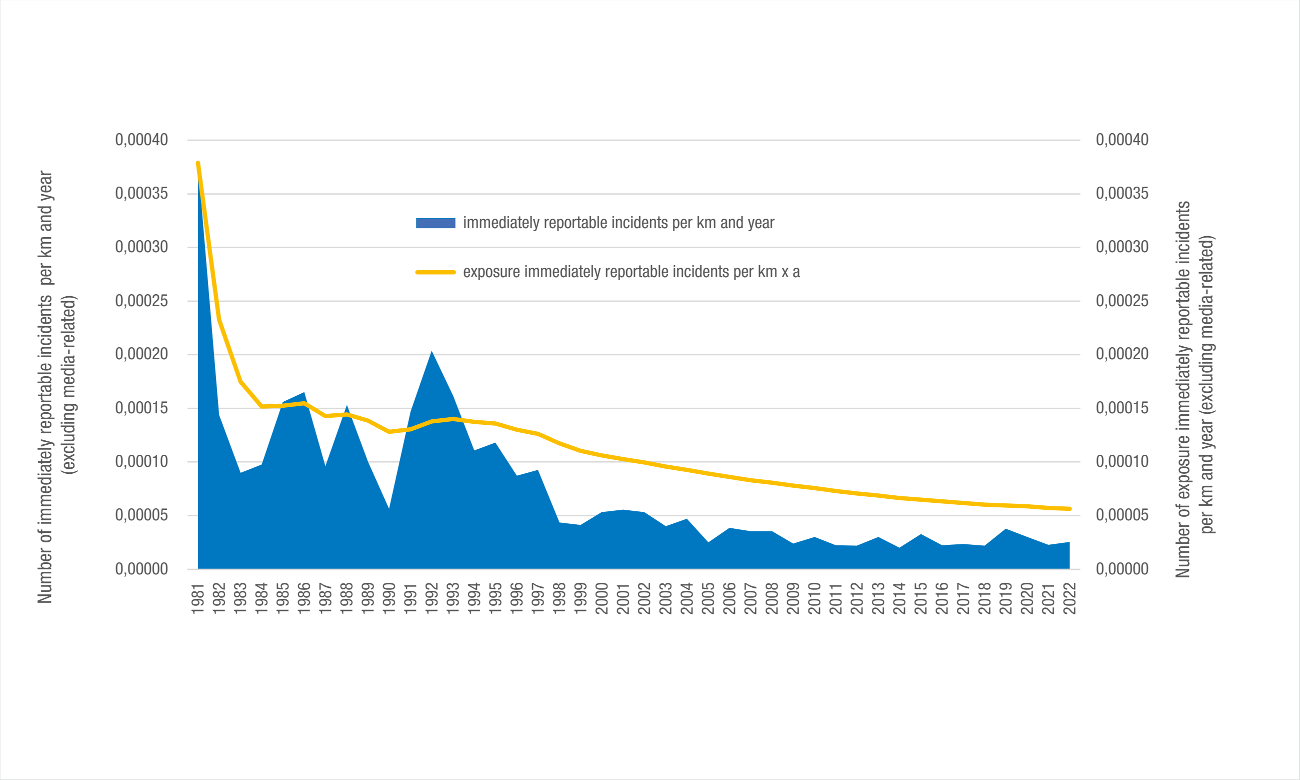
In the European EGIG database, data on all incidents since 1970 is now recorded by 19 gas transmission system operators in Europe. This provides a reliable source of information that is used to determine the failure frequency of pipelines and to analyse the causes of faults. For the year 2022, the failure frequency was 0.277 incidents per 1,00 km*yr [19]. For comparability with this database, the total number of incidents in Germany was also normalised to the total exposure and amounted to 0.0562 incidents per 1,00 km*yr in Germany in 2022 (Fig. 4).

SUMMARY

The introduction of technical and procedural improvements based on incidents recording and analysis has resulted in a consistently high level safety in the German gas supply system, which will also be adapted to the hydrogen network in the future.

Safe handling of hydrogen

For many years, natural gas has been transported, distributed and stored in the existing gas infrastructure at a very high safety level and used in numerous processes in various sectors. The production and utilisation of hydrogen is also nothing new. Several million tonnes of hydrogen have been produced annually for decades in reforming processes, for example, and used for the large-scale industrial production of basic chemicals, among other things. These decades of experience in the safe handling of hydrogen show that its use can be just as safe as that of natural gas.



Source: [18]

Figure 4: Trend in immediately reportable incidents since 1981 of all gas pipelines [18]

Nevertheless, switching from natural gas to hydrogen means switching to an energy source with different physical, chemical and combustion properties (**Tab. 2**), which must be taken into account in the risk assessment along the entire value chain. In order to take account of the specific risk profile of hydrogen during production, in the gas infrastructure and during use, the experience of industry and the gas sector must be built on to achieve a safe value chain. As shown in **Figure 5**, this includes carrying out comprehensive risk assessments and developing safety concepts and standards based on them. In the case of hydrogen, explosion and fire protection and automated ventilation concepts in particular must be defined due to its wider ignition limits. Hydrogen is colourless and odourless, so sensors or odorants are used as required.

In addition, the safety level must be maintained at a consistently high level through regular staff training, maintenance of safety-relevant system components and processes and consideration of the current state of the art.

The database of the European Industrial Gas Association (EIGA) has recorded a total of 208 significant hydrogen-related accidents in the industrial sector since 1976, of which around 21 have occurred in the last ten years (**Fig. 6**). Of these, around 26 % were due to human error, 23 % were process-related problems, while accidents due to contamination (such as air infiltration) and material incompatibilities were less common. Safety requirements are governed by standards and regulations that govern the safe design, maintenance and operation of equipment, systems and installations. These guidelines provide experts and safety officers with the information they need to approve installations. [20]

As the global transition to hydrogen-based energy systems accelerates, ensuring the safety and reliability of hydrogen infrastructure is becoming a critical aspect of regulatory and industrial planning. Hydrogen pipelines are a key component of this infrastructure and must meet stringent safety standards to prevent leaks and operational failures. Historically, these have had low accident rates. Between 2015 ▷

	H_2-Production	Gas infrastructur	Applications
Safety aspects	- Production processes with partly high temperatures & pressures - Colorless & odorless gas with wide ignition limits in air - Gas with smaller molecule size & density than methane	- Colorless & odorless gas with wide ignition limits in air - Gas with smaller molecule size & density than methane - Material compatibility of gas pipes & gas infrastructure components (hydrogen embrittlement)	- Production processes with sometimes high temperatures & pressures - Handling of a gas with physical, chemical and combustion properties that are sometimes very different from those of methane
Actions	- Consideration of current regulations / standards for construction & operation - Consideration of the state of the art based on current research & operating experience - Risk assessments in planning & operating phases (e.g. HAZOP & risk graph) - Safety concept (including explosion protection & fire protection concepts) as a basis for granting construction & operating permits - Oversizing & regular testing of pressure vessels	- Compliance with & further development of technical regulations based on current research projects and operating experience - Safety concept with risk assessments & needs-based explosion protection, ventilation concept & use of blowers & sensors - Use of H_2-ready products, components & materials - Adaptation of equipment & operating materials - Odorization of hydrogen where necessary for safety reasons - Adaptation of technical processes, including operating & maintenance strategies, taking occupational health & safety into account - Organizational safety - technical safety management	- Consideration of current regulations / standards for construction and operation - Consideration of extensive operating experience with industrial H_2 applications - Consideration of dedicated research & development projects with adapted & newly developed burner systems - Risk assessments in planning & operating phases (e.g. HAZOP & risk graph) - Safety concept (including explosion protection & fire protection concepts) as a basis for the granting of construction & operating permits - Oversizing & regular testing of pressure vessels
	- Qualification of specialists and service providers through regular training courses - Acceptance by experts - Regular maintenance		

Source: DVGW

Figure 5: Safety aspects and measures to maintain a high level of safety for various links in the hydrogen value chain

and 2019, the normalised leakage rate for hydrogen pipelines was around 0.09 incidents per 1,000 km per year. In comparison, natural gas pipelines in the United States and Europe have rates of 0.16 and 0.13 incidents per 1,000 km per year respectively over the same period [21]. Even if the numbers are not directly comparable, they at least provide an indication that hydrogen networks can be operated with an equivalent level of safety as natural gas networks.

SUMMARY

Hydrogen is just as safe as natural gas when handled properly and in compliance with the technical standards. Hazards do not usually arise from the substance itself, but often from human error. As with natural gas, safety depends largely on users recognising the specific properties and observing appropriate safety measures.

3 Gas infrastructure in Germany

The existing gas pipeline network, which is almost 600,000 km long, enables large quantities of energy to be transported safely over long distances throughout Germany [14, 15]. The gas transport network consists of around 40,000 km of high-pressure gas pipelines, over 90 % of which are made of steel [1, 2]. The German gas distribution network covers a total length of around 560,000 km. The pipelines in Germany are made of: [24]

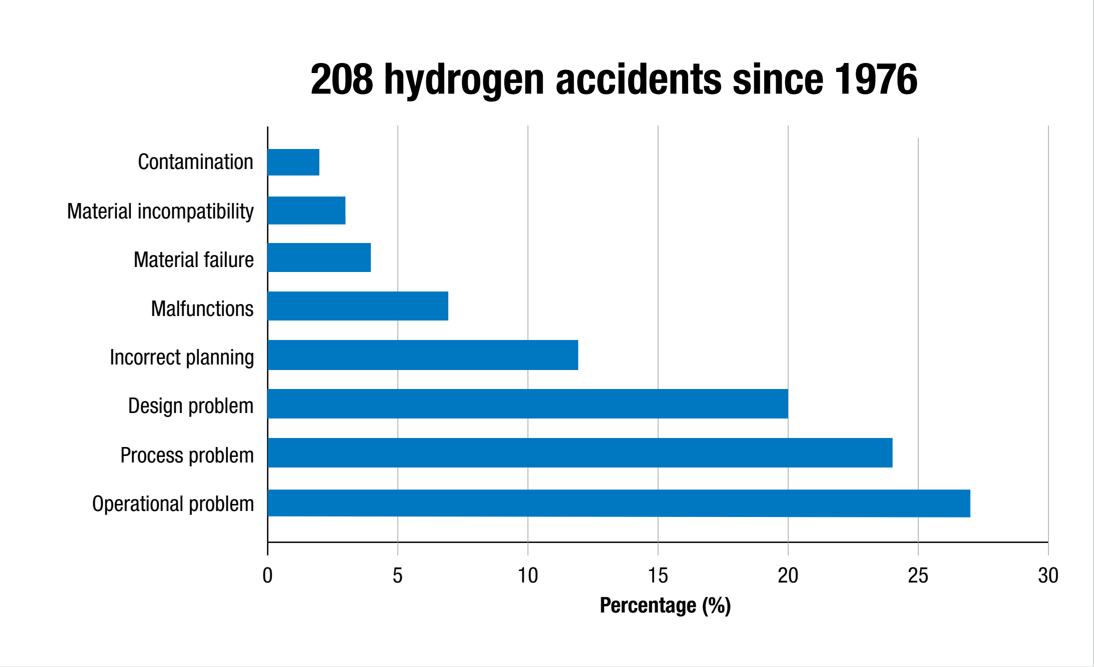
- Plastic (approx. 69 %)
- Steel (28 %)
- Ductile cast iron (1.3 %)
- Grey cast iron, laminar (0.02 %)
- Unknown material (1.3 %)

Due to the physical and chemical differences between natural gas and hydrogen mentioned in the chapter 2, it is important to ensure compatibility and safe and reliable operation. The specific challenges are therefore discussed below. In the case of metallic pipelines, this concerns the phenomena of corrosion and hydrogen embrittlement and, for all pipelines, tightness.

3.1 Influence of hydrogen on the material

Fundamentals of hydrogen embrittlement in metallic materials

Hydrogen embrittlement is a phenomenon in which hydrogen can penetrate metallic materials and influence their mechanical properties. High-strength steels can be particularly affected due to their brittleness, in which the diffusion of hydrogen under certain conditions, such as high pressure, can influence the toughness and load-bearing capacity. This can lead to an increased susceptibility to cracking and ultimately to component failure under load [25]. In the case of hydrogen embrittlement in metal materials, hydrogen is broken down into atomic hydrogen atoms (H atoms), which are adsorbed on the inner surface of the metal, especially on fresh cracks or bare surfaces (**Fig. 7a**). These H atoms



Source: [20]

Figure 6: Main causes of hydrogen releases

diffuse through the metal lattice and collect at the lattice defects (**Fig. 7b**). There they exert a localised stress that weakens the lattice and can ultimately lead to fracture. This process initiates and promotes the propagation of cracks (**Fig. 7c**), which impairs the structural integrity of the material and increases the risk of component failure [26]. By reducing inclusions and defects in the materials of pipes and fittings, the likelihood of cracking due to hydrogen embrittlement can be significantly reduced.

