



# Hydrogen infrastructure – the pillar of energy transition

The practical conversion of long-distance  
gas networks to hydrogen operation

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# **“In developing and deploying a clean hydrogen value chain, Europe will become a global front-runner and retain its leadership in clean tech”**

*Frans Timmermans, First Vice President of the European Commission, 08.07.2020<sup>1)</sup>*

## **Executive Summary**

Within the framework of energy sector integration and together with the expansion of the electricity grids, a needs-based hydrogen infrastructure is a central building block for the reliable supply to industrial, public and private customers of CO<sub>2</sub>-free energy:

- Hydrogen can be produced by electrolysis with energy from renewable sources in large quantities and completely CO<sub>2</sub>-free, stored, transported and made available via gas networks, and integrated into the international gas markets.
- Pure hydrogen, as an energy source in pipelines, has an almost comparable transport energy density as natural gas. It can therefore provide the market with the required capacities for climate-neutral energy.
- The highly integrated German and European natural gas transmission networks represent an economically advantageous way to distribute large quantities of energy as required. The pipeline networks are available, socially accepted, and can be gradually converted to hydrogen operation with an investment of an estimated 10-15% of the cost of new construction (calculations are based on general observations and consumptions).
- The generation of hydrogen based on renewable energy sources is subject to strong fluctuations. Concrete model calculations show that the needs-based supply of customers via existing gas storage – temporarily – can be supplemented with ‘blue’ hydrogen. To increase the proportion of green hydrogen, a consequent expansion of renewable electricity generation is required.
- The technologies for converting the gas infrastructure to hydrogen operation are already largely available; the large-scale application at a high level of technical standardization will foreseeably lead to economically sensible solutions.
- To establish a hydrogen industry in line with the market, uniform and appropriate framework conditions are needed to ensure the competitiveness of climate-neutral hydrogen on the energy market. In parallel, the regulatory framework for the network must be adapted to enable hydrogen transport using the publicly-accessible gas network.
- Various regional model projects for the establishment of hydrogen economies with industrial customers are already being planned. An expansion of these model projects can form the basis for a Germany and Europe-wide hydrogen industry by 2030.



# Foreword

Energy transition presents all nations with major economic and logistical challenges.

A central question when converting to renewable energy sources is: how can the energy be effectively stored and made available? As regenerative energy production is subject to strong natural fluctuations, powerful and needs-based storage and transport solutions are required to compensate for the inevitable energy-market differences. In contrast to the existing gas and electricity infrastructure, new construction of the necessary infrastructure is subject to elaborate and complex planning and approval procedures.

The establishment of a hydrogen industry creates comparatively cheap solutions to the above-mentioned challenges that can be implemented in the short term. Numerous countries, including those in the EU, have already identified hydrogen as the energy source of the future – in addition to expanding power grids – to promote industrial decarbonization, enable sector integration, and achieve climate goals.

Hydrogen as a source of energy per se is a storage medium. Like natural gas, it can be stored in large underground storage facilities, transported to the end-user by pipeline, and even achieves a similarly high transport energy density due to its material properties.

Countries like Germany also have extremely well-developed natural gas transmission networks that are well integrated with the international market. As current studies and practice cases show, the existing networks can be converted to hydrogen operation step by step and in a needs-oriented way with comparatively little effort – notably without the complex procedural steps of new construction.

Based on real practice cases and from the perspective of technology companies and network operators, this paper examines what a German and European hydrogen infrastructure could look like in practice based on the existing natural gas systems, what opportunities it offers, and what challenges must be overcome for a successful changeover.



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# 1. Hydrogen: Overview

Hydrogen is the most common element in the universe and, with molecular weight 2 (0.09 kg/Nm<sup>3</sup>), the lightest of all gases. Its melting point is –259.14 °C. On earth, it occurs in a bonded form, mostly as water (H<sub>2</sub>O). Hydrogen is not toxic, not corrosive, not self-igniting, and burns to water vapor without the emission of CO<sub>2</sub>.

Hydrogen has a low energy density (3 kWh/Nm<sup>3</sup>) due to its extremely low weight (compared to methane: 10 kWh/Nm<sup>3</sup>), but its calorific value is significantly higher at around 33 kWh/kg (methane: 14 kWh/kg). Compression allows the energy density to be increased to a level comparable to that of natural gas<sup>2</sup>). As a gas, hydrogen can be transported in large quantities in pipelines and stored in gas storage facilities. As an energy source, hydrogen can be used in industry and by end users in fuel cells for mobility and heating applications or it can be used to generate electricity in turbines. At the same time, it serves as a raw material and resource for numerous industrial applications.

Hydrogen can be generated in different ways – from ‘gray’, CO<sub>2</sub>-intensively obtained, via CO<sub>2</sub>-neutral ‘blue’, to CO<sub>2</sub>-free ‘green’ hydrogen from renewable energy sources.

## Hydrogen: categorized according to the CO<sub>2</sub> balance

In public discussion, types of hydrogen are often simply given ‘colors’ that refer to the CO<sub>2</sub> balance of their production. In the context of the present analysis, according to this ‘color theory’ (in addition to other forms of production), ‘green’, ‘gray’ and ‘blue’ hydrogen are particularly relevant:

- Green Hydrogen is produced by water electrolysis: water is split into hydrogen and oxygen by an electric current and with the help of an electrolyte. If the electricity required for electrolysis comes exclusively from renewable, CO<sub>2</sub>-free sources, the entire production process is completely CO<sub>2</sub>-free.
- Blue Hydrogen is generated CO<sub>2</sub>-neutral from fossil fuels. The CO<sub>2</sub> is separated and stored or reused (Carbon Capture and Storage (CCS) or Carbon Capture Usage (CCU)).
- Gray Hydrogen is obtained from fossil fuels. For example, natural gas is converted under heat into hydrogen and CO<sub>2</sub> (‘steam reforming’). Approximately nine tons of CO<sub>2</sub> are generated to produce one ton of hydrogen from methane.

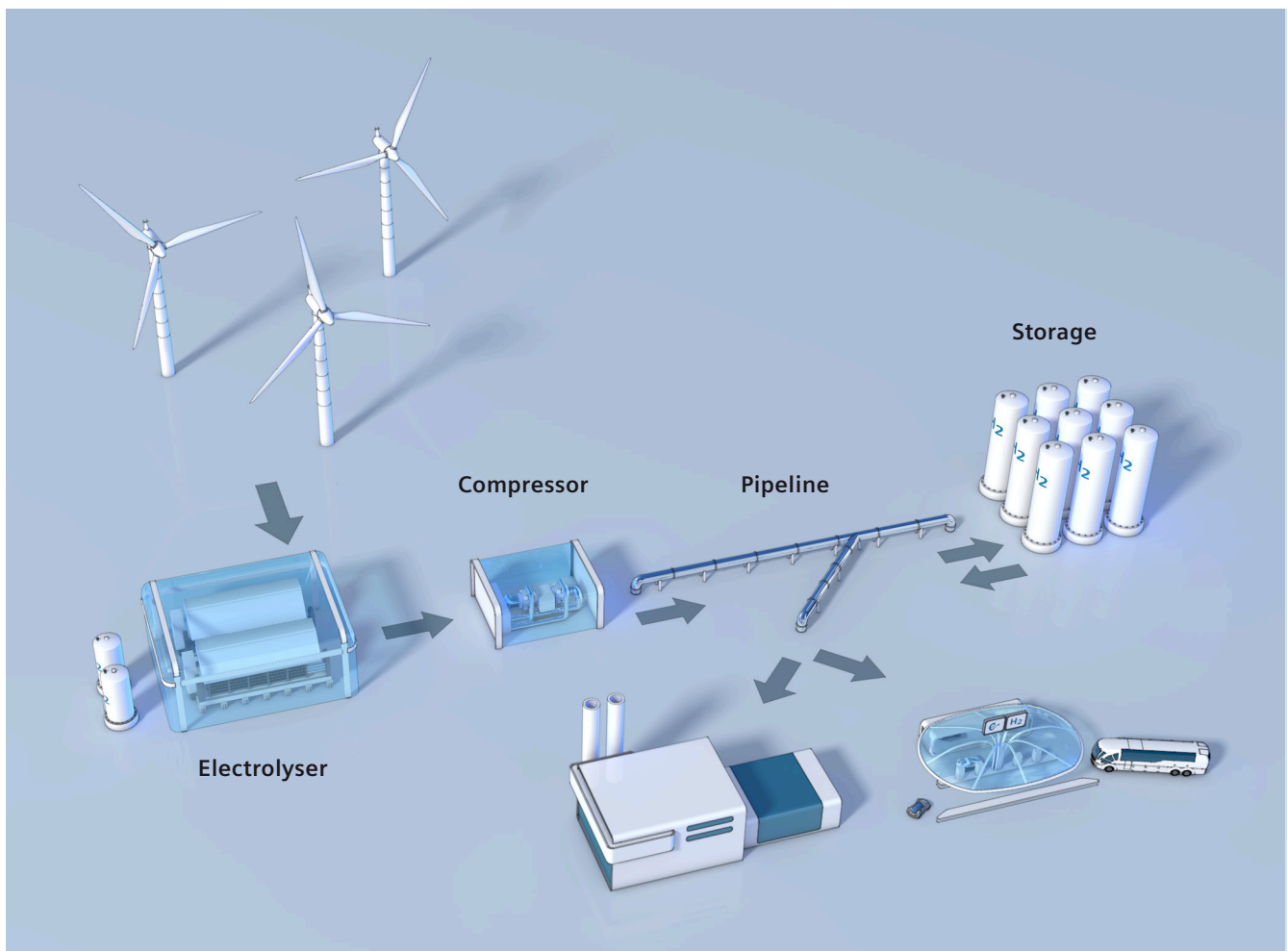
## 1.1 Green hydrogen as the energy source of the future

With its completely CO<sub>2</sub>-free production, 'green' hydrogen offers the potential for permanent decarbonization of the energy landscape and compliance with climate goals. This potential is still largely undeveloped today:

Around 75 million tons of hydrogen are generated annually worldwide<sup>3)</sup>. Around 95% of the production takes place in refineries, in fertilizer production, and in petrochemical plants as a raw material for further processing in various branches of industry<sup>4)</sup>. Apart from specialized industries, however, hydrogen is so far unused on a larger scale as an energy source.