Pressure and pressure fluctuations are key factors for assessing the effects of hydrogen embrittlement on steel and other metal pipelines [26]. The topic of pressure is therefore examined in more detail below.

Influence of pressure and pressure fluctuations using the example of pipelines

Pressure fluctuations can lead to fatigue failure in pipelines [27]. This fatigue failure occurs in two phases: Crack initiation and crack propagation [28]. Internal crack initiation typically begins at non-metallic inclusions, defects or flaws, followed by subsequent crack propagation [29]. The pressure fluctuation loads in pipelines can accelerate the initiation and propagation of cracks. Over time, the crack continues to grow until the pipeline can no longer withstand the maximum pressure, which eventually leads to rapid failure [27].

Experimental and practical studies show that pressure fluctuations of hydrogen gas in pipelines under normal operating conditions do not lead to failure or significant wear of the pipelines. Pressure cycling tests in the UK gas network, simulating 50 years of the highest voltage fluctuations, did not reveal any pipe ruptures or significant deterioration in performance. Minimal degradation was recorded in the elongation and other material properties of the steel samples, with the greatest effects occurring in the vicinity of welds. This underlines the importance of weld quality and highlights the need for further analysis and potential monitoring of welded pipes in hydrogen service [30].

Another study carried out on a pilot gas network in Hørsholm, Denmark, investigated the effects of 100 % hydrogen by volume on gas pipelines. The pipelines studied were made of API 5L X70 carbon steel with a diameter of 20 inches and a wall thickness of 7 mm. The pipe sections contained circumferential weld seams. As part of the tests, pressure cycling was carried out at a maximum pressure of 70 bar. Each test series comprised 15,000 and 30,000 cycles, which corresponds to a service life of 40 and 80 years respectively, based on one pressure cycle per day.

The dynamic tests, which simulated operating times of up to 80 years with pressure fluctuations that were twice as high as the maximum fluctuations in the Danish gas transmission system, sho-

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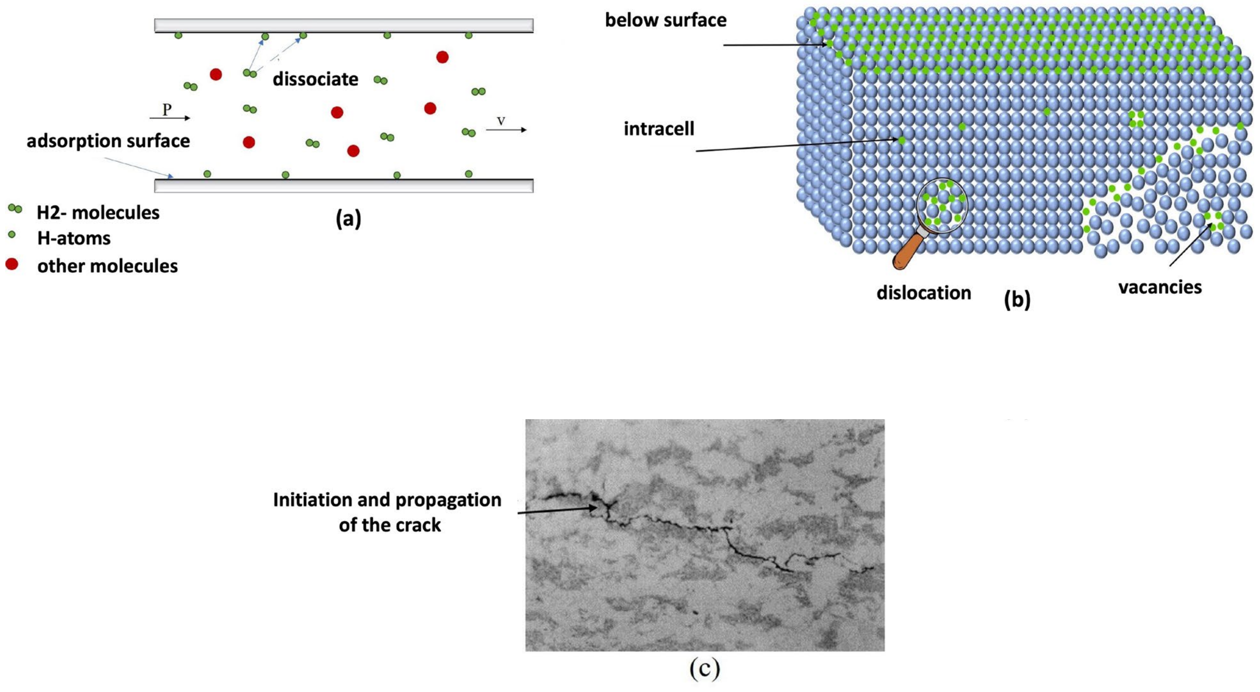


Source: [26]

Figure 7: (a) Dissociation and adsorption of hydrogen on the inner surface "Steel material as an example", (b) The H atoms migrate in the lattice structure and attach to lattice defects, (c) Hydrogen breaks the lattice, which leads to the initiation and propagation of the crack

wed no growth of material defects. These results suggest that the addition of hydrogen to existing transport network pipelines is technically feasible, provided the pipelines do not have any significant weld defects [31].

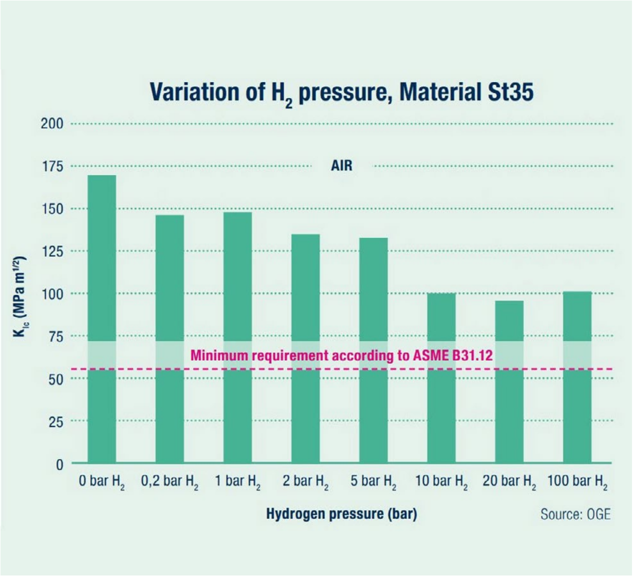
Another study, which was carried out from September 2020 to January 2023 as part of the SyWeSt H2 project, investigated the hydrogen suitability of steel, which is typically used in gas pipelines in Germany and Europe [32].

Fracture mechanics tests on common steel grades in Germany and Europe were compared to the American standard ASME B31.12 to assess the effects of hydrogen exposure. **Figure 8** shows a slight decrease in the fracture toughness (K_{Ic}) of steel (St35) with increasing hydrogen pressure before stabilisation occurs, with all values above the ASME B31.12 limits [33].

Figure 9 shows a conservative modelling of crack growth in a steel pipe (DN 600, DP 67.5, L 415, wall thickness 8 mm) with a defined defect (50 mm long, 0.8 mm deep) assuming a daily pressure fluctuation of 10 bar. The simulation shows a minimal progressive crack growth over 100 years and a possible failure only after 10,000 years. These results confirm the complete hydrogen suitability of the tested steel materials under the usual operating conditions in the transport network, support the adaptation of the DVGW standards and enable the safe use of existing gas networks for hydrogen transport [33].

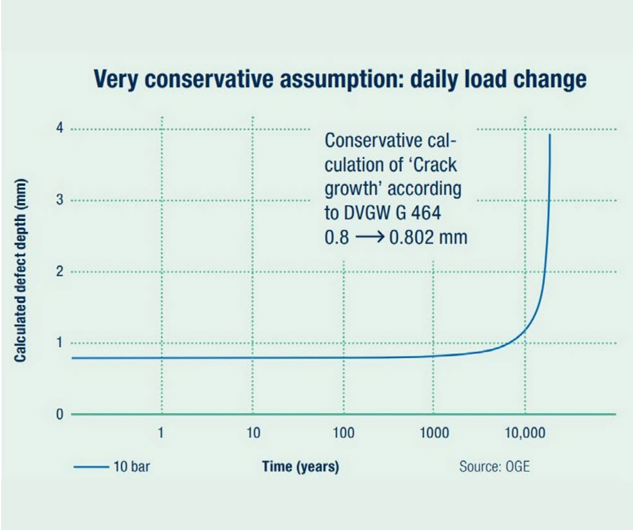
SUMMARY

The gas network in Germany is mainly made of plastic and steel. When adapting the system for hydrogen transport, one of the biggest challenges is hydrogen embrittlement in metal pipelines, which can weaken the material and favour the formation of cracks. Under realistic conditions, such as pressure fluctuations and hydrogen exposure, existing steel pipelines remain structurally flawless. Long-term tests and fracture mechanics analyses prove the suitability of the material and confirm the technical feasibility of using the current gas transport and distribution network for hydrogen.



Source: [33]

Figure 8: Influence of hydrogen pressure on the fracture toughness (K_{Ic}) of steel St 35



Source: [33]

Figure 9: Conservative calculation of crack growth in a steel pipe under daily fluctuations

3.1.1 Proof of suitability for steel pipelines and valves

Materials must be selected and operated in such a way that they meet the requirements for integrity and tightness over the entire service life. Even though gas pipelines are generally subject to predominantly static loads and therefore only a negligible growth of defects occurs, potential crack growth can be greater when operating a high-pressure gas pipeline with hydrogen than with natural gas due to hydrogen embrittlement. The hydrogen suitability of the gas pipeline must therefore be verified. For high-pressure gas pipelines made of steel pipes with a design pressure of more than 16 bar, a fracture mechanics assessment in accordance with DVGW Code of Practice G 464 is required [34]. Extensive investigations as part of SyWeSt H2 (see also chapter 3.1) show that the steel materials used are generally suitable for hydrogen [32].

As part of the research and development project BAG464 ″Fracture mechanics of hydrogen pipelines″, fracture mechanics assessments were also carried out for the gas distribution network. An area was identified in which fracture mechanics assessments under conservative boundary conditions offer no additional benefit for the safe design of the pipelines. This area fulfils several criteria for a safe design and shows that with a maximum allowable operating pressure (MOP) of $p \leq 16$ bar, a fracture mechanics assessment is only necessary in rare exceptional cases. [35]

With an MOP of $p \leq 12$ bar, no fracture mechanics assessments are generally required if the described boundary conditions are observed, regardless of the pipe outside diameter and steel material. For an MOP of 12 bar ≤ p ≤ 16 bar, no fracture mechanics assessments are required up to including DN 200. For larger diameters, however, individual case analyses must be carried out. [35]

There are also other research projects on the subject of valves, such as KuFeH2, LeA H2 and UWaSpin H2 as well as UKoBaRi H2 and UKoBaRiS H2.