Approximately 95% of the hydrogen is obtained 'gray' and 'blue' by steam reforming from methane, oil, or coal; for a ton of hydrogen, an average of about nine tons of CO<sub>2</sub> are generated<sup>5)</sup>. So far, however, energy from renewable sources is largely unused.

To make renewable energies universally usable with the help of green hydrogen, in addition to sufficient capacity for green electricity and hydrogen generation, a storage and transport network infrastructure is required that can effectively and reliably serve the needs of business and consumers.



**Figure 1:** Core elements generation – compression – transmission/storage

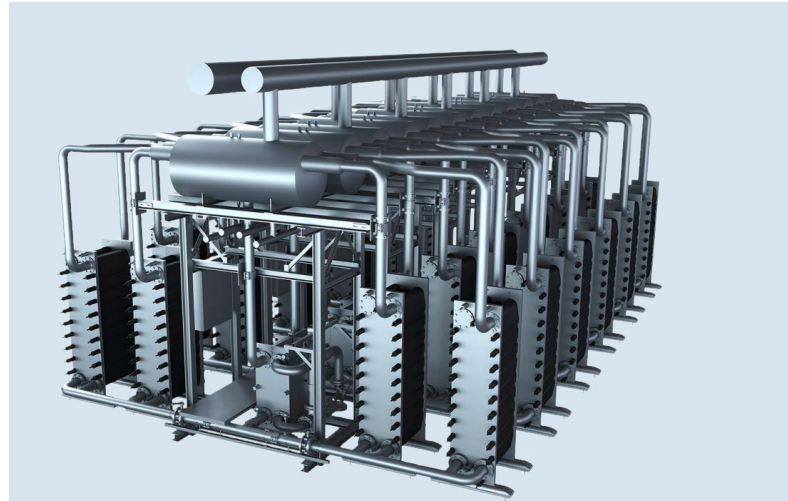
## 2. Generation

The industrial production of green hydrogen takes place by means of water electrolysis using exclusively regenerative energy. In large-scale production, the usual demineralized water is split by an electrical current into oxygen and hydrogen in an electrolyzer. When using desalinated sea water, an additional approx 5 MWh of energy per ton of hydrogen is required for the electrolysis. In contrast to the conventional method of steam reforming, e.g. from natural gas ('gray' or 'blue'), this type of production is completely CO<sub>2</sub>-free. Around 55 MWh of electrical energy is required to generate one ton of hydrogen.

Commercially available water electrolysis systems for industrial use today usually utilize alkaline electrolysis with a potassium hydroxide electrolyte, or a 'Proton Exchange Membrane' (PEM) electrolysis with a proton-permeable polymer membrane.

Alkaline water electrolysis is a technology that has been established on the market for many years and does not require the use of precious metals.

The still relatively new PEM electrolysis, on the other hand, achieves a significantly higher power density and extremely high power versatility. It is therefore also suitable for grid stabilization and for fluctuating electricity feed-in from wind power and photovoltaic systems. As this technology was first scaled into the megawatt range in recent years, significant cost reductions can still be expected for large-scale applications.



**Figure 2:**  
*Modern PEM electrolyzer for large- scale applications - stock/Siemens Energy Silyzer 300*

Figure 2 shows an example of a modern PEM electrolyzer for large-scale applications with a power consumption of 17.5 MW and a production of approx. 335 kg hydrogen per hour. The system efficiency (depending on the mode of operation) is approx. 75,5%. Oxygen and low-temperature heat are generated as by-products, which can also be used via connected applications.

## 3. Transmission

Regardless of how the hydrogen is generated, if it is not produced directly at the point of use it must be transported. There are various technical processes for this: for example as a gas in high-pressure containers, as liquefied gas in thermally-insulated containers, further processed into methanol or ammonia in liquid form, or chemically dissolved in a carrier medium using the so-called 'Liquid Organic Hydrogen Carrier' ('LOHC')<sup>6)</sup>.

Transport via pipelines is particularly economical. Due to the high calorific value and the compressibility of the hydrogen, an extraordinarily high energy density can be achieved. In comparison to a 380 kV double system overhead line with 1.5 GW, a gas line (PN 80, DN 1000) can transmit up to ten times the power in natural gas and hydrogen operation – at around a fourteenth of the specific costs<sup>7)</sup>.

Pipeline systems at a length of several hundred kilometers each are already in use in pure hydrogen operation worldwide.

### 3.1. Intrinsic value of the existing gas infrastructure

The German gas network is highly developed with approx. 40,000 km of transmission lines and more than 470,000 km of distribution networks<sup>8)</sup>. Germany also has the largest gas storage facilities in the EU with a working gas volume of approx. 24.3 billion m<sup>3</sup>. As an important transit country for gas supply, Germany is also extremely well connected to the European gas market. The German gas infrastructure is therefore predestined as a central building block for sector integration and the maintenance of security of supply within the framework of an ecologically sustainable power-to-gas strategy.

The existing pipeline routes represent an extremely valuable element of the transmission system and offer the opportunity to build a climate-neutral hydrogen industry in a manageable time and with little investment.

As measuring devices, compressors and fittings can be exchanged relatively easily, replacing or building new pipelines would be very expensive. In addition to the technical costs, the necessary spatial planning and planning approval procedures are extremely time- and cost-intensive. In the best-case scenario, the process takes five to seven years from initial planning to commissioning. The gas network's pipeline routes, including their rights of way and use, are however available and accepted by the population.

### 3.2. Pipeline capacity when switching to hydrogen

Contrary to popular belief, the transport energy density of hydrogen is only slightly lower than that of natural gas. Therefore, the switch from natural gas to hydrogen has little impact on the capacity of a pipeline to transport energy.

The upper calorific value of natural gas at around 11 kWh/ Nm<sup>3</sup> is about three times higher than that of hydrogen at 3.5 kWh/ Nm<sup>3</sup>, so that at the same pressure, around three times the volume of hydrogen is required to keep the energy content constant.

When comparing the energy flow of two gases through a pipeline, it is not only the volume that is important, but above all the parameters of density, flow velocity, and pressure. As hydrogen has a density nine times lower and three times the flow rate of natural gas, almost three times the volume of hydrogen can be transported in the pipeline at the same pressure, and during the same time. The energy density is only slightly reduced, as the following model calculation shows.



## Comparison of energy flow and pipeline capacity: natural gas (methane) and hydrogen

As the following pressure loss calculation shows, the lower calorific value of hydrogen during transport in pipelines can be largely compensated for:

$$p_2 = p_1 * \sqrt{1 - \lambda * \frac{L}{D} * \frac{\rho_{1,i}}{p_{1,i}} * c^2 * K_m}$$

with $\Delta p$	Pressure loss	$\lambda$	Pipe friction coefficient
$L$	Pipe length	$D$	Pipe diameter
$p_1$	Gas pressure	$\rho_1$	Gas density
$C$	Flow velocity	$K_m$	Compressibility number

As the compressibility numbers  $K_m$  of hydrogen and natural gas are different, the pressure loss can be calculated as follows:

$K_m$  is calculated for methane up to a pressure of 70 bar (simplified) as follows:

$$K_m = 1 - \frac{p_{abs}}{450 \text{ bar}}$$

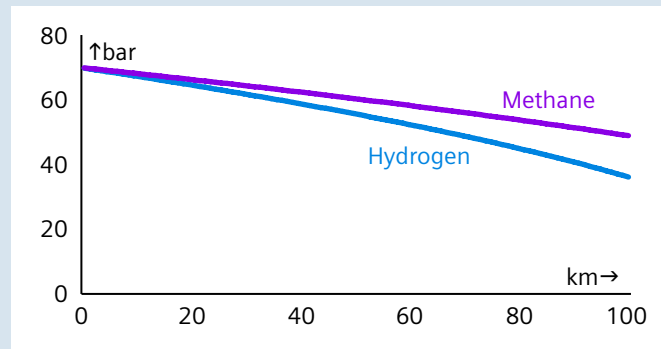
A pressure of up to 300 bar can be used for hydrogen:

$$K_m = 1 + \frac{p_{abs}}{1500 \text{ bar}}$$

As the pressure changes during transport, an average pressure  $p_m$  is used to calculate an average compressibility number  $K_m$

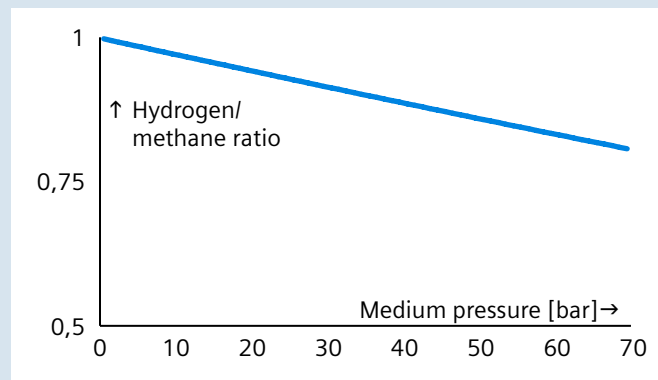
$$p_m = \frac{2}{3} * \frac{p_1^3 - p_2^3}{p_1^2 - p_2^2}$$

From equations (1) to (4), the pressure curve for a pipeline 100 km long and 1,000 mm in diameter results as follows:



**Figure 3:** Pressure curve when transporting methane and hydrogen with the same energy content in a 100 km long high-pressure pipeline with a diameter of 1,000 mm

If the pressure loss is to be kept the same over the distance, in this case the energy flow of the hydrogen is 83%. Figure 3 shows the ratio of the energy flows when the mean pressure changes.



**Figure 4:** Energy flows with the same pressure loss clearly shows that the hydrogen/methane ratio tends toward one when the pressure is reduced (0.997 at normal pressure). The higher the pressure, the greater the influence of the different compressibility numbers of methane and hydrogen. This reduces the inherently good flow properties of hydrogen compared to methane. This negative effect on the energy flow of the lower calorific value is largely compensated by the higher flow rate. This effect also occurs in transmission line networks, and particularly at high pressures, so that the energy flow hardly decreases in comparison to natural gas operation.

### 3.3. Suitability of the pipelines for hydrogen operation

Relevant studies and previous practical knowledge indicate that it is possible to convert the existing steel pipelines from natural gas to hydrogen operation to the extent required for the ramp-up of a hydrogen industry<sup>9</sup>).

A significant reduction in the service life of high-pressure lines due to the influence of hydrogen does not seem likely. Nevertheless, further examination is needed on whether the operating parameters must be adjusted for certain types of steel and operating conditions. In the case of fittings and control valves, the suitability for hydrogen of the membranes and seals used must also be determined. In the case of safety shut-off valves and pressure regulators, it must be clarified if the control and regulating functions must be adapted for the flow properties of hydrogen. Specific conditions of the existing infrastructure would need to be inspected and assessed and the relevant codes and regulations consulted prior to determining if the pipelines are suitable.

### 3.4. Compaction requirements for transport

To be fed into the transmission system, the hydrogen must be compressed to the operating pressure of the network. Compressor stations at certain intervals along the line ensure that the pressure is maintained despite loss of flow in the pipeline. To enable optimal utilization with high transport energy density in hydrogen operation, more and higher-power compressors are required than in natural gas operation.

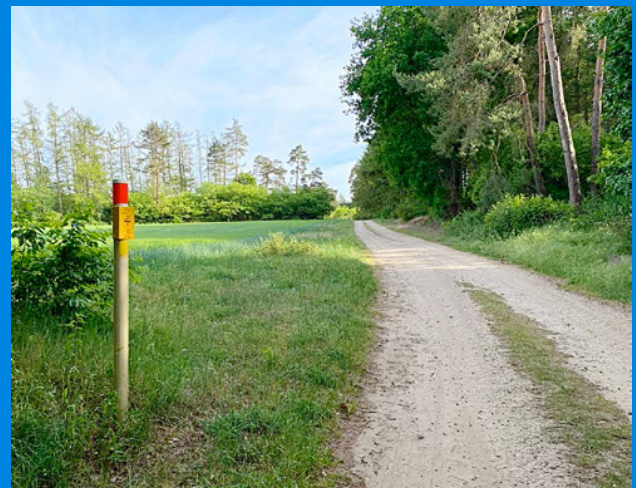
For the planned pipeline projects with the short and medium-term expected amounts of hydrogen, the necessary compressor technologies are available in the form of 'tried and tested' piston compressors. In the long-term, where a nationwide switch to hydrogen with a transport requirement in the gigawatt range, the turbo-compressor concepts currently used will be optimized for hydrogen. It can be assumed that these will be available in a few years if the market demands them<sup>10</sup>).

## Material testing in the 'GET H<sub>2</sub> Nucleus' model project

The transmission system operator Nowega and TÜV Nord are currently testing the GET H<sub>2</sub> Nucleus model project near Lingen in Emsland, regarding the conversion of a first line for the transport of hydrogen (material: STE360.7, length: approx. 11 km, DN 250, built in 1996).

Based on the existing line documentation and technical regulations, the project participants and examiners assume that they are fundamentally suitable. Coordination is currently underway as to which additional measures (including strength and fracture mechanical analysis) will be taken as part of this model test to demonstrate the pipeline's suitability for hydrogen at the maximum operating pressure and the expected change in operating load. Subsequently, three further lines in the project are to be tested using the same procedure.

The corresponding guidelines from the German Gas and Water Association (DVGW) for the conversion of gas transmission lines were approved in September 2020<sup>11</sup>).



**Figure 5:** This existing natural gas pipeline near Lingen in Emsland/Germany converted to hydrogen operation in the GET H<sub>2</sub> Nucleus project

## H<sub>2</sub> readiness of the German gas infrastructure

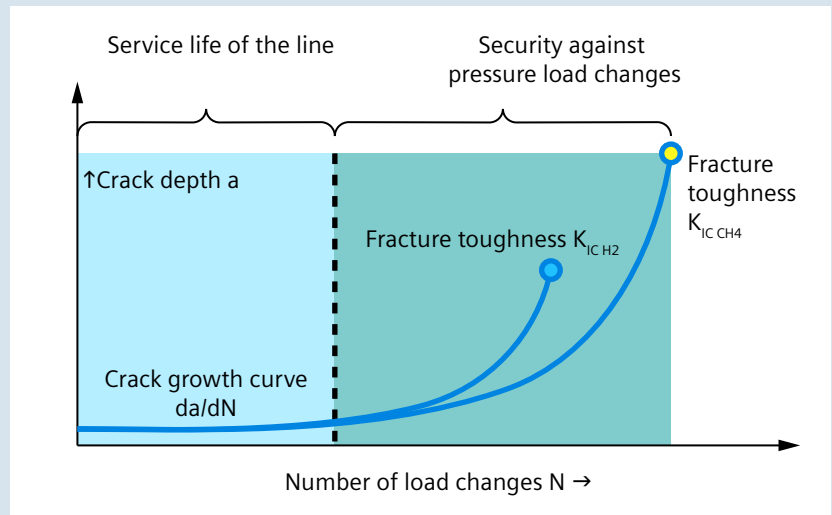
The physical H<sub>2</sub> readiness of the German natural gas system essentially depends on the possible influence of hydrogen on the materials used. Especially for pipeline pipes and fittings made of steel, a reduction in material toughness can be measured under the influence of hydrogen ('hydrogen embrittlement'). Depending on the steel grade and the operating conditions of the pipeline, this reduction in toughness can lead to the growth of existing crack-like defects. In these cases, the service life of the line is therefore reduced.

According to current knowledge, the following factors are essential:

- Existing crack-like defects, especially on the inside of the pipeline
- Hydrogen in atomic form
- Strong dynamic line pressure changes

However, these factors are unlikely to coincide, as usually:

- Crack-like defects are uncommon
- No major pressure load changes occur during regular operation
- No atomic hydrogen is produced during transport



**Figure 6:** Schematic representation of the growth of a crack with the initial depth  $a_0$  depending on the number of load changes  $N$ . The critical crack depth is determined here by the fracture toughness  $K_{IC}$ .

Figure 6 shows the crack growth in dependence on load changes and change in fracture toughness under the given operating conditions. The influence on the material properties of the pipeline steel is recognizable, however, this effect does not lead to a significant decrease in the service life.

Nevertheless, it cannot be ruled out that the binding energy of the H<sub>2</sub> molecule is broken up by various effects during transport and that atomic hydrogen is generated on the inner wall of the tube. This can diffuse into the steel and, among other things, reduce its fracture toughness. A comprehensive and continuous integrity management of the systems is therefore recommended to counteract any risks from hydrogen embrittlement at an early stage. The observation and analysis of the material conditions is carried out by physical internal and external inspection devices and monitoring systems, as well as tests of the pipeline.

Special technologies and inspection devices exist that can detect various changes in the pipeline during operation. An essential means of determining the condition and maintenance of natural gas pipelines today is the so-called 'pigging technique'. Depending on the test technology used, this 'pigging' allows the pipe wall to be checked repeatedly for any anomalies that may already exist. The existing maintenance concepts and tools can be adapted to the requirements of hydrogen transport with minor adjustments that ensure the safe and reliable long-term operation of the hydrogen transport lines. In 2017 and 2019, for example, a hydrogen transport line built in 1996 with correspondingly designed pigs was inspected in the USA. The required tool components have been adjusted to ensure resistance to uneven wear. At a pressure of 20 bar and a flow of 13,000 Nm<sup>3</sup>/h, the tool was able to move safely and without damage, and the inspection was completed with a 100% sensor cover<sup>12)</sup>.



**Figure 7:** Natural gas compressor station in Lippe, Germany (Photo: stock/Gascade Gastransport GmbH)

#### **a) Extensive maintenance and conversion**

of the compressor infrastructure Germany's natural gas infrastructure mainly uses turbo-compressors with one or two impellers. These compressors are operated with gas turbines or motors with a drive power of up to 30 MW. Depending on the hydrogen content in the pipeline, this infrastructure can be maintained or adapted accordingly:

- Up to approx. 10% H<sub>2</sub>, the compressor can generally continue to be used without major changes.
- The compressor housing can be maintained up to approx. 40% H<sub>2</sub>, impellers and feedback stages as well as gears must be adjusted.
- From approx. 40% H<sub>2</sub> the compressor must be replaced.