KuFeH2 focused on the long-term behaviour of surface coatings on shut-off valves and spring assemblies in operation with hydrogen. This involved simulating a load period of around 50 years in order to determine the extent to which a pure hydrogen atmosphere influences the stability of different types of surface coatings on shut-off valves or the properties of cyclically loaded compression springs. It was shown that the influence of hydrogen on the coatings and the base material as well as their hardness were marginal, so that it can be assumed that they are suitable for operation with pure hydrogen. From the determination of the spring forces, no influence of the load changes under hydrogen atmosphere could be determined, regardless of the material, so that a general suitability of the investigated spring assemblies can be assumed. [36]

The aim of UWaSpin H2 + LeA H2 was to investigate the possible applications and limits of shut-off valves with regard to their hydrogen tightness and the expansion of the standards. The project focussed on the internal and external tightness of existing valves in the gas network, whereby various designs and sealing systems such as shut-off bodies and spindles were investigated with regard to hydrogen tightness. In particular, the focus was on recording the immediate leakage rate and long-term tests on the hydrogen resistance of valves, testing the tightness in the area of the stuffing boxes and spindle seals and recording possible interactions with hydrogen. The investigations of the valve samples showed that the existing network is in a hydrogen-compatible condition, particularly with regard to external leak tightness, which forms the basis for a future conversion to hydrogen operation. Nevertheless, a condition inspection and assessment of the affected valves should be carried out before a planned pipeline conversion. [37]

The focus of UKoBaRi H2 "Investigation of existing valve designs with regard to crack initiation in a hydrogen atmosphere" was to investigate the integrity of existing valves in operation with hydrogen. In combination with experimentally determined, fracture-mechanical material properties with computational verification methods, a safe operation for the existing valves was to be derived. The evaluation method should be applicable to different valve types and geometries as far as possible. Using fracture mechanics calculations, sufficient safety against the failure of an existing valve with an existing or postulated crack-like defect was to be guaranteed. The focus was on finite element analyses (FEA) for representative valve designs and the performance of elastic stress analyses. These findings were incorporated into the UKoBaRiS H2 research project. In order to assess the fracture mechanics of the valves, it is essential to calculate the residual welding stress (SES) of weld seams and their effect on fracture mechanical behaviour. Up to now, these values have been estimated conservatively using recommended rules and standards and material data. This is where the research project comes in and determines the SES for a representative cross-section of the materials used in the gas networks and the types of welding used for the valves. The aim was to calculate realistic operating conditions and statements about the service life of valves in the future hydrogen network. Taking into account the numerically determined residual stresses, sufficient safety reserves for operation in pressurised hydrogen can be demonstrated for all valves investigated. The findings from the project are representative of existing valves installed in the gas transport system and have been incorporated into DVGW Code of Practice G 405. [38]

Further requirements for materials and components for gas pipelines are specified in DVGW Code of Practice G 462, G 463, G 265-3 and DVGW Code of Practice G 221 as well as in G 405 for existing valves and G 406 for new valves. The hydrogen suitability of individual components can be found in the DVGW verifHy database. [39]

SUMMARY

Research projects show that the steel materials and valves used are generally suitable for hydrogen. Under certain operating conditions, fracture mechanics assessments must be carried out to ensure the safe operation of steel pipelines.

3.1.2 Proof of suitability for plastic pipes

To assess the suitability of commercially available pipe and moulded part solutions for hydrogen transport, the plastic pipe industry has conducted numerous studies. These studies, including international and national test field and pilot installations, have shown that even after several years of exposure to hydrogen (at 100 % hydrogen by volume), no negative effects on the durability of PE or PVC materials have been observed [40]. Based on these studies and investigations, both the German plastic pipe association KRV and the European plastic pipe association teppfa have confirmed the hydrogen suitability of pipes and moulded parts made of PE63, PE80, PE100, PE100-RC, PA-U12 and PVC. No restrictions are expected in the system analysis either. [41, 42]

3.1.3 Proof of suitability for ductile cast iron

In Germany, less than 10,000 km of the pipelines in various gas distribution networks are made of ductile cast iron instead of steel or plastic. These pipelines could be used to supply hydrogen or hydrogen-containing gases in the future, provided the material is suitable. The H_2 ductile cast iron project ▷

investigated whether ductile cast iron pipelines can be operated safely for the transport and distribution of hydrogen. The aim was to adapt the DVGW standards for the transport and supply of hydrogen and hydrogen-containing gases, similar to what has already been done for steel and plastic. [43]

The tests showed consistently positive results. The results of the testing of representative components indicate that no negative changes are to be expected when converting existing ductile iron systems to hydrogen gas under constant operating conditions. In a follow-up study, open questions are to be clarified in order to generally ensure the utilisation of ductile casting systems for operation with hydrogen. [43]

3.1.4 Grey cast iron

Cast iron pipes were dismantled in Germany except for a few kilometres because they have significant disadvantages compared to modern materials. In particular, their brittleness and susceptibility to corrosion led to an increased risk of breakage and a shortened service life. For this reason, no new gas pipelines have been built from grey cast iron since 1960 and existing grey cast iron pipelines have increasingly been replaced by ductile iron pipes or other materials. Due to a series of accidents, the grey cast iron rehabilitation programme was launched at the end of the 1990s, which provided for the dismantling of grey cast iron pipelines in Germany. As a result, the number of grey cast iron pipes has been reduced from approx. 10,000 km to 84 km since the end of the 1990s. [44] For these reasons, the use of grey cast iron pipes for operation with hydrogen is ruled out.

3.2 Construction and conversion of gas pipelines to hydrogen

The construction of new hydrogen pipelines made of steel or plastic is based on DVGW standards. DVGW Code of Practice G 462, G 463, G 472 and G 265-3 and DVGW Code of Practice G 221 must be applied. Areas such as welds and potential defects can be checked in accordance with GW 350. In order to ensure safety when using hydrogen in existing pipelines, a more intensive inspection is carried out at important operating points for a certain period of time after the conversion. With regard to explosion safety, the requirements of Ordinance on Hazardous Substances (GefStoffV) and Ordinance on operational reliability (BetrSichV) must be observed. Qualification requirements for construction companies for pipelines for hydrogen are specified in DVGW Code of Practice GW 301. [34]

The basic prerequisite for the use of hydrogen in the existing gas infrastructure is the technical suitability of the system. The influence on the pipeline material requires precise testing and assessment. DVGW Code of Practice G 407 and G 408 for gas distribution and G 409 for gas transport apply to the conversion of gas pipelines for hydrogen. Requirements for new valves or for valves in hydrogen pipelines to be converted are specified in DVGW Code of Practice G 405 and G 406. Conversion to operation with hydrogen can be a significant change that requires corresponding tests and certificates. [34]

The interfaces to the connected systems must be considered as an overall system of gas infrastructures. Transport pipelines and distribution networks are prepared for a conversion to hydrogen if the connected networks and connection users are also prepared. The network operator needs precise knowledge of all entry and exit points as well as appropriate planning for the conversion. All necessary test certificates must be available at the time of conversion. [34]

SUMMARY

The future hydrogen network will consist of converted and newly constructed pipelines. A comprehensive set of technical standards already exists for the construction and conversion.

3.3 Construction and conversion of storage facilities to hydrogen

The update of the National Hydrogen Strategy emphasises the importance of developing a concept for hydrogen storage. In an energy system that is increasingly characterised by volatility due to the strong growth of renewable energies, this can create a temporal decoupling of generation and demand, which is essential for year-round security of supply. [45]

Table 1 shows current projects for the conversion and new construction of underground hydrogen storage facilities in Germany. The results and experience gained from these projects must be incorporated in future into a set of technical standards that enable safe operation of the entire storage site with hydrogen. The different conditions in cavern and pore storage facilities must be taken into account.

3.4 Leakage

Hydrogen leaks pose a particular challenge due to the low density and small molecular size, as the permeation rate of hydrogen is theoretically four to five times higher than that of methane [54].

This underlines the need for comprehensive research into the leakage and accumulation behaviour of hydrogen and gas mixtures in order to ensure safety. However, the leakage rate is highly dependent on the operating pressure in the pipelines. According to Mejia et al., practical measurements on existing low-pressure natural gas infrastructures show that hydrogen and methane can leak at comparable rates under similar conditions [55]. Therefore, the use of hydrogen in domestic low-pressure systems is harmless in terms of leakage rates.

Dedicated hydrogen pipelines, including those converted from steel natural gas pipelines, typically have low leakage rates. By 2050, it is estimated that around 76.5 million tonnes of hydrogen will be transported annually via local distribution networks – of which around 0.4 % could be lost during transport through

Table 1: Projects for the conversion and new construction of underground hydrogen storage facilities in Germany (as of March 2025)

Project/Company	Location	Capacity	Completion
GET H2 [46]	Epe	265 GWh	2027-2029
Hydrogen Pilot Cavern [47]	Krummhörn	250 GWh	2029
SaltHy [48]	Harsefeld	250 GWh	2030-2032
JemgumH2 [49]	Jemgum	200 GWh	2029
Green Octopus [46]	Bad Lauchstädt	150 GWh	2028
TH2Eco [50]	Kirchheilingen	140 GWh	n. b.
Clean Hydrogen Coastline [51]	Huntorf	70 GWh	2027
HyCAVmobil [52]	Rüdersdorf	Research	in operation
H2Cast Etzel [53]	Etzel	Research	2025

Source: DVGW

the pipelines. If other components of the gas infrastructure, such as storage facilities and compression processes, are taken into account, the potential hydrogen losses increase [56].

In steel and ductile iron distribution network pipelines, the majority of leaks occur mainly via threaded connections or mechanical joints [57]. Preventing and repairing hydrogen leaks requires strict safety measures and procedures. In hydrogen piping systems, seals, gaskets and joints must be designed to withstand the high-pressure hydrogen gas and ensure leak-free operation over an extended period of time. [58]

Plastic pipes, especially those made of polyethylene (PE), are frequently used in most distribution networks. Despite the higher diffusion rate of hydrogen compared to natural gas, leakage losses in PE pipes are minimal. Studies show that the annual hydrogen losses due to leaks only account for 0.0005–0.001 % of the total transported volume [59]. The pilot study in Denmark shows that four years of exposure to hydrogen has no negative impact on the performance of PE80 and PE100 pipes, including their oxidative resistance, mechanical properties and slow crack growth resistance. These results prove that both MDPE PE80 and HDPE PE100 are suitable for hydrogen transport. In addition, pipes previously used for natural gas transport show no deterioration in these properties even after 20 years, and show the same performance as new pipes after a total of 24 years of use for natural gas and hydrogen transport. [60]

DVGW Code of Practice G 469 specifies the pressure test procedures that are used to verify the strength and tightness of a pipeline or system before commissioning. This has always been based on proper operation with natural gas. In the future, pipelines and systems in gas distribution will have to be tested if they are converted or constructed for proper operation with hydrogen. As hydrogen has different physical properties to natural gas, which call into question the suitability of the existing pressure test methods for safe operation, the DVGW has carried out the ECLHYPSE "Leakage rate gas mixtures" research project. The research results show that some pressure test methods need to be adapted so that safe operation of a pipeline or system is guaranteed for proper operation with hydrogen (5th gas family according to DVGW Code of Practice G 260) [61].

3.5 Technical operation

The organisation and equipment of the technical operation for hydrogen applications includes ▹

- Qualification of specialists and service providers
- Adaptation of technical processes and equipment
- Adaptation of risk assessments and protective measures
- Organisational safety - Technical Safety Management (TSM)

Specifications for this can be found in DVGW Code of Practice G 466-1, G 465 series and DVGW Code of Practice G 221. The requirements for the qualification and organisation of companies for the operation of pipelines and systems for the pipeline-based supply of gas and hydrogen are described in DVGW Code of Practice G 1000, G 1010 and G 1030 as part of technical safety management. The qualification requirements for gas infrastructure experts are incorporated in the DVGW Code of Practice of the G 102 series. [34]

SUMMARY

Leaks occur at threaded joints and mechanical connections, which in the case of hydrogen require more stringent sealing measures than natural gas due to the smaller molecular size.

3.6 Necessary adaptations of components for the integration of hydrogen in the gas network

The integration of hydrogen into existing gas networks requires a thorough assessment of the infrastructure components to ensure safe and efficient operation. Certain components in gas transport and distribution networks are already suitable for 100 % hydrogen by volume and do not require adaptation or renewal. These include the pressure regulator, the house pressure regulator and the house inlet combination and main shut-off device (ball valve) [62]. However, certain other components in the gas network and in the application technology must be replaced or adapted before the switch from natural gas to hydrogen can take place. The most important of these are explained here.

Compressor stations

The existing natural gas compressor stations must always be converted for operation with pure hydrogen. For the 5th gas family, the entire compressor station must be thermodynamically designed, including the machine technology used. The reason for this lies in the considerable changes in the flow parameters compared to natural gas. For example, due to the lower volumetric energy density of hydrogen compared to natural gas, a significantly higher compressor drive power is required to achieve the same energetic transport capacity [63].

Filter

The technical-physical function of a filter, which mechanically cleans the gas flow of accompanying substances, is independent of the type of gas. With increasing hydrogen concentration in the gas mixture and while maintaining the energetically constant transport capacity (which means an increase in flow velocity), the specific surface load of the filter increases. For example, a hydrogen content of 25 % by volume leads to an almost 30 % higher surface load of the filter. Similar to steel materials, the material resistance remains guaranteed up to a hydrogen content of 100 % by volume. The static load on the filter housing is therefore not considered to be critical. However, depending on the previous design of the filter, replacement may be necessary at higher hydrogen concentrations. The durability of filter materials in hydrogen applications is particularly critical at high flow rates. Increased flow rates can lead to higher pressure losses, lower dust collection efficiency and material damage. Therefore, filters specifically designed for hydrogen are essential [64]. Based on experience from the time of town gas utilisation, when the gas mixture contained at least 40 % hydrogen by volume (1st gas family, Group A, DVGW G 260:2000), the suitability of the filter for hydrogen is set at 40 % by volume [62]. It should be noted that for operation with the 5th gas family, the design of the filter must be checked in each individual case.