Due to the intensive development work in this area, it can be assumed that by 2030 the standard compressor drive turbines can be operated with up to 100% hydrogen or can be converted accordingly. Compliance with the applicable NO<sub>x</sub> can be 'limited' with Dry Low Emission (DLE) technology.

#### **b) Maximizing the pipeline hydrogen**

transport capacity In the pure hydrogen operation of a pipeline, an energy flow of 80-90% of the natural gas capacity can be achieved by roughly tripling the amount of gas extracted (depending on the operating parameters). This increase can also be achieved in the existing pipeline network due to the higher flow rate of the hydrogen. However, this requires a higher drive power than is reserved for the transportation of natural gas. To maximize the hydrogen capacity of the gas network, approximately three times the drive power and therefore a correspondingly higher number of turbines and compressors are required than in natural gas operation.

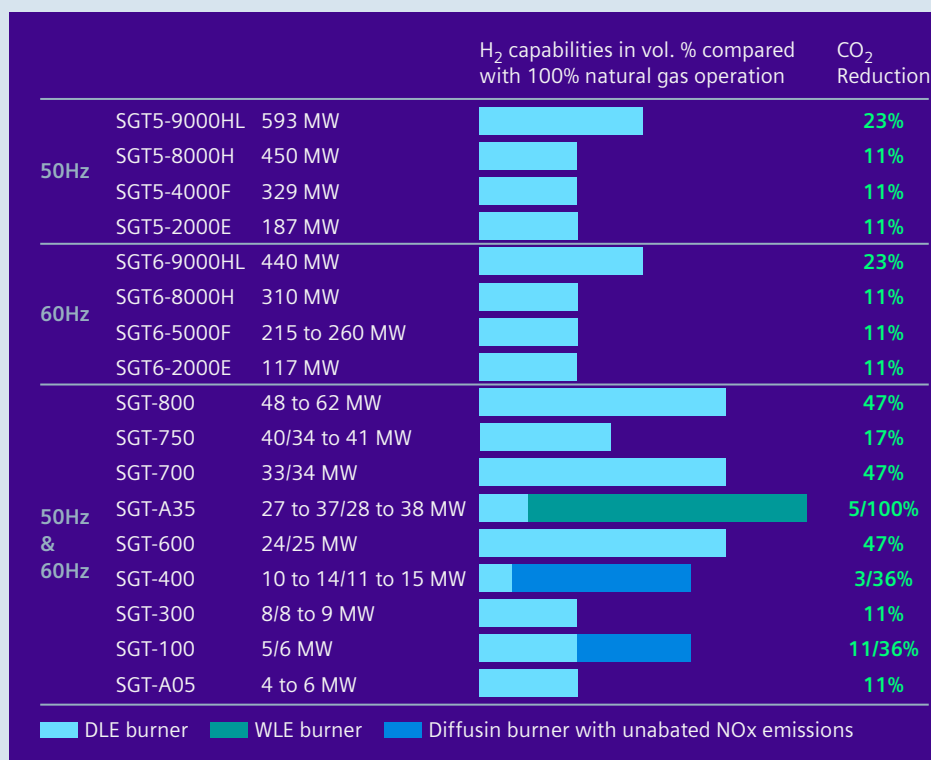
For transport capacities of up to 750,000 Nm<sup>3</sup>/h, current state-of-the-art piston compressors are the most economical solution. For transport capacities above 750,000 Nm<sup>3</sup>/h, however, turbo-compressors are required. These should be available within a few years<sup>13</sup>.



## Adaptation requirements for compressor drives

Compressors that are driven by gas turbines draw their drive energy directly from the line and must be adapted accordingly to the hydrogen admixture. Most common gas turbines for pipelines can already burn a significant amount of H<sub>2</sub> in the fuel: Figure 8 shows an example of the H<sub>2</sub> compatibility for relevant gas turbines from Siemens Energy.

If the compressors are electric driven, no major changes are required for the motors. At most, the speed must be adjusted and safety in hydrogen operation checked.



**Figure 8:** Siemens Energy gas turbines are suitable for hydrogen in the new system portfolio<sup>14)</sup>

## Comparison of compressor technologies

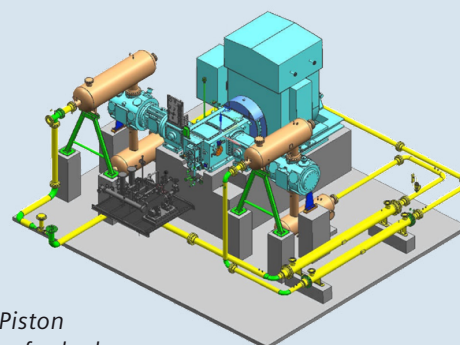
### Piston compressor

In the piston compressor, the gas is compressed with high efficiency in the cylinders. By increasing the number of cylinders and drive power as well as a parallel arrangement of compressors, an economically viable transport capacity of up to 750,000 Nm<sup>3</sup>/h can be achieved.

### Turbo-compressor

In the downstream and petrochemical sector, turbo-compressors for hydrogen-rich synthesis gases have been used for many decades. The technology is already available, but its efficiency is currently lower than that of piston compressors. As a result, many impellers are required to achieve an acceptable compression ratio. Therefore, there remains a need for optimization for future large-scale hydrogen applications.

Studies recommend increasing the peripheral speeds of the impellers to over 700 m/s due to the low molar weight of hydrogen to achieve a compression ratio of approximately 1.3-to-1 per impeller. This corresponds approximately to a tripling of the circumferential speed that is common today. This requires new hydrogen-resistant impeller materials that can withstand high centrifugal forces. The necessary developments have already been initiated so that appropriate wheels should become available in the coming years<sup>21)</sup>.



**Figure 9:** Piston compressor for hydrogen  
(Inlet pressure 24 bar, outlet pressure 52-75 bar with 3 MW motor-drive power - stock/Siemens Energy)



**Figure 10:** Turbo compressor for hydrogen - stock/Siemens Energy)



## 4. Storage

The generation of energy from renewable sources, such as wind power and photovoltaics is subject to strong natural fluctuations. To be able to use the energy efficiently and as required, large and flexible storage options are required that can compensate for these fluctuations. Electricity cannot provide the necessary large industrial capacities (especially via grid buffers and battery storage) for the foreseeable future at economically viable terms.

Alternatively, hydrogen is well suited as an energy source due to its compressibility and storage capacity in storage facilities and can supplement the electricity grid based on the gas storage facilities in Germany – at short notice and at low cost.

### 4.1. Existing gas storage capacities

In addition to its gas pipeline network, Germany has massive underground gas storage facilities (UGS), which are mainly located in Northern Germany. Total capacity, including cushion gas, accounts for:

- Pore storage: 9,1 billion m<sup>3</sup>
- Cavern storage: 17,6 billion m<sup>3</sup> <sup>15)</sup>

This corresponds to approximately 24% of the European storage capacity. With these existing UGS, all of Germany can be supplied with natural gas over a period of about three months<sup>16)</sup>. With their low specific costs, these gas system storage capacities are an economically attractive option for the large-scale storage of energy from renewable sources.

The large UGS therefore open the possibility of both, compensating for short-term discrepancies between fluctuating generation and the needs of customers, as well as bridging lengthy 'dark periods' to ensure security of supply in the energy transition.

### 4.2. H<sub>2</sub> readiness of German gas storage facilities

The operating regime of storage facilities in a gas infrastructure geared towards renewable energies differs fundamentally from previous natural gas operations. While natural gas storage primarily serves long-term security of supply, in hydrogen operation they primarily compensate for the short-term fluctuations in 'green' generation.

Therefore, cavern storage facilities are particularly suitable for storing hydrogen, as their flexible storage and retrieval options make them ideal for the fluctuating availability of renewable energy sources. In addition, its geographical position in Northern Germany offers the strategic advantage of storage close to the producer and the associated relief of the electricity grids. Moreover, numerous cavern storage facilities in the liberalized and European integrated energy market are no longer fully used. Some of them are already available for new uses<sup>17)</sup>.

To check the hydrogen capability of the storage in individual cases, technical and geological investigations, as well as corresponding adjustments of certain components and materials are necessary (see information box).

In practice, UGS hydrogen capability was successfully tested years ago in two large caverns near Houston, USA and a smaller cavern in Teesside, United Kingdom<sup>18)</sup>. A pilot project 'H<sub>2</sub> Research Cavern' for green hydrogen is also being planned in Bad Lauchstädt in Germany<sup>19)</sup>. In addition, since 2016, a storage facility in Epe, North Rhine-Westphalia, has been actively and reliably operating a cavern filled with helium (with comparable requirements for tightness of the salt dome and purity when the gas is stored).<sup>20)</sup>

## Comparison of H<sub>2</sub> storage options in Germany

In Germany, there are two types of UGS for storing natural gas: pore storage and cavern storage.

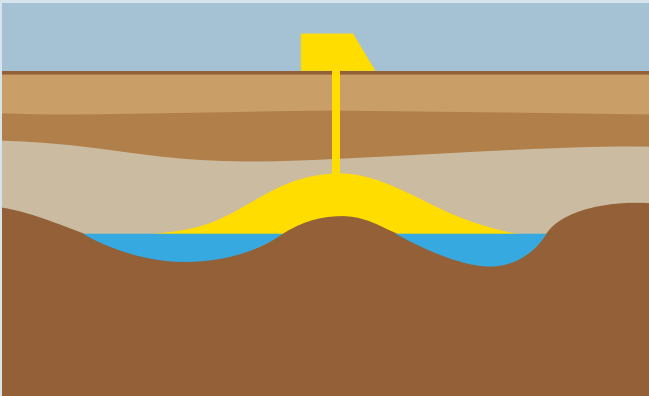


Figure 11a: Pore storage

- Gas is pressed into porous rock like a sponge
- Mainly extracted natural gas or oil reservoirs

Advantage:

- Receives large volumes

Disadvantages:

- High pressure required
- Time-consuming storage process
- Saline water in combination with hydrogen attacks rock, steel, and cement
- Bacterial methanation in existing stores

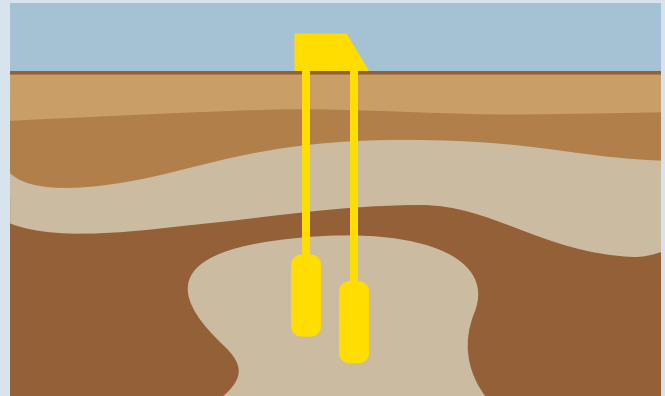


Figure 11b: Cavern storage

- Cavities in underground salt domes
- Found predominantly in northern Germany

Advantage:

- Injection and withdrawal process in the cavity possible at short notice
- Volume control through brine pendulum cavern (reduction of cushion gas)
- Short link to the above ground facility

Disadvantages:

- Saline water in combination with hydrogen attacks rock, steel, and cement
- Mixing with remaining stocks of methane in used storage facilities

## H<sub>2</sub> readiness of the storage system

An examination of the technical and geological integrity is necessary to check the hydrogen capability of the storage facilities<sup>21)</sup>:

- Corrosion and diffusion resistance of the materials used
- Thermodynamic properties under operating conditions
- Permeability, long-term stability, and barrier effectiveness of casing, cement, and storage rock
- Microbial activities (e.g. methanation processes)
- Qualification of materials for the use of components such as fittings, compressors, piping, containers, etc.
- Evaluation of compression ability using compressors in the injection and withdrawal area with a working pressure depending on the filling level at approx. 200 bar. Definition of the materials and the required speed for the compression.

## 5. Hydrogen industry in operation

The success of energy transition crucially depends on ensuring that the energy supply is tailored to current needs. In particular, customers must be able to trust that their needs can always be met. To ensure security of supply reliably and permanently, two components are required: the build-up of the necessary generation, storage, and transport capacities as a resilient basis for a functioning hydrogen industry; and its integration into the German and international gas market enabling trading and creating additional redundancies.

### 5.1. System start-up and first model projects

The first customers in the start-up phase of a climate-neutral hydrogen industry are particularly large industrial consumers with extensive on-site production quantities that can be replaced in the short term by green hydrogen. A successful start-up phase with this target group is a central building block for establishing the system as a confidence-building signal for the overall industry. The same applies to the area of mobility, with its high level of public visibility.

The needs of large industrial consumers and mobility applications are subject to only slight fluctuations. With a supply that is designed for renewable energy sources, there is a steady decrease in the fluctuating generation. As customer processes are based on the extremely high availability of the existing electricity and gas systems, this discrepancy between generation and demand must be reliably balanced from the start of operation to win the customers over to the purchase of green hydrogen.

In the start-up phase, supply can be achieved via existing hydrogen generation plants and the purchase of green electricity for the operation of the electrolysis. If required, a rapidly increasing demand can be met by 'blue', as well as 'green' hydrogen from new plants. Steam reformation of 'gray' hydrogen from methane – analogous to the substitution of fossil generated electricity with green electricity – will be gradually replaced via the expansion of 'green' generation capacities.

The additional integration of cavern storage facilities with their flexible storage and retrieval options means that the hydrogen system can be permanently stabilized in line with demand and security of supply can be guaranteed<sup>22)</sup>. At the same time, large-scale storage creates the conditions for a quick and complete decarbonization of the electricity sector by converting CO<sub>2</sub>-free hydrogen back into electricity in gas power plants during prolonged dark periods.

Putting this in perspective, the first parts of the existing gas networks in regional model projects can be converted to hydrogen operation with comparatively little effort. As intermediate steps on the way to a German and European hydrogen industry, these systems can be gradually established to progressively expand generation capacities to supply networks covering the whole area.

## Hydrogen industry in the 'GET H<sub>2</sub> Nucleus' model project

Between Lingen and Gelsenkirchen, the companies BP, Evonik, Nowega, OGE, and RWE Generation are currently developing the first publicly-accessible hydrogen infrastructure over a length of 130 kilometers in the GET H<sub>2</sub> Nucleus project. The project depicts the entire process chain for a reliable, sustainable hydrogen industry in Germany: from the production of clean hydrogen on an industrial scale, to transport using existing gas infrastructure, and continuous industrial acceptance in Lower Saxony and North Rhine-Westphalia. The system is scheduled to start at the end of 2022 and then start producing clean hydrogen to supply customers:

- The clean hydrogen is to be generated at the RWE power plant site in Lingen in an electrolysis plant delivering an output of more than 100 MW from wind power.
- Existing gas lines from Evonik, Nowega, and OGE will be completely converted to hydrogen transport and supplemented by smaller new buildings.
- This network transports hydrogen to chemical parks and refineries in Lingen, Marl, and Gelsenkirchen, where it reduces CO<sub>2</sub> emissions.
- In the next step, the connection of an existing cavern storage facility, as well as further H<sub>2</sub> generation and customers will take place.

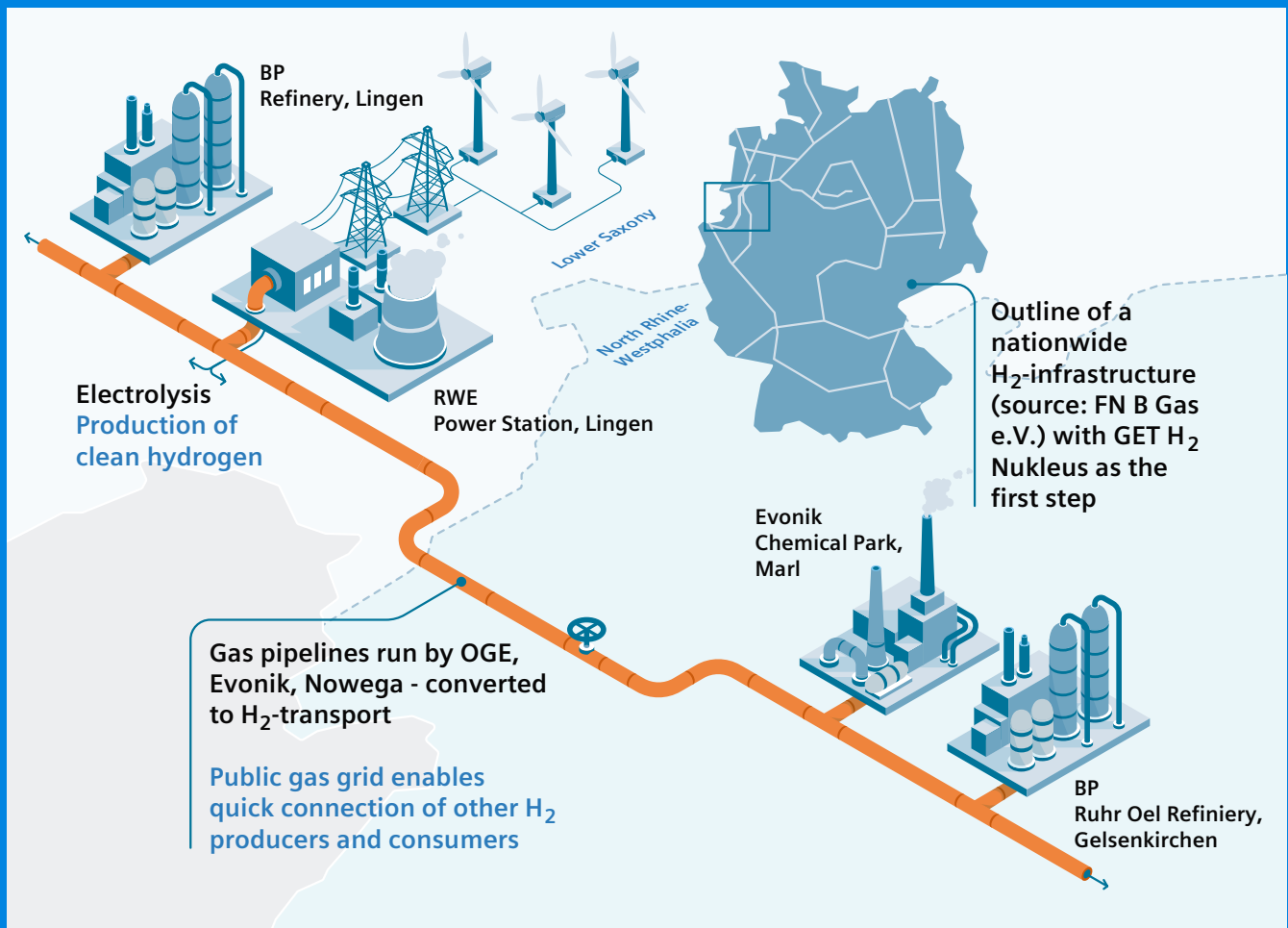


Figure 12: Hydrogen infrastructure in the GET H<sub>2</sub> Nucleus project<sup>23)</sup>

## Projections for a needs-based hydrogen industry in a practical test model

Based on the key data of the GET H<sub>2</sub>-Nucleus project, a realistic hydrogen management system can be modeled. The following scenario exemplifies the requirements, critical factors, and stabilizing elements of a regional hydrogen industry geared to customer requirements.