Preheater

The required preheating capacity for gas decreases with increasing hydrogen content in the gas mixture, provided that the energetic transport capacity remains constant. This is due to the inverse Joule-Thomson effect compared to natural gas. According to calculations with the "GasCalc" software, the Joule-Thomson coefficient becomes less than or equal to zero from a hydrogen content of around 85 % by volume under the operating conditions of a compressor station. This means that as the hydrogen content continues to increase, the gas mixture is expected to heat up during expansion. Based on experience from the town gas era, in which the gas mixture contained at least 40 % hydrogen by volume (1st gas family, Group A, DVGW G 260:2000), the hydrogen suitability of the preheater is set at 40 % by volume [62]. This means that the current preheating technology used for natural gas can heat a mixture of natural gas and up to 40 % hydrogen by volume. No preheating is required for operation with the 5th gas family due to the specific Joule-Thompson effect of hydrogen.

Safety valves (SAV and SBV)

Several manufacturers, including Fiorentini, Honeywell, Itron and gAvilar, confirm that safety valves are suitable and resistant for use with hydrogen. In the DVGW research project "Development of modular concepts for the production, storage and feed-in of hydrogen and methane into the natural gas network", it was assumed that the components of control systems sold in Europe are approved and suitable for gases with a hydrogen content of up to at least 60 % by volume. From the manufacturer's specifications and the results of the aforementioned research project, it can be deduced that the safety shut-off valves (SSV) and safety blow-off valves (SBV) are suitable for a hydrogen content of up to 60 % by volume in the best case [62]. Any uncertainties will be clarified by an ongoing research project at the DVGW.

Gas flow monitors

Since 2002, gas flow monitors have been mandatory in mains connection pipes in the pressure range 25 mbar < p ≤ 5 bar in Germany. There are currently two disc designs: with and without overflow opening. Without an overflow opening, the disc of the gas flow switch must be opened again from the closed position by applying counterpressure from the downstream side. The majority of gas flow monitors installed in Germany have a so-called overflow opening in the valve disc. A maximum of 30 litres of air per hour may flow through here at the design point [65].

The three volume flows – design flow, response flow and overflow – increase by a factor of 2.8 from methane to hydrogen, i.e. the overflow volume flow will increase from 40 l/h methane (30 l/h air) to 114 l/h for hydrogen. In this case, the network operator is obliged to passively protect the indoor installation in accordance with DVGW Code of Practice G 459-1 until the first active measure is taken. This will probably always be the case when switching to hydrogen [61, 65].

To summarise: The gas flow monitors do not need to be replaced for the use of hydrogen with the same load. This has been confirmed in numerous pilot projects [40, 65, 66].

Process gas chromatographs (PGC)

PGCs are generally not able to analyse hydrogen in the gas mixture and often only have a limited suitability for hydrogen, which is 0.2 vol.-%. According to the manufacturer, the measurement of up to 20 vol.-% hydrogen in the gas mixture can be made possible by officially tested retrofitting of individual existing devices [62]. For operation with higher hydrogen contents, the use of new, hydrogen-compatible PGCs is required, which enable precise purity analysis. This requires optimised calibration, the use of suitable carrier gases, high-precision sensors and software modifications to ensure maximum measurement accuracy and calibration capability [67].

Gas meters

Gas meters in the distribution network would have to be retrofitted or replaced to a considerable extent if more than 20 % hydrogen by volume is used. Due to three times higher gas volume flows with hydrogen in order to deliver the same energy content to the consumer as with fossil gas, the demands on the measuring performance of the gas meters increase immensely. Furthermore, diaphragm gas meters must be checked before a changeover, as they use large elastomer or polymer components which could under-read the flow rate for hydrogen-containing gas mixtures [68]. All gas meters approved for natural gas are approved for hydrogen concentrations of up to 5 % by volume in accordance with PTB TR G1914. Use with hydrogen contents of up to 10 % by volume must be expressly authorised in the corresponding manufacturer documentation. In addition to the manufacturer's declaration, a clearance certificate from the PTB is also required for the use of gas meters with hydrogen concentrations above 10 % by volume, including pure hydrogen. According to the manufacturer, rotary gas meters, turbine gas meters and ultrasonic gas meters are suitable for hydrogen contents of at least 10 % by volume from a material, functional and safety point of view [62]. Diaphragm gas meters that fall within the scope of TRGI (DVGW G 600) can be used for hydrogen contents of up to 20 % by volume. [69]

State volume correctors are special calculation units that convert the gas volume flow from operating conditions to standard conditions. The compressibility number (K) is calculated using various mathematical models, such as GERG2004, GERG2008, AGA8 and SGERG-88. However, these functional equations are subject to certain limitations, as a high accuracy of ≤ 0.1 % or ≤ 0.25 % deviation compared to real measurement results is required (see DIN EN ISO 12213-1 and DVGW G 685-6). As a result, state volume correctors can process a maximum hydrogen content of 10 mol % (for SGERG-88 and AGA8) or approx. 40 mol % (for GERG2004/08) when using these models. For hydrogen, the AGA8 equation can be used in state correctors in accordance with DIN EN ISO 12213-2 and DVGW G 265-3. [62]

▷

Figure 10 shows a general overview of the suitability of the gas network components for a conversion to hydrogen, given in per cent by volume.

There are a large number of appliances in German households and businesses that run on natural gas. These include hot water heaters, gas heating systems, room heaters, cookers and ovens. When switching from natural gas to hydrogen, these must either be adapted or replaced. [71]

SUMMARY

The integration of hydrogen into existing gas networks requires careful testing of the components to ensure safe and efficient operation. Certain components in gas transport and distribution networks are already suitable for 100% hydrogen by volume and do not require adaptation or replacement. Components such as compressors, filters, gas meters and chromatographs must be adapted or replaced due to the specific properties of hydrogen. Components such as gas flow monitors and some safety valves can remain in operation with minimal modifications. Household appliances must also be adapted or replaced for the full utilisation of hydrogen.

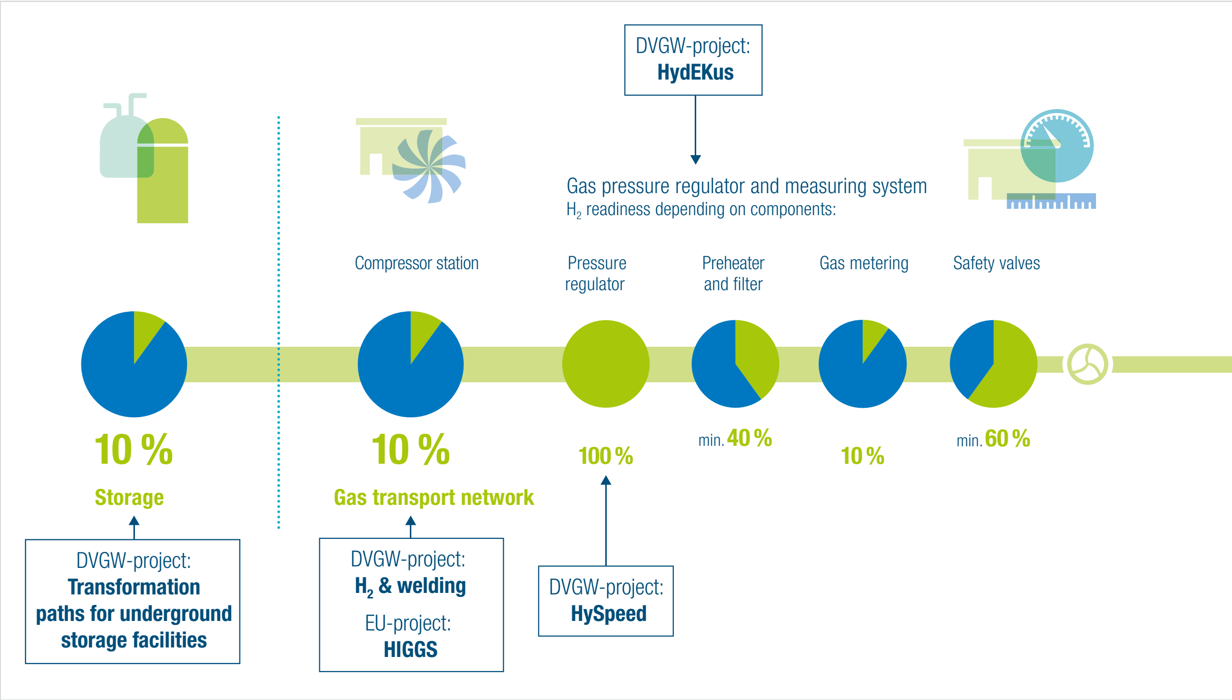
3.7 Scientifically based derivations for the technical standards

Suitability of existing pipelines for hydrogen transport

Analysing the suitability of gas networks for the use of hydrogen involves two main levels of consideration: the material suitability of the pipelines and the suitability of the network components, both in the transport network and in the distribution network. As the pressure and material in the transport and distribution networks are different, it is necessary to consider hydrogen suitability in both network types separately. Existing pipelines can be used for hydrogen transport if pressure fluctuations are limited to a manageable level and the maximum operating pressure is controlled. This approach can help to reduce the costs of hydrogen transport, although the suitability of each pipeline must be assessed individually. Factors such as potential leaks, the effects of hydrogen on pipe materials and hydrogen embrittlement, which can affect the pipes, fittings and end-user equipment, must be considered. [72]

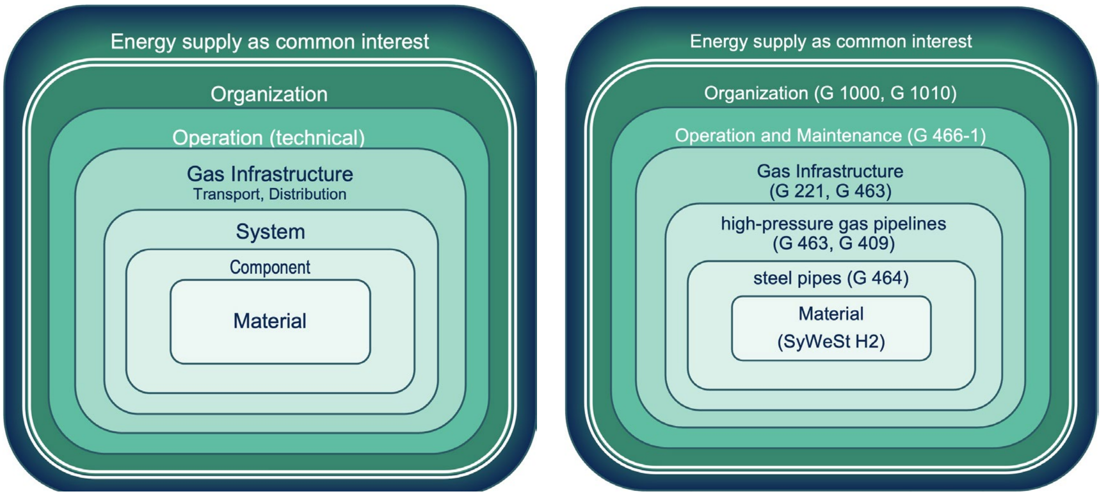
Assessment of gas pipelines for hydrogen applications

The assessment criteria for newly constructed or converted gas pipelines are defined in various DVGW regulations. The shell modell of DVGW Information GAS No. 29 (**Fig. 11**) illustrates the different assessment levels, from material testing



Source: [70]

Figure 10: General overview of the suitability of gas network components for hydrogen conversion by volume percentage



Source: [34]

Figure 11: Levels for the application of the term "H_2-ready"; general representation according to DVGW information GAS No. 29 (left), representation for high-pressure gas pipelines (right)