The following customer groups, which are particularly relevant for system start-up and sector integration, were accounted for as follows:

- **Industry:** Three industrial customers with peak loads typical of refineries or chemical parks of up to 50,000 m<sup>3</sup> H<sub>2</sub>/h each
- **Mobility:** Continuous provision of approx. 25,000 Nm<sup>3</sup> H<sub>2</sub>/h, for example for the supply of approx. 50% of the public transport bus fleet in NRW<sup>24)</sup>
- **Heat:** Supply of a municipal gas distribution network with a peak load of 50,000 Nm<sup>3</sup> H<sub>2</sub>/h and approx. 3,000 full-load hours. This here shown assumption applies equally to 100% converted to H<sub>2</sub> as well as to distribution networks operated with the addition of H<sub>2</sub>
- **Reverse power generation:** Supply of a gas turbine (60 MWeI) for use in the generation valleys (residual load) of wind power generation (approx. 500 operating hours)

### Initial scenario: H<sub>2</sub> supply with 100% onshore wind power

The following decrease curve in Figure 13 shows an extrapolation of the needs of the customers compared to the potentially available energy for hydrogen production from regional onshore wind power.

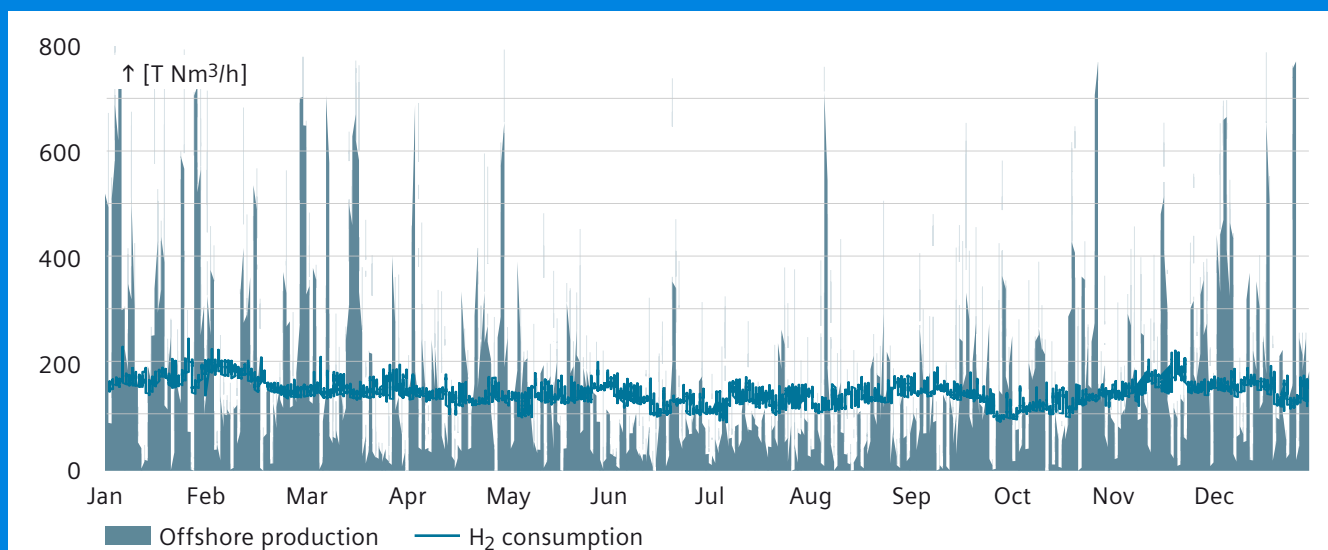
This model calculation leads to enormous discrepancies between demand and the available energy. To produce the required annual amount of hydrogen and use the peak loads of energy generation, it would therefore be necessary

to have generation capacities that exceed the average demand by four times. Such a system would also require disproportionately large capacities to store the hydrogen produced during peak times to compensate for the high volatility – or would have to fall back on hydrogen, for example from existing capacities for 'gray' steam reformation.

An ecologically and economically sensible scaling does not appear realistic under these conditions.

#### Model of a hydrogen energy system

Decrease from industry, mobility and heating market, generation from wind energy



**Figure 13:** While the hydrogen demand of customers is comparatively stable, renewable energy for production is subject to strong fluctuations<sup>25)</sup>



## Extended scenario: H<sub>2</sub> supply from predominantly renewable generation

Using a mix of onshore and offshore wind in the concrete example for hydrogen production and adding a fully flexible storage element (e.g. cavern storage), this leads to a significant steady state of production and approximation to the acceptance curve. In addition, it can be assumed that in the system's start-up phase, not all the capacities required to generate clean hydrogen will be available from the start. In this phase, bottlenecks can be temporarily compensated by existing steam reforming capacities and gradually replaced by electrolysis as renewable energies expand.

In the hydrogen system considered here, an intermediate level of only 13% 'gray' hydrogen would have been reached during the start-up phase (Figure 14)<sup>26)</sup>.

The remaining discrepancies between generation and demand can be covered by integrating existing storage capacities. Cavern reservoirs are particularly suitable for the short-term compensation of the natural fluctuations in 'clean' hydrogen production<sup>27)</sup>.

### Model of a hydrogen energy system

Decrease from industry, mobility and heating market, generation from wind energy backup using existing steam reformers

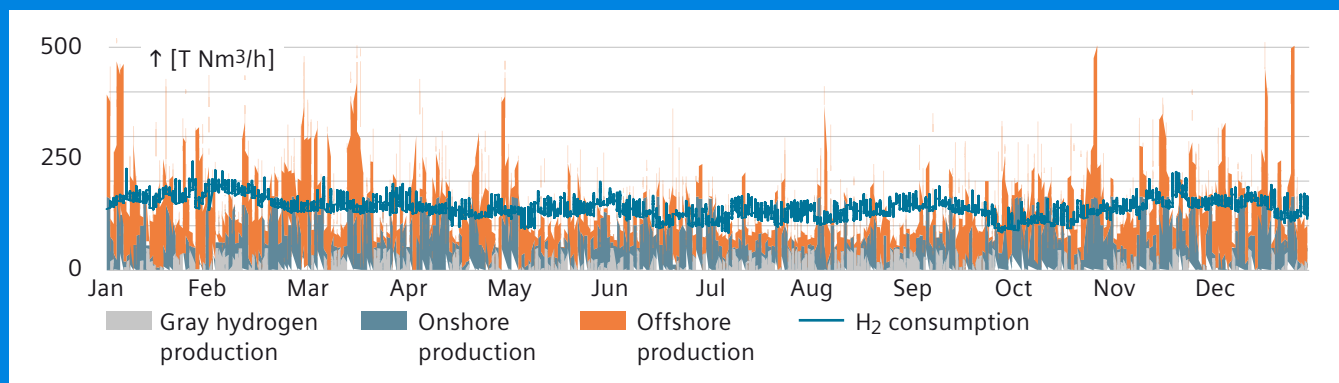


Figure 14: Realistic start-up phase of the market ramp-up in a hydrogen system with predominantly renewable generation

### Resulting requirements for a memory module

Decrease from industry, mobility and heating market, generation from wind energy

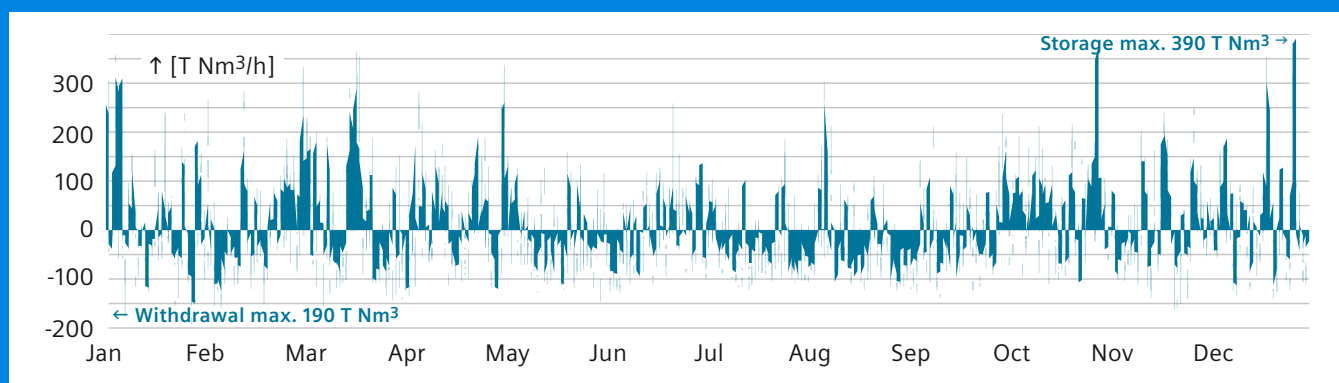


Figure 15: Requirements for injection/withdrawal capacities of the gas storage in the model system  
The expected peak loads of 390,000 Nm³/h when loading and 190,000 Nm³/h during withdrawal can in principle be handled with existing cavern storage facilities<sup>28)</sup>

## 5.2. Integration into the German and international gas market

As things stand today, the integration of hydrogen into the German and European gas systems will take place gradually. It is now time to set the right framework and create the first application markets in Europe to provide an efficient hydrogen infrastructure across the board from 2030.

To ensure security of supply during this transition phase, hydrogen transport capacities can initially be built up in parallel and cumulatively with existing natural gas systems. In many places, existing infrastructures in the form of parallel natural gas lines can also be used for this. For example, climate-neutral hydrogen can initially supplement natural gas as an energy source and gradually replace it by converting further lines as needed.

A parallel hydrogen and natural gas infrastructure at the long-distance gas level also offers the possibility of adapting the composition of the gas – and so the degree of decarbonization of the energy supply – to the local boundary conditions via mixing stations and ensuring a secure transition at all levels (Figure 16).

Figure 17 shows a possible hydrogen network based on existing gas infrastructures as a starting point for a hydrogen industry in Germany. More than 100 locations could be connected to this network, which make up approximately 90% of today's total hydrogen requirements in Germany and are located within a narrow corridor along the routes shown.

According to initial estimates, the current demand in Germany of around 1.5 million tons of hydrogen per year could be transported via this infrastructure.

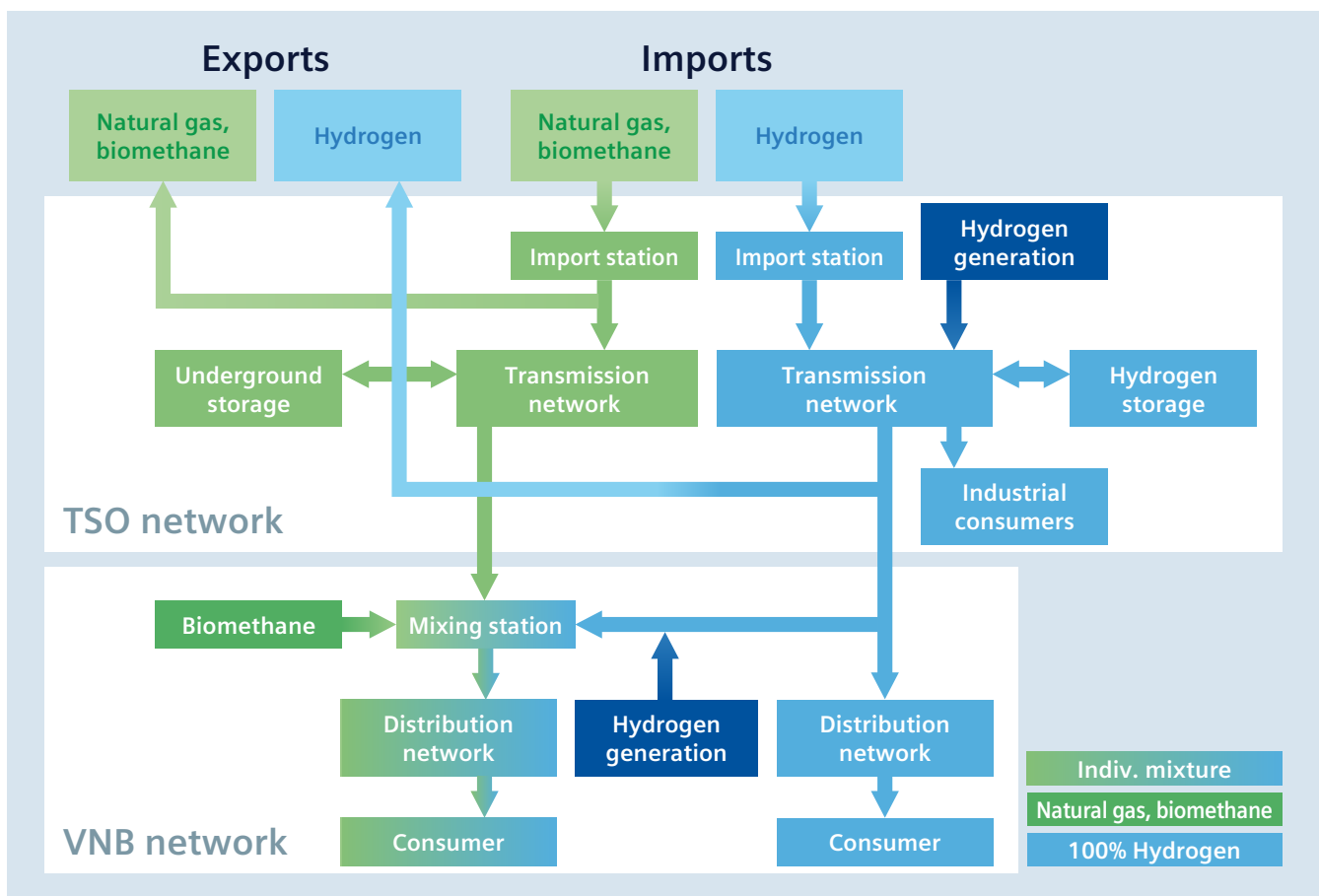
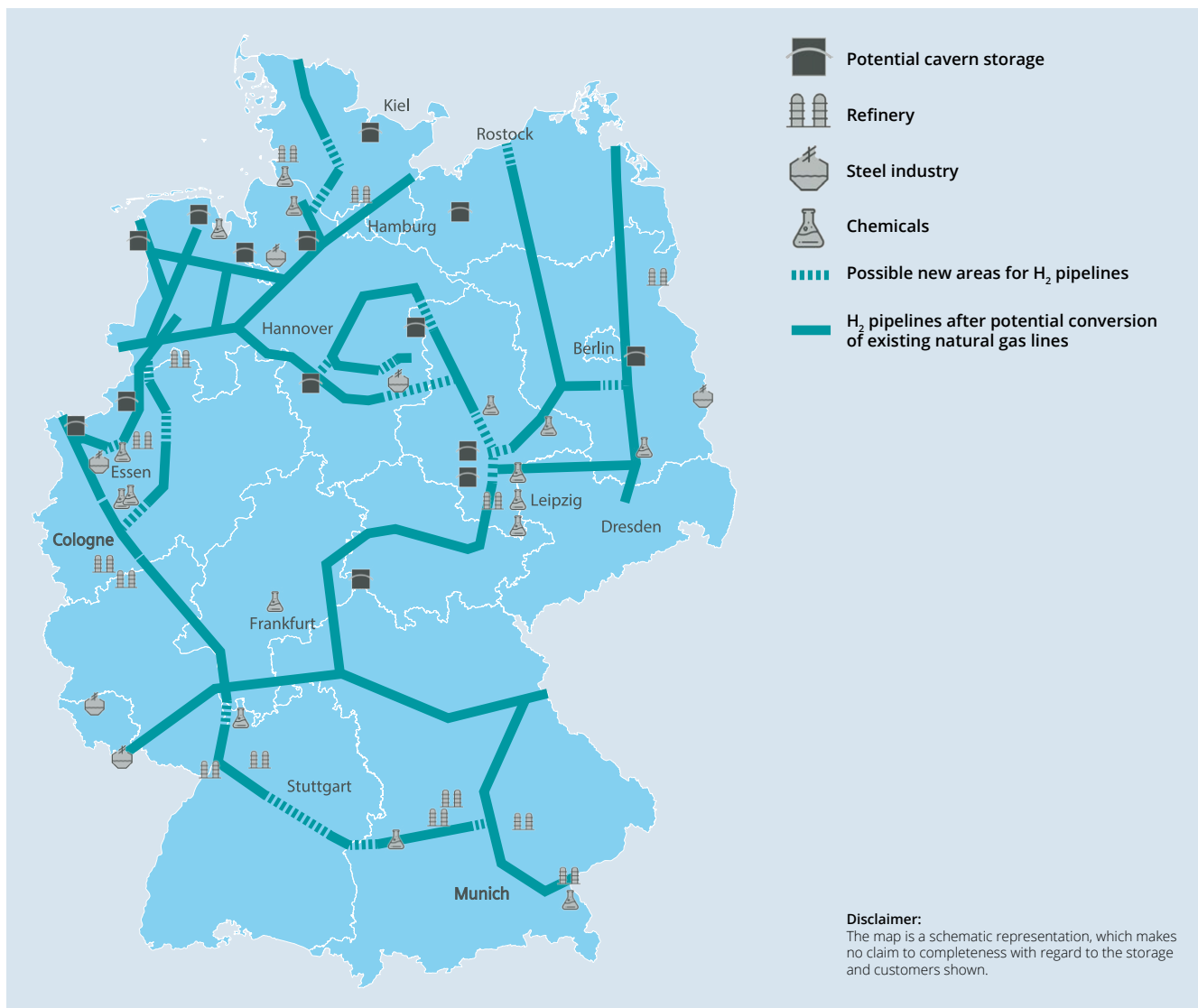