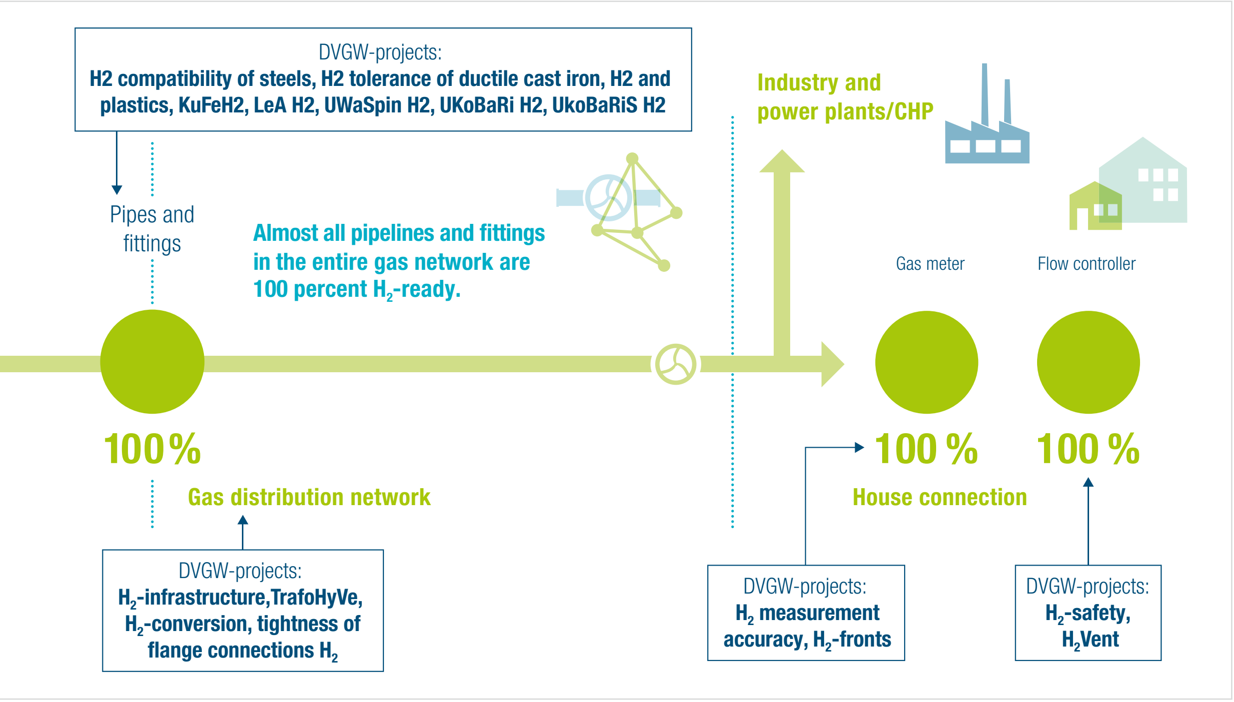
to technical operation. H_2-readiness and operation with hydrogen is only possible if all requirements are met. H_2-ready means that a gas pipeline is prepared for operation with hydrogen, although additional measures may be required. [34]

For the basic suitability of a material for use with hydrogen, the specific design of the component, the operating conditions and the current condition (integrity) must be known. The assessment levels are described in various DVGW regulations and summarised for high-pressure gas pipelines in Figure 11. [34]

3.8 Capacity of hydrogen transport in the gas network

The existing gas network in Germany and Europe offers an efficient basis for hydrogen transport, with 40,000 km of transport networks and 560,000 km of distribution networks, which enable extensive integration with little new construction [15]. As hydrogen has a lower volumetric energy density ($\sim$3.5 kWh/Nm^3 compared to $\sim$11 kWh/Nm^3 for natural gas), the flow rate must be increased by a factor of about three to transport the same amount of energy. Due to the approximately nine times

▷



lower density of hydrogen, this is possible with a slightly higher pressure loss, so that when converting a transport pipeline to hydrogen, a comparable amount of energy can be transported per unit of time at analogue inlet and outlet pressures. [73, 74]

As part of a publication by the European Hydrogen Backbone, capacity analyses have been carried out for the European hydrogen network. A 48-inch pipeline, one of the largest in the European gas network, can transport up to 17 GW of hydrogen (LHV), while a 36-inch pipeline can transport around 9 GW (LHV).

However, studies by gas transport network operators show that operation with reduced capacity utilisation, for example at 13 GW (LHV) for a 48-inch pipeline and 7 GW for a 36-inch pipeline, enables significantly lower transport costs per MWh. The main reason for this is the reduction in expensive high-performance compressor stations and the associated energy consumption. Although the fixed costs per MWh for the pipeline increase, the lower compressor costs and the reduced energy requirement outweigh this effect. A similar principle applies to new pipelines: if more than 13 GW of capacity is required for a 48-inch hydrogen pipeline, it often makes more economic sense to lay a second pipeline with a similar or greater capacity instead of expanding the existing infrastructure with powerful compressors. The optimum balance between compression and pipeline dimensioning, taking into account the existing gas network infrastructure, is therefore a decisive factor in increasing cost efficiency. [74]

3.9 Infrastructure costs

The cost of converting a gas network from natural gas to hydrogen depends on technical, economic and infrastructural factors. The hydrogen compatibility of components such as pipelines, fittings, compressors, measurement technology and GDRM systems (gas pressure standard and measurement systems) is essential for the costs. Furthermore, upgrades may be necessary due to capacity bottlenecks in the existing network after a switch to hydrogen due to the calorific value of hydrogen (3.54 kWh/m³ NTP) compared to natural gas (e.g. 11.2 kWh/m³ NTP) (Tab. 2). However, this shows that the conversion can be estimated to be rather low due to capacity bottlenecks. On the one hand, due to the physical properties of hydrogen, a higher flow rate can compensate for part of the higher volume flow required. On the other hand, a lower amount of energy is expected to be required in the future, which means that a lower volume flow will be required compared to today. These considerations apply to both the distribution and transport networks. Nevertheless, the distribution networks and transport networks are analysed separately below.

Transport network costs

In the gas transport network, the transmission system operators have determined that hydrogen and natural gas or renewable methane will be transported separately, i.e. no admixture of hydrogen in natural gas/methane needs to be considered. Real planning has also already been carried out in the network development plan for the hydrogen core network, which was approved by the Federal Network Agency on 22 October 2024. As a result, the costs for the approved 9,040 km can be estimated at € 18.9 bn [75]. It should be noted that approx. 60 % of the pipelines are existing pipelines and only approx. 40 % need to be newly built. Converting the infrastructure for hydrogen transport is associated with comparatively low investments, as it only requires 10–15 % of the costs of new construction. [76]

Distribution network costs

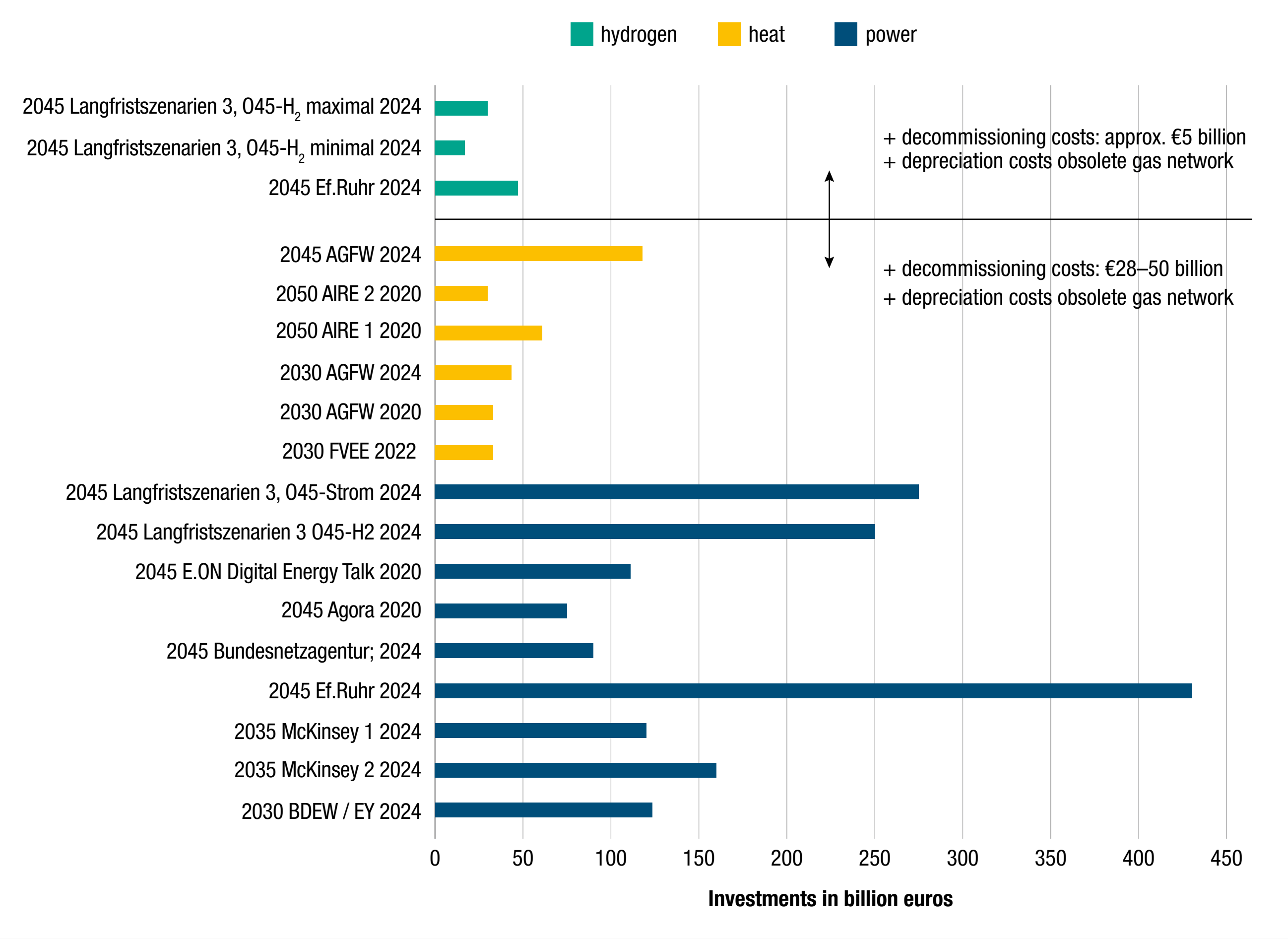
In the gas distribution network, a distinction must be made between admixing hydrogen and converting to hydrogen. The admixture of up to 20 % by volume can be carried out with little effort. Apart from a few components such as measurement technology and safety shut-off valves and undocumented pipe materials (< 1.3 % of the network), the gas network can currently be considered suitable for an admixture of up to 20 % hydrogen by volume. However, individual testing of the network to be converted is currently still advisable and recommended. The requirements of the DVGW standards must be complied with. The costs are therefore more in the manageable range of approx. € 13 bn. [77]

A conversion to 100 % by volume is also already described in the DVGW standards and is significantly more complex than an admixture of 20 % by volume hydrogen. In addition to the material-specific requirements, issues relating to the capacity of the hydrogen network must also be taken into account. According to chapter 3.8, however, no significant restrictions or network expansions are to be expected here, so that the costs for an upgrade are negligible compared to the remaining conversion costs. The conversion costs were estimated in DVGW studies at around € 50 bn, [77, 78] and in the long-term scenarios 3 at € 17 bn (O45-H_2) and € 30 bn (O45 electricity) (Fig. 12) [79]. This includes the replacement of non-hydrogen-compatible components. A key factor in the low costs compared to the expansion scenarios for electricity and local/district heating is the strategy of making components that need to be replaced at regular intervals hydrogen-compatible. This means that only the additional costs for retrofitting can be taken into account. It has been shown (see chapter 3.1) that most materials, fittings and components are already suitable for hydrogen under the operating conditions of the distribution network. The studies have also shown that most of the components to be replaced are above ground and therefore easily accessible. It should also be noted that further knowledge regarding hydrogen compatibility is gradually being gained in order to close gaps and further substantiate the findings to date. This in turn means that the stated costs are calculated rather conservatively.

When analysing costs, it should also be noted that an energy source cannot be considered alone in an energy system, but only in the context of the entire energy system with all energy sources and infrastructures. A look at the alternatives of heating networks and electricity networks (**Fig. 12**) shows that the expansion costs of heating networks are slightly higher and those of electricity distribution networks would be many times higher than the switch to hydrogen. In the case of heating networks, it should be noted that these only cover part of the areas currently supplied with gas and would therefore incur significantly higher costs if the coverage were similar to that of the gas network.

It is also important to realise that uneconomical areas would also have to be developed. Overall, a sensible reorganisation of the existing energy system to achieve GHG neutrality must be achieved, taking into account the local conditions, the wishes and possibilities of the users and the timeline for feasibility. From an economic cost perspective, renewable hydrogen or, alternatively, renewable methane could then be an option.

Another cost aspect of converting the energy infrastructure, which adds to the expansion and conversion costs, is that parts or all of the gas distribution network will become obsolete when the heating and electricity networks are expanded. This means that the decommissioning costs must be added to the depreciation costs of gas networks that have not yet been depreciated. During decommissioning, ▷



Source: [78-84]

Figure 12: Investments for upgrading the energy infrastructure distribution networks

pipes with larger diameters must be partially dismantled and smaller diameters sealed or insulated. The decommissioning costs are estimated in AIRE at around € 29 bn in the electricity scenario and € 5 bn in the PtG scenario [85]. In the long-term scenarios 3, the decommissioning costs in the O45 electricity scenario are estimated at € 50 bn and in the O45-H_2 scenario at € 28 bn – € 38 bn, which is significantly higher [79]. Added to this are the costs for the physical dismantling of domestic connections, which are currently still estimated at between € 1,000 and € 3,000 per household (for example [86–91]). It can be assumed that higher costs are to be expected in the future, as the dismantling is still often subsidised by the gas network operator.

Overall, it can be concluded from the costs explained that the continued utilisation of the gas networks is a sensible option from the perspective of investment and direct follow-up costs.

SUMMARY

Converting the gas networks to hydrogen is technically feasible and often cost-effective. The cost of converting the transmission networks for the core network is € 18.9 bn, mainly utilising the existing infrastructure. The retrofitting of the distribution networks ranges from € 13 bn for blending to € 50 bn for conversion. Most components are already hydrogen-compatible. Compared to the expansion of heat or electricity networks, the switch to hydrogen is generally cheaper, especially as the decommissioning of old gas pipelines could cost up to € 50 bn.

4 Applications

4.1 Transformation paths

The use of climate-friendly hydrogen offers numerous sectors and companies the opportunity to organise their processes in line with the objectives of the Federal Climate Action Act ("Bundes-Klimaschutzgesetz"). The challenges associated with this transformation depend very much on the characteristics of the respective transformation pathway.

From "grey" to "green"

Around 1.4 million tonnes of hydrogen are already produced in Germany every year. Production capacities are dominated by reforming processes (86 %) and various industrial processes that produce hydrogen as a by-product. The market structure throughout Europe is characterised by captive consumption, which accounts for around 88 % of the total market [92]. For the industrial processes that are supplied here, it is essentially a question of switching from grey hydrogen to climate-friendly hydrogen and thus the challenges of procuring or producing sufficient amounts of climate-friendly hydrogen and, for many locations, switching from captive consumption to public infrastructures. Technologically, the challenges of the transformation are comparatively minor due to the chemical equality. Any deviating compositions or impurities must be taken into account, particularly with regard to their effects on sensitive catalysts and for planning any purification processes.

Conversion of the energy source

Numerous sectors and users currently utilise natural gas as an energy source in thermal processes. A study by the DBI identified 5,600 industrial sites in Germany that require 192 TWh of gas-based process heat per year. In addition, there are 1.1 million sites in other manufacturing industries, which require a further 12 TWh of gas-based process heat each year [93]. For those companies that will use hydrogen in the future, the key technological challenge is the transformation of combustion processes to a gas with different physical, chemical and combustion properties. The same applies to the energy sector, which is called upon to build hydrogen-capable gas-fired power plants as part of the German government's power plant strategy ("Kraftwerksstrategie"), and to manufacturers of heating appliances, as natural gas currently is still by far the most commonly used energy source in German households in 2023. [94]

Conversion of the raw material base

The material utilisation of natural gas is of central importance for many industrial processes as the basis for synthesis gas-based products. Synthesis gas production is a product-specific, thoroughly optimised process that results in a synthesis gas with a defined composition. The challenge of transformation is particularly relevant for those processes that are dependent on the carbon in the synthesis gas as well as the hydrogen. This applies, for example, to methanol, Fischer-Tropsch and hydroformylation products. Economically competitive production processes must be developed for these products, which can be based on a synthesis gas with hydrogen and CO_2 (CCU processes). A key challenge here is the development of a suitable catalyst system and the commercialisation of the processes on a sufficiently large scale.

Development of new processes

After the transformation, climate-friendly hydrogen will not only replace grey hydrogen and natural gas, but will also be an option in other industrial processes and in the mobility sector. New production routes for established products will play a role here, as will the development of completely new products. Examples include the steel industry, which is working on converting the coke-based blast furnace process to direct reduction with hydrogen, and refineries, which are developing processes for the production of sustainable aviation fuels as an alternative to established fossil-based aviation fuels.

The extent to which hydrogen will be used in the respective sectors in the future can only be predicted with considerable uncertainty at the present time. This is reflected, among other things, in the ranges of hydrogen demand forecast by the National Hydrogen Council in 2024 [95]. It is striking that in the scenario of the German National Hydrogen Council ("Nationaler Wasserstoffrat) in 2045, even with the forecast minimum quantities, there is a considerable demand for hydrogen in all sectors considered (process industry, transport/mobility sector, heating market and energy supply) and thus also explicitly for energy and material use. In the following analysis, the main focus is placed on the development status and the specific challenges of those processes that are being converted from other energy sources and raw materials to hydrogen. This mainly concerns energy utilisation and here the use in industry and households.

SUMMARY

In the transformation towards a hydrogen economy, hydrogen will replace various energy sources and raw materials and be used across all sectors. The technical challenges associated with this transformation on the application side are individual and depend on the respective sector and the framework conditions.

4.2 Differences in combustion properties

While the substitution of natural gas with biomethane or synthetic natural gas is already unproblematic in existing plants, the integration of hydrogen as an admixture or as the sole energy source requires more detailed consideration due to the different physicochemical and combustion properties. The relevant properties are shown in **Table 2**. It should be noted that natural gas is a natural product that is extracted from various sources. Accordingly, the composition and thus also the physico-chemical and combustion properties vary. For reasons of clarity, the table does not show bandwidths and instead shows typical values. Detailed information on fluctuation ranges for natural gas depending on origin and composition can be found at [96]. Calorific properties such as heating value, calorific value and Wobbe index, but also deviating air requirements and combustion temperatures and velocities are particularly relevant for energy utilisation. The influence of individual important values on thermal utilisation is roughly described below; more detailed discussions of the influence of varying admixtures of hydrogen in natural gas can be found at [97–99].

In thermal processes, the physical, chemical and combustion-related differences have a particular impact on the design and operation of the burner and the flue gas system. For example, the significantly lower calorific value of hydrogen must be compensated for by a higher volume flow of the supplied fuel gas in order to achieve a constant burner output. In addition, there is a different oxygen or air requirement during the combustion of hydrogen, which requires control to optimise the volume flow in order to maintain high combustion efficiencies. In addition, lower exhaust gas volumes and CO_2 proportions in the exhaust gas lead to an increased adiabatic combustion temperature when using hydrogen as a fuel gas [100]. Higher combustion temperatures favour the formation of nitrogen oxides (NO_X) and may therefore require suitable exhaust gas aftertreatment to comply with emission limits. The extent of the increased concentration of nitrogen oxides depends on the burner used, the operating point and the overall system. According to a study by the Federal Environment Agency (“Umweltbundesamt”), emission-reducing measures are currently required in hydrogen-fuelled steam boilers, for example. However, various simulations and tests have already shown that it is possible to burn hydrogen or natural gas-hydrogen mixtures with air with low NO_X emissions [101]. When using hydrogen with associated increased water vapour content in the exhaust gas, the evaluation of limit values, e.g. NO_X emissions in ppm or mg/m³, must be rethought, as the emissions are measured dry, i.e. the water vapour is removed from the analysis sample before the measurement. A specification of emissions in mg/kWh or mg/tproduct is currently being discussed with the industry associations. Further information can be found at [102], [103], [104] and [105]. In addition, localised overheating can lead to special requirements with regard to the refractory materials used [106]. The significantly higher flame speed when using hydrogen is also of crucial importance, which means that design changes to the burner and system technology are necessary to prevent flashback [101]. This is particularly important for premixed burner systems that are designed for natural gas [100, 106]. With non-premixed natural gas burner systems, the higher combustion rate does not have such a strong effect on flame stabilisation and safe operation with hydrogen is often possible [106]. The flame front can also move closer to the burner nozzle due to the higher combustion velocity post-mix burners, which can lead to overheating problems in existing appliances [100]. The wider ignition range of hydrogen is particularly relevant from a safety point of view. As the proportion of hydrogen in the fuel gas mixture increases, the ignition range widens upwards and reaches the upper ignition limit at 77 % by volume when hydrogen is used alone. This must be taken into account in the safety concept of the system, but in practice the lower ignition limit is often more important. This is due to the fact that the necessary ignition energy is available in the event of an incident, but the ignition capability is only given when the lower ignition limit is reached [97]. In addition, a suitable flame monitoring system must be used; in appliances operated with natural gas, this is usually an ionisation electrode [107–109]. With a hydrogen admixture of up to 60 % by volume, these systems can still be used for flame monitoring, but with the sole combustion ▹

Table 2: Comparison of the combustion properties of natural gas and hydrogen

Feature	Description	Natural gas[1]	H_2
Adiabatic combustion temperature at λ = 1[2] (°C)	Maximum temperature that can occur during a combustion process with specified operating conditions (theoretical value).	1,982	2,096
Gross and (net) Calorific Value) at reference conditions 25 °C/0 °C (kWh/m^3)	The amount of energy released per unit of mole, volume or mass in the form of heat during combustion.	11.2 (10.3)	3.54 (3.00)
Wobbe index at reference conditions 25 °C/0 °C (kWh/m^3)	Measure for the exchangeability of fuel gases in a combustion process.	15.0	13.4
Standard density (kg/m3) (and relative density (-))	The density of a gas corresponds to the ratio of its mass to its volume or amount of substance. (The ratio of the standard density (at 0 °C and 1.01325 bar) of the gas and the standard density of air.)	0.74 (0.57)	0.089 (0.0695)
Laminar combustion velocity at λ = 1[2] (cm/s)	Propagation speed of an unstretched one-dimensional flame relative to the unburned combustible mixture, in the perpendicular direction of the flame surface	38.57	209
Minimal air requirement (m^3 air/m^3 fuel)	Stoichiometric air requirement of a complete combustion of a fuel	9.5	2.4
Lower and (upper) flammability limit (Vol.-%)	Describes the concentration limits of a fuel in a mixture with air in which ignition is possible (named also as an explosion limit).	5.0 (17.0)	4.0 (77.0)
Flame colour		yellow to blue	almost colourless
Methane number (-)	Measure for the knock resistance of a gas	91	0
Minimum ignition energy (mJ)	Minimum value of the capacitively stored electrical energy in the discharge circuit which, when discharged via a spark gap with the lowest possible losses in the supply lines, just ignites the mixture at rest in the most ignitable composition	0.29	0.017

[1] Values for natural gas fluctuate and depend on the respective natural gas quality

[2] Air-fuel ratio λ is the ratio of supplied air to the theoretically required or stoichiometric air volume

Source: DVGW

of hydrogen, not enough ions are produced to be detected with the usual systems [110]. In addition, the position of the flame changes in such a way that reliable detection is no longer possible [111]. Various technologies such as UV, light and IR sensors are available for flame monitoring with hydrogen [107, 112].

The differences in combustion technology described above affect the various users in different ways. One example is the influence of combustion on product quality in industrial production processes, which must be assessed on a product-specific basis (see chapter 4.4 Industrial sector). On the other hand, there are the specific challenges of the mostly premixed burners in the household sector (see Chapter 4.3 Household and commercial sector). The following sections take an assessment of current findings with regard to the challenge of switching to hydrogen and present individually tested solutions.

SUMMARY

When switching from applications currently fuelled by natural gas to hydrogen, particular attention must be paid to the physical, chemical and combustion-related differences between the two gases and their influence on the application process in order to ensure safe, efficient and low-emission operation.

4.3 Household and commercial sector

When assessing domestic applications, a distinction must be made between the addition of hydrogen to natural gas and the use of 100 % hydrogen by volume. The gas appliances typically used today in the domestic environment are mainly used for heating and cooking and have been designed and optimised for the use of natural gas. An admixture of hydrogen leads to a mixed gas with combustion characteristics which, depending on the hydrogen concentration, deviate from the characteristics of natural gas. The extent to which hydrogen can be added to existing appliances safely and efficiently and with what fluctuations has been intensively tested in laboratory tests as part of the Roadmap Gas 2050 and THyGA projects and demonstrated in field trials (**Tab. 3**).