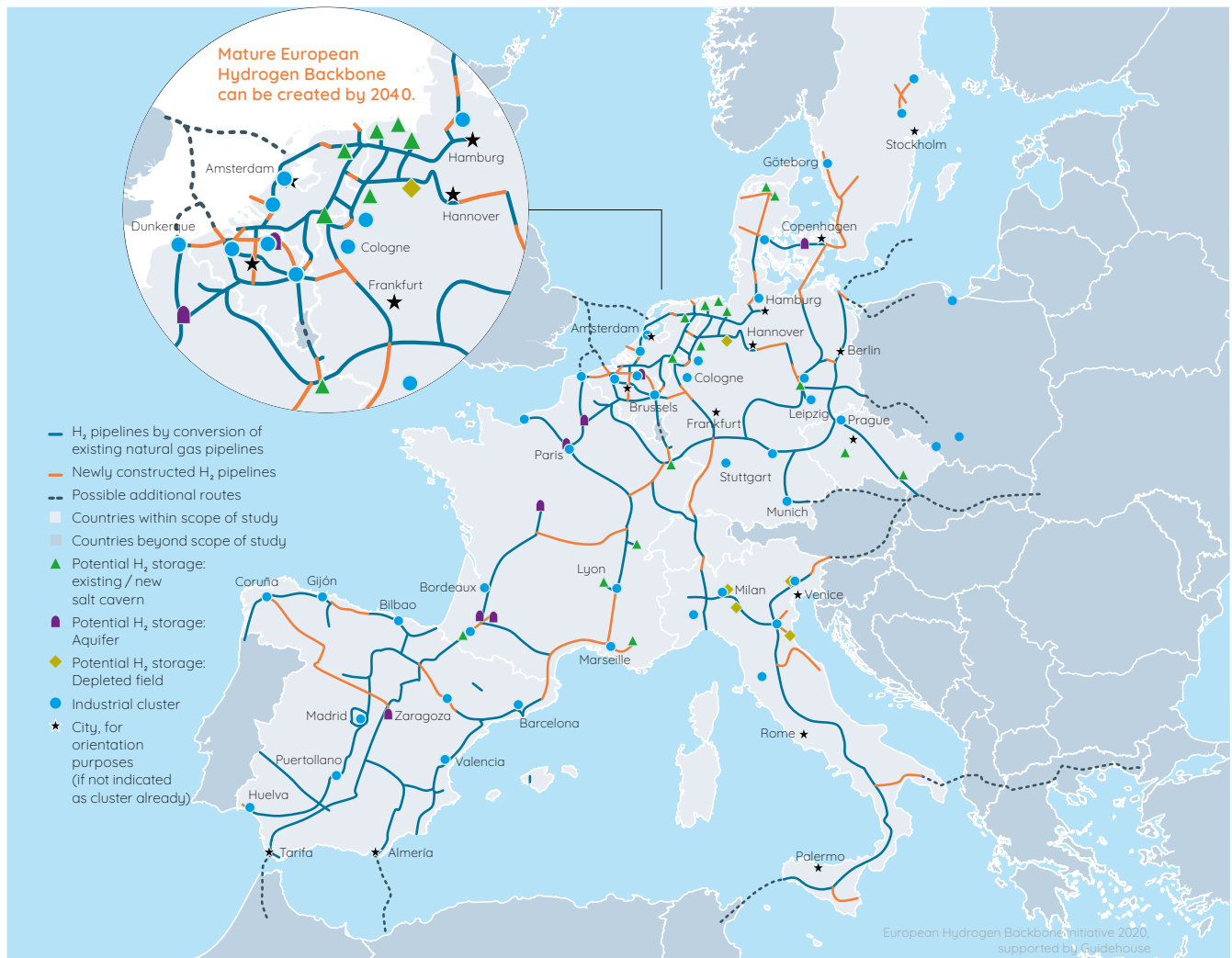
Figure 16: Possible hydrogen integration in the German gas market



**Figure 17:** Vision for a German H<sub>2</sub> network (stock/Association of Gas Transmission Systems Operators)

The outlined pipeline system therefore appears to be sufficiently dimensioned for a rapid start-up phase and equipped for future energy supply. In the future, this hydrogen demand in Northern Germany could be met from regenerative energies and imports to support the profitable expansion of offshore wind turbines and, at the same time, to relieve the power grids in a targeted way.

The integration into the German gas networks also offers the possibility of connecting and significantly helping to shape a future international hydrogen market. The pan-European gas market, which is highly developed in international comparison, offers very good conditions for entry into a global hydrogen industry.



**Figure 18:** Vision for a European H<sub>2</sub> network (stock/Association of Gas Transmission Systems Operators)

Figure 18 shows a possible hydrogen network for Europe. Here too, the existing gas infrastructure is the starting point for a perspective view of an international hydrogen market. The marked pipeline routes show potential transport routes within Europe as well as docking stations for global import and export by land and sea.

By connecting terminals to the North and Baltic Seas, the Mediterranean and international pipeline systems, hydrogen can be imported even from distant producing countries, such as Morocco or Argentina, and imported and exported from neighboring countries via the existing pipeline network. In combination with the storage systems, the network can react flexibly to the respective requirements of producers and customers. Such a market could therefore both guarantee provide security of supply with hydrogen and efficiently control the degree of decarbonization of energy supply in Germany and Europe.

## 6. Economics

The success of a green hydrogen economy essentially depends on whether hydrogen can meet the needs of customers in a competitive way under future market conditions. In addition to technological developments for the efficient production of green hydrogen on an industrial scale, above all this requires uniform and appropriate framework conditions for the hydrogen market.

### 6.1. System startup and first model projects

- The costs for hydrogen production and infrastructure are low compared to the costs of the entire value chain. Investment and production costs for green hydrogen obtained by electrolysis will in future decrease further due to large-scale applications, better production processes and new technologies, as well as cheaper materials.
- Due to the existing gas infrastructure, the transportation, storage, and distribution of hydrogen can also be carried out beyond Germany – at short notice and with little investment.
- There are still challenges with the efficient compression of hydrogen. However, the technologies and materials required for this are already in development.

### 6.2. Legal framework<sup>29)</sup>

So far, hydrogen has not been sufficiently accounted for in numerous regulations – especially the Energy Industry Act (EnWG) and the Renewable Energy Sources Act (EEG). Given this and the uncertainty regarding how hydrogen may be regulated with future legal requirements, it is therefore economically disadvantaged compared to other

energy sources. To achieve at least economic equality, the current framework conditions regarding the gas infrastructure require, among other things, the following adjustments<sup>30)</sup>:

- Creation of legal options for the conversion of existing natural gas infrastructures to hydrogen operation (EnWG)
- Enabling the operation of pure hydrogen networks (EnWG)
- Generation-independent regulations for the transport and storage of hydrogen (EnWG)
- Regulation of the hydrogen feed into natural gas and hydrogen networks (EnWG)
- Cancellation of the final consumer status for the energy conversion from electricity to hydrogen (EEG)
- Compensation for lost feed-in tariffs when generating green hydrogen (EEG)

Short-term economic opportunities also offer a quick and targeted implementation of the European RED II requirements into national laws. Targeted incentives for the use of green hydrogen can be created for refineries in particular<sup>31)</sup>.

Integration into a future international hydrogen market and renewable energy certificate (REC) trading also offers further economic opportunities. This would require uniform European regulations for reliable proof of origin and a transparent differentiation, especially between green, blue, and gray hydrogen.

## Cost estimate for the conversion of the gas infrastructure

According to current estimates, the establishment of a hydrogen infrastructure is possible with limited economic effort. In particular, the use of existing pipeline routes eliminates lengthy and time-consuming planning and approval procedures. The development of new technologies and materials also faces few fundamental challenges and has already been initiated in many areas.

Against this backdrop, the costs for retrofitting the lines – including decommissioning, water pressure tests, replacement of fittings and blowers and dismantling of connections, etc. – can be estimated at around 10-15% of a new

construction according to current estimates by transmission system operators (cost estimate Gascade Gastransport GmbH and Nowega GmbH, 2020).

Converting the compressor infrastructure to maximize the flow of energy in hydrogen operation requires approximately three times the compression performance compared to natural gas operation (cost estimate (cost estimate Gascade Gastransport GmbH and Nowega GmbH, 2020). Accordingly, the compression equipment of a hydrogen pipeline, including the drives, would be about three times the cost of a natural gas pipeline.



## 7. Outlook

The conversion of existing gas infrastructures to hydrogen operation has the potential to achieve a breakthrough for the hydrogen industry.

Using existing storage and transport capacities, hydrogen, as the main pillar of energy transition, can reliably ensure security of supply during the change to renewable energy sources. In this way, energy transition – and sector integration specifically – can be promoted comparatively quickly and inexpensively along with the expansion of the power grids.

At the same time, the long-distance gas networks open up the prospect of a European and global hydrogen market – and therefore the opportunity to consider the expansion of the regenerative energies increasingly globally: linking generation capacities in countries that are rich in renewable energy sources with markets and customers in different regions of the world, reliably and on competitive terms.

The technical challenges of hydrogen technology can largely already be addressed today. The anticipated progress and the use of digital solutions will lead to continuous improvements of the overall system. The utilization and interactions of gas and electricity grids can increasingly and more effectively be controlled to compensate for discrepancies between the generation of renewable energy and individual needs in national and international operations.

Politics, industry, and the energy industry are widely committed to hydrogen as one of the central energy sources of energy transition. Two things must now follow: the consistent expansion of capacities for renewable electricity generation; and the appropriate regulatory framework showing the route to an efficient German, European, and global hydrogen economy.

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