In the projects described, numerous appliances were tested for their suitability for operation with natural gas-hydrogen mixtures both in the laboratory environment and under real conditions. In the field tests, existing appliances were analysed with the heterogeneity found in appliance type, manufacturer, performance and year of manufacture. The investigations were accompanied by comprehensive safety concepts. These provide answers to safety-related questions. The projects came to the conclusion that gas installations and gas appliances are generally suitable for an admixture of up to at

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Table 3: Laboratory and field tests for hydrogen admixture in typically used gas appliances in a domestic environment

Project	**Roadmap Gas 2050 [116]**	**THyGA [117]**	**H2-20 [118]**	**H_2-Island [119]**	**H2-MiX**
Surroundings	Laboratory	Laboratory	Field	Field	Field
Number of devices	20	approx. 100	352	32	approx. 100
Device types	5 ATM; 9 CB; 3 KA; and 1 each SOFC, CHP + SH	6 WH; 46 KA; 5 CHP; 1 HP; 4 SH; 39 different HA	254 CB and CGB; 84 HA + WH; 14 GC + HAG	25 CB; 5 ATM; 2 GC	
Power class (kW)	2-300	1-232	10-250	14-300	up to 50
Year of manufacture of devices			1989-2021	1989-2022	
Tested concentrations (% by volume)	10-40	up to 60	10/15/20/ dynamic	8/10/20/30	up to 20

ATM = atmospheric appliances, CHP = combined heat and power unit, CB = condensing boiler, GC = gas cooker, CGB = conventional gas boiler, HA = heating appliance, KA = kitchen appliance, SH = space heater, SOFC = solid oxide fuel cell, WH = (circulating) water heater, HAG = warm air heater, HP = heat pump

Source: DVGW

least 20 % hydrogen by volume. This applies if the gas installations with the appliances have been properly installed, maintained and adjusted. Admixtures of more than 20 % by volume occasionally led to thermo-acoustic effects, which were assessed as a reduction in comfort with no relevance to safety. Detailed information on the procedure and analyses can be found in the respective project reports. [116–119]

The chemical, physical and combustion properties of mixed gases with hydrogen contents beyond the range investigated in the projects mentioned above, up to 100% hydrogen by volume, change to such an extent that some existing equipment can no longer be used safely and efficiently. In such cases, appliances specifically designed for operation with higher hydrogen concentrations should be used. In addition to the selection of suitable materials, the higher combustion rate, the higher combustion temperature, the wider ignition limits and the lower calorific value of hydrogen must be taken into account (see chapter 4.2 Differences in combustion). Burners and systems for the use of hydrogen must be designed in such a way that (1) high flame stability can be guaranteed even at high combustion rates, (2) safe and long-lasting operation within prescribed NO_X emission limits is ensured even at high combustion temperatures and (3) volume flows for hydrogen and air can be regulated. Gas condensing boilers currently offered by numerous manufacturers can be operated with natural gas and hydrogen admixtures today and can be converted to operation with 100 % hydrogen by volume in the future using conversion kits. Other manufacturers announce corresponding systems for 2025 [5, 120, 122–124]. In some pilot and demonstration projects, hydrogen condensing boilers in domestic and commercial environments have been and are being operated with 100 % hydrogen by volume (**Tab.** 4).

The known interim results from these projects with hydrogen condensing boilers are consistently positive in terms of operational safety and functionality and provide an important basis for the conversion of larger areas to 100 % hydrogen by volume [128–130].

In the DVGW research project "Sicherheitskonzept TRGI", the effects of hydrogen admixtures of up to 30 % by volume in natural gas on gas installations were analysed in accordance with DVGW Code of Practice G 600. It was shown that with regard to material compatibility, leak tests, explosion protection and the design of pipework and gas flow monitors, no amendments to the standards are necessary up to an admixture of 20 % hydrogen by volume [131]. Previous 100 vol.-% projects in existing networks have also shown suitability for 100 vol.-% hydrogen for large parts of the domestic installation, as detailed investigations in the run-up to the projects have shown [132, 133]. The TrafoHyVe project, in which 40 indoor installations were surveyed and tested, came to similar conclusions. According to these results, the hydrogen compatibility of steel pipes (screwed, hemp), copper pipes (soldered), pressed copper connectors, diaphragm gas meters, thermal shut-off devices and gas flow monitors is given up to 100 % by volume. It must be mentioned as a limitation for diaphragm gas meters and gas flow monitors that although they are suitable for hydrogen in terms of material compatibility and measurement accuracy, they often have to be replaced with larger components due to the larger volume flow of hydrogen. Existing gas sockets were rated as not suitable for hydrogen. [134]

SUMMARY

For existing appliances in the household sector, the suitability for an admixture of at least 20 % hydrogen by volume has been proven in various projects without safety-related restrictions. Utilisation of 100 % hydrogen by volume can be achieved with new appliances or, in the case of more modern existing appliances, with retrofit kits.

Table 4: Field tests with 100 % hydrogen in domestic and commercial environments

Pilot/demonstration	Location	Number of devices	Start
H2Direkt [125]	Hohenwart	10	2023
H2HoWi [126]	Holzwickede	4	2022
H2-Linnich [127]	Linnich	2	2022
Pilot Lochem [128]	Lochem (Netherlands)	12	2022

Source: DVGW

4.4 Industrial sector

In 2022, the industrial sector had a final energy consumption of 667 TWh. Over two thirds of this (495 TWh) was consumed for the provision of process heat with heterogeneous temperature levels. The dominant energy sources for the generation of process heat today are gases (44 %) and coal (24 %) [135]. In the future, process heat is to be made available primarily via climate-friendly gases and electrification. When assessing the challenge of transformation, attention must be paid to the immense heterogeneity of the existing plants, the site specifics and the required temperature levels. Particular attention must be paid to the fact that in industrial combustion processes, in addition to the issues of operational optimisation and safety, which are also relevant for household appliances, the influence of hydrogen on product quality and, in particular, on plant components such as refractory materials is of crucial importance.

As with domestic appliances, the physico-chemical and combustion-related differences between the fuel gases hydrogen and natural gas must also be taken into account for industrial burners for generating process heat based on hydrogen (see description in chapter 4.2 Differences in combustion). These differences are known and are taken into account in the development of new thermoprocessing plants. Commercial hydrogen-based systems are already available today for the provision of hot water and steam. In the chemical industry, hydrogen-fuelled boilers are already being used in some processes with internal hydrogen flows [136]. One development advantage of steam generation is that the use of hydrogen can be optimised independently of the subsequent area of application of the steam. On the other hand, there are numerous sensitive high-temperature processes with their individual requirements in terms of, for example, furnace type, temperature distribution, heat input and flame temperature. This applies to numerous processes in the metals (including steel, foundries, aluminium and copper) and minerals (including glass, bricks and ceramics, cement and lime) sectors [137]. Some sub-processes in the various sectors have already been operated with 100 % hydrogen by volume in numerous pilot and demonstration projects (**Tab. 6**). The Fraunhofer In-

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Table 5: Selection of practical examples of cogeneration plants that are operated with hydrogen or hydrogen admixtures in a real environment

Project/Company	Location	Start	CHP plant	Hydrogen
Wasserstoff BHKW [178]	Hamburg-Othmarschen	2020	1 MW Jenbacher J416 gas engine	Conversion to up to 100 % H_2
mySMARTLife [179]	Hamburg-Bergedorf	2020	2x 50 kW$_{el}$ power plant gas engines	Up to 30 % by volume
CH2P [167]	Amberg	2023	170 kW$_{el}$ 2G agenitor 406 gas engine	Conversion to up to 100 % H_2
Stadtwerke Haßfurt [180]	Hassfurt	2019	150 kW$_{el}$ 2G agenitor 406 gas engine	Up to 100 % H_2
APEX Energy [181]	Rostock	2020	115 kW$_{el}$ 2G agenitor 404c gas engine	Up to 100 % H_2
Neue Weststadt [182]	Esslingen	2021	150 kW$_{el}$ 2G agenitor 406	Up to 100 % H_2
Metadynea	Krems	1996	4 x Jenbacher J320	Process gas with 19 vol.-% H_2
Metadynea	Krems	2024	4 x Jenbacher J420 (3,3 MW$_{el}$ in total)	Process gas with 19 vol.-% H_2
Hydrogen CGS [183]	Kobe, Japan	2018	1 MW$_{el}$ Kawasaki gas turbine with diffusion combustion chamber	Up to 100 % H_2
CPChem [184]	Tessenderlo, Belgium	2023	1,8 MW$_{el}$ Kawasaki GPB17D gas turbine (DLE)	Conversion from natural gas to up to 30% H_2 by volume
Hydrogen Park Consortium [185]	Fusina, Italy	2009	11,44 MW$_{el}$ GE PGT10/1 gas turbine with steam injection	Operation with 97 vol.-% H_2
HYFLEXPOWER [176]	Saillat-sur-Vienne, France	2023	10 MW$_{el}$ Siemens Energy SGT-400 gas turbine (DLE)	Up to 100 % H_2
Wien Energie [186]	Vienna, Austria	2023	395 MW$_{el}$ Siemens Energy SGT5-4000F CCGT plant	Conversion from natural gas to up to 15 % H_2 by volume

Source: DVGW

stitute for Systems and Innovation Research, together with the Department for Industrial Furnaces and Heat Engineering at RWTH Aachen University, has analysed possibilities for CO_2-neutral process heat with a focus on electrification and the use of hydrogen [137]. The authors come to the conclusion that although the technology readiness levels for the use of hydrogen in industrial furnaces are currently still low, no major technical hurdles are seen for the conversion to hydrogen heating in conventionally gas-fired furnaces. Consequently, a rapid increase in technology readiness and operation at an industrial level is expected.

When converting existing systems from natural gas to hydrogen, a distinction must be made between nonpremixed and premixed burner systems. The majority of industrial thermoprocessing plants use nonpremixed burner systems and require modifications to central plant components, e.g. burners including flame monitoring and flue gas system, and adjustments to the control system, but a fundamental new construction is usually not necessary [101, 137]. In the case of premixed burner systems, which are only occasionally used in industry, a conversion is more complicated e.g. due to the risk of flashback. In these cases, major adjustments or completely new combustion concepts are necessary when changing the fuel from natural gas to hydrogen [106]. The individuality of the respective application and the associated need for adaptation must therefore be taken into account not only when developing new thermoprocessing systems, but also in the event of a conversion.

However, due to possible local overheating and increased water vapour content, attention must be paid to the long-term stability of refractory materials [106]. Table 6 also shows examples of the conversion of existing thermal processing plants in an industrial environment.

A key aspect for operators of thermal processing plants is maintaining the required product quality. Numerous research projects have been and are being carried out in this area. Examples for the glass industry are: HyGlass [138], H2-Glass [139], COSIMa [140] and MiGWa [141]; for the aluminium industry: H2AL [142], H2-Alu [143] and HyAlu [144]; for the brick industry H2TO [145] and H2-Ziegel [146] and for the thermoprocessing industry in general: TTGoesH2 [147]. The test results show that product quality can be affected in some cases, depending on the specific composition. This influence does not usually take place directly via the hydrogen, but via the increased water vapour content in the exhaust gas.

A large part of German industry is currently supplied with natural gas via the gas distribution networks. In its first stage, the hydrogen core network serves the initial development of a hydrogen infrastructure in Germany. With its 9,040 km length, it will not be able to supply the total of 5,600 industrial sites and the more than one million sites in other manufacturing industries with process heat requirements with hydrogen. Accordingly, the gas distribution network will continue to have the task of providing considerable amounts of energy for process heat and securing Germany as a business location. In this context, an assessment of possible admixtures for the various existing plants in industry is important - analogous to households - especially for the ramp-up phase. The effects of the different properties on industrial combustion processes have been analysed in the DVGW project G 202145 "TransNetz - Entwicklung von robusten Transformationspfaden zur Umsetzung der Klimaziele auf Verteilnetzebene" [106]. This project report also addresses how fluctuating hydrogen concentrations can be dealt with in the event of blending. Measurement and control technology has a significant impact, as the effects on the process under consideration can be reduced if control measures are initiated in a timely manner as a result of detected changes in the fuel gas composition. Conceivable measurement methods include correlative, calorimetric, optical and chromatographic methods.

Dual-fuel burners that can be operated flexibly with natural gas, hydrogen or a mixture of natural gas and hydrogen have already been developed and industrially tested for the transition phase. [148–150]

SUMMARY

The transition to hydrogen in industry is highly individual due to the heterogeneity of the processes and the possible influences of the fuel change on process stability, product quality and emission behaviour. The suitability of using hydrogen for various production processes has been demonstrated in numerous pilot and demonstration projects and important foundations have been laid for the transition to large-scale industrial operation.

4.5 Cogeneration plants

Cogeneration plants are characterised by the simultaneous generation of electrical and thermal energy. Depending on the power class, they are used in private households, in combined heat and power plants (CHP), in industry and in gas and steam power plants. Different technologies dominate depending on the field of application.

For electrical outputs of typically 1–50 kW in households and up to 1,000 kW in commercial use, for example for hospitals, leisure pools and hotels, combustion engines (in the case of natural gas: gas engines) are primarily used. Stirling engines and fuel cells are currently less important. [165]

In addition, steam turbines and gas turbines with larger electrical output between 500 kWel and 20 MW_{el} are preferred for industrial applications, with natural gas as the most important fuel. Industrial cogeneration plants above 20 MW_{el} can also include gas and steam turbine power plants and are primarily found in the chemical and paper industries. [165]

In the public utiliy sector, gas and steam turbine power plants with an electrical output of between 10 and 800 MW_{el} are typical. [165]

The various technologies differ characteristically, so that the conversion from natural gas-fuelled systems to hydrogen cannot be described in general terms.

Gas engines

A distinction must be made between different types of gas engines. On the one hand, there are appliances designed for hydrogen or hydrogen and natural gas, which have been available on the market from numerous manufacturers for years. On the other hand, there are existing appliances that were originally designed for operation with natural gas.

Consequently, numerous manufacturers of gas engines offer engines that can be operated with hydrogen admixtures, H_2-ready engines that can easily be converted to 100 % hydrogen by volume and entire series that can already operate with up to 100 % hydrogen by volume. On the other hand, existing systems can often be operated with hydrogen concentrations of between 10 and 20 % by volume without any design changes, depending on the manufacturer, model and age of the system [166]. For a higher admixture of up to 100 % hydrogen by volume, adjustments to the control system and design changes are usually necessary to take the specific properties of hydrogen into account. Typically, the higher combustion velocity and the higher ignitability must be considered. Injection systems adapted to the fuel are used, which reduce the risk of uncontrolled combustion by mixing hydrogen and air at a later stage. In addition, turbochargers are used which consider the greater air requirement of hydrogen combustion. A lower compression ratio when operating a hydrogen engine can be achieved by adapting the pistons [167, 168]. The details of the respective solutions depend on the respective manufacturer and model; a more detailed overview of possible solutions is discussed in [169]. **Table 5** shows some references of gas engines that

Table 6: Demonstration projects for the use of hydrogen in industrial high-temperature processes

Industry	Company/Project	Information on	
Glass	Schott [151, 152]	Three-day large-scale production of optical glass with 100 % H_2 by volume in a furnace at temperatures of up to 1,700 °C	C
	Saint Gobain [153]	Five-day industrial tests on the use of 60 % H_2 by volume in flat glass production	A
Ceramics	H2-Factory [154]	Production of a ceramic slab with up to 7 % H_2 by volume in natural gas at an Iris Ceramica Group site	A
Steel	HYBRIT [155]	Pilot project for the direct reduction of iron ore with H_2 with subsequent processing of the resulting sponge iron in an electric arc furnace	N
	EMSTEEL [156]	Pilot project for the direct reduction of iron ore with H_2	N
	MIDREX [157]	The standard MIDREX process involves direct reduction in a shaft furnace with an H_2-rich gas (up to 80 vol.-% H_2). Operation with 100 vol.-% H_2 has been carried out on a pilot scale, process in commercialisation.	N
	GEiSt [158]	Direct reduction plant using the Hylron process in a pilot-scale rotary kiln	N
Copper	Aurubis [159]	Use of a gas mixture of H_2 and N_2 instead of natural gas on an industrial scale to pole copper melt in an anode furnace	C
Aluminium	Hydro [160]	Recycling aluminium by using H_2 instead of natural gas in a foundry in the extrusion plant in Navarra	C
Cement	HeidelbergCement [161]	H_2 as part of a net zero fuel mix (39 % H_2) on an industrial scale in the main burner of a cement kiln	A
Brick	HyBrick [162]	Use of 100 vol.-% H_2 over three firing cycles in a small customised kiln at > 1,000 °C	C
	H2-Ziegel [163]	Use of 100 vol.-% H_2 in a three-week test operation under real conditions with a dual-fuel burner in the tunnel furnace of a clinker plant	C
Paper	Essity [164]	Large-scale industrial use of 100 vol.-% H_2 in the drying process at up to 600 °C in an existing system after installation of new burners	C

N = newly designed furnace, C = furnace converted to hydrogen, A = admixture

Source: DVGW

are operated with hydrogen in the field. This is an exemplary and non-exhaustive list.

Turbines/combined cycle gas turbine (CCGT) power plants

Gas turbines and combined cycle gas turbines are usually premixed or partially premixed combustion processes with high excess air, which are operated at the limits of combustion stability for reasons of NO_X reduction. Numerous gas turbines around the world are operated in a real environment with process gases from steel mills, refineries and petrochemical plants, for example, which have different hydrogen contents (see [170] and Table 5). Due to the heterogeneity of the gas turbines currently commercially available, the admixture limits for hydrogen are heavily dependent on the model. Typically, these are 30–100 % by volume. The combustion of very high hydrogen concentrations has so far mainly taken place in systems up to the medium power class and using diffusion burners or wet low emission (WLE) systems, which avoid high NO_X emissions by injecting water or water vapour [171, 172]. As this is associated with disadvantages in terms of efficiency and high water consumption, gas turbine manufacturers are working on efficient and low-emission DLE (dry low emission) systems for the combustion of hydrogen. The main challenges include flashback, NO_X emissions, thermal stress on turbine components and combustion-induced thermoacoustic instabilities [171, 172]. Flow conditioners can be used to lean the fuel-air mixture on the combustion chamber walls and reduce the risk of flashback even with increased hydrogen concentrations [173]. In addition, various manufacturers have developed systems that utilise numerous small hydrogen flames to avoid flashback and high NO_X emissions (Kawasaki: Micromix with auxiliary burner; Mitsubishi: multi cluster; GE: multi tube) [170, 174, 175]. In the HYFLEXPOWER project, a DLE gas turbine was operated for the first time in test mode with 100 % renewable hydrogen by volume in October 2023 [176]. With a 10 MW plant, this is a gas turbine in the low to medium power class. However, the findings from these and similar projects will be used over the next few years to commercialise solutions for the combustion of 100 % hydrogen by volume in larger power classes and in compliance with NO_X limits, which currently generally tolerate maximum admixtures of up to 50–60 % by volume [171, 172]. In their #PowerTheEU Commitments, the members of the European Union of Gas and Steam Turbine Manufacturers EUTurbines have pledged to offer hydrogen-capable gas turbines on the market by 2030. [177]

SUMMARY

The development status of the transition to hydrogen in the heterogeneous group of cogeneration plants must be assessed in a differentiated manner. While gas engines are already commercially available today with up to 100 % by volume and there are numerous industrial examples of gas turbines that operate with high admixtures, development work is still required, particularly for gas turbines and combined cycle power plants in large power classes.

5 Conclusion

Germany is undergoing a far-reaching transformation process towards a climate-neutral energy supply. Achieving the goal of climate neutrality by 2045 will require considerable investment in increasing efficiency, electrification and the use of renewable molecules. Particularly in the transition phase, the focus should be on pragmatic, swift and safe implementation, taking into account existing infrastructures and resource-saving CO_2 reduction. The volatile generation patterns of renewable energies also require short-term and seasonal storage solutions and network expansion, which is associated with considerable financial and time costs. Hydrogen is a promising CO_2-free option, as the existing natural gas infrastructure can be adapted for its use with relatively little effort. In addition, hydrogen can be imported, which can compensate for the phase-out of fossil fuels.

However, the practical implementation of political decisions requires a comprehensive assessment of technical feasibility, safe operation as well as economic and security of supply aspects. Hydrogen offers both technological advantages and challenges. On the one hand, it is chemically inert for the gas infrastructure, which means that it does not cause corrosion. On the other hand, hydrogen has a high diffusivity due to its small molecular size, which can lead to hydrogen embrittlement, particularly in high-strength steels. This occurs when hydrogen atoms penetrate into existing material defects, generating localised stresses and thus weakening the structure. However, research results show that in the typical operating areas of gas infrastructures, only pressure fluctuations are relevant as a potential cause of hydrogen embrittlement. Experimental studies show that operational pressure fluctuations do not cause any direct material damage. In addition, scientific studies confirm that steel gas pipelines are fundamentally suitable for hydrogen. Fracture mechanics assessments are required for operating pressures above 16 bar. Between 12 and 16 bar, fracture mechanics analyses are only necessary for pipe diameters > DN 200. In distribution networks with a pressure of less than 12 bar, no relevant influences from hydrogen are to be expected and fracture mechanics considerations can be omitted.

Plastic pipes and non-ferrous metals used in gas infrastructure are highly resistant to hydrogen and show no negative effects even with long-term exposure. Tests on ductile iron pipes also prove that they are safe to use, meaning that existing networks can continue to be used with moderate modifications. These findings were incorporated into the development of the DVGW regulations in order to transfer the established safety level of natural gas to hydrogen.

The specifications for the construction and operation of hydrogen infrastructures are set out in DVGW Code of Practice G 462, G 463, G 472 and G 265-3 as well as Code of Practice G 221. Tests of welds and potential defects are carried out in accordance with GW 350, while regular inspections ensure safety. Explosion protection requirements are based on Ordinance on Hazardous Substances (GefStoffV) and Ordinance on Operational Reliability (BetrSichV), and construction companies must prove their qualifications in accordance with GW 301. DVGW Code of Practice G 407, G 408 and G 409 must also be consulted for conversions. In addition to these technical aspects, qualified personnel, optimised operating processes, risk assessments and technical safety management (TSM) are required, as specified in DVGW Code of Practice G 466-1, the G 465 series and G 221.

Adjustments are also required on the consumer side. For the household sector, various projects have shown that existing appliances are suitable for an admixture of at least 20 % hydrogen by volume without any safety restrictions. However, higher admixtures up to the utilisation of 100 % hydrogen by volume can generally only be achieved with special new appliances or, in the case of modern existing appliances, with retrofit kits. The first hydrogen condensing boilers have already been successfully tested in pilot projects and are currently being launched on the market. Domestic gas installations are also suitable for operation with 100 % hydrogen by volume, with the exception of a few components such as gas sockets and diaphragm gas meters, as confirmed by the TrafoHyVe project and the Gas 2050 roadmap, among others.

In industrial applications, the heterogeneity of the processes and the influence of the differing properties of the two gases on process stability, product quality and emission behaviour must be taken into particular account when switching from natural gas to hydrogen. The suitability of hydrogen for various production processes has been proven in numerous pilot and demonstration projects, and important foundations have been laid for the transition to large-scale industrial operation. The progress made in switching to hydrogen in the diverse group of CHP plants must be viewed in a differentiated manner. While gas engines with up to 100 % hydrogen by volume are already commercially available today and there are numerous industrial examples of gas turbines that are operated with high hydrogen admixtures, further development work is still required, particularly for gas turbines and combined cycle power plants in large output classes.

Safety aspects play a central role in the hydrogen infrastructure. Hydrogen has been used safely in the chemical, manufacturing and utility industries for decades. However, its increasing use in public spaces is creating new challenges. Hydrogen differs physically from methane in that it has an extended ignition range (4–77 % by volume in air) and a higher combustion rate. Nevertheless, it can be used just as safely as natural gas if appropriate safety measures are observed. The existing DVGW standards have contributed significantly to the safe use of natural gas and town gas containing up to 50 % hydrogen by volume and have been adapted for up to 100 % hydrogen by volume. In addition, statistics show that hydrogen pipelines have comparable or even lower accident rates than natural gas pipelines.

In addition to safety, economic factors are also decisive for the conversion of the gas infrastructure to hydrogen. The addition of up to 20 % hydrogen by volume requires only minor adjustments to the gas distribution network and is associated with comparatively moderate costs of around € 13 bn. A complete switch to 100 % hydrogen by volume is more complex and cost-intensive. In addition to adjustments to individual parts and components, capacity issues must be taken into account, although significant network reinforcements are not required. The estimated costs for a complete conversion vary between € 17 bn and 50 bn, depending on the study. A gradual renewal as part of the necessary maintenance measures for components can significantly reduce costs. Recent findings also show that the gas networks are better suited to hydrogen than originally assumed, which means that earlier cost estimates can be categorised as conservative.

A comparison with alternative infrastructures makes it clear that the expansion of heating networks would be more expensive and the expansion of the electricity network many times more expensive. In addition, the decommissioning and dismantling of the gas network incurs high costs, which can amount to between € 5 bn and € 50 bn depending on the scenario. The dismantling of house connections also costs between € 1,000 and 3,000 per household.

To summarise, it can be said that using the existing gas infrastructure for hydrogen is a technically sustainable option. It enables a resource-conserving transformation of the energy system, taking into account local conditions and user requirements. The switch to hydrogen is technically feasible and safe. Extensive research results have been incorporated into the DVGW regulations and guarantee safe operation. Hydrogen must also be considered as a realistic economic solution to replace fossil fuels and drive forward the energy transition in all sectors.

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