Cost estimation of hydrogen admission into existing natural gas infrastructure and end use

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ABOUT MARCOGAZ

Founded in 1968, MARCOGAZ is the technical association of the European gas industry. It represents 29 member organisations from 20 countries. Its mission encompasses monitoring and policy advisory activities related to European technical regulation, standardisation and certification with respect to safety and integrity of gas systems and equipment, rational use of energy as well as environment, health and safety issues. It is registered in Brussels under number BE0877 785 464.

DISCLAIMER

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bn. .... billion (109)
DBB .... Double block and bleed
DP .... Design pressure
e.g. .... exempli gratia (for example)
EGIG .... European Gas pipeline Incident data Group
EHB .... European Hydrogen Backbone
EMAT .... Electro Magnetic Acoustic Transducer
ENTSOG .... European Network of Transmission System Operators for Gas
GC .... Gas Chromatograph
GIE .... Gas Infrastructure Europe
GPRMS .... Gas pressure regulation and metering stations
GPRS .... Gas pressure regulation station
GSE .... Gas Storage Europe
i.e. .... id est (that is, that means)
IGU WGC .... International Gas Union, World Gas Conference
ILI .... Inline inspection
IS .... Infrastructure
km. .... Kilometre
LCCS .... Last cemented casing shoe
LNG .... Liquefied Natural Gas
Max. .... Maximum, maximal
MFL .... Magnetic flux leakage
MG .... MARCOGAZ
Min. .... Minimum, minimal
Mil. .... Million
MOP .... Maximum operating pressure
N/A .... Not available, not applicable
No. .... Number
PGC .... Process gas chromatograph
SF .... Surface Facility
SSV .... Subsurface Safety Valve
TEG .... Tri-Ethylene-Glycol
TGV .... Total Gas Volume
TYNDP .... Ten Year Network Development Plan
UGS .... Underground Gas Storage
vol. .... Volume
WGV .... Working Gas Volume
WH .... Wellhead

1 ACKNOWLEDGEMENT

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2 MOTIVATION

To achieve climate neutrality in Europe by 2050, the use of renewable gases, namely H_2, in the gas sector, is becoming a necessity. In this transformation process, the gas grids play a key role in transporting H_2 to industries, households and other locations where it is going to be used. H_2 combines a whole set of important properties, e.g. a high gravimetric energy density, non-toxicity, safety and, most importantly, it has been proven to be a strong candidate to help the energy sector transition to the new age of decarbonisation. It is therefore increasingly considered as a key energy carrier in the future EU energy system. This led to a growing appreciation of H_2, as seen in the EU-Hydrogen Strategy, as well as in national H_2 strategies.

However, this acknowledgment of H_2 did not necessarily cover all relevant sectors in the heating market, where a strong case can be made for blending natural gas with certain levels of H_2. As a result, the full advantages (including low landscape consumption, high safety, reliability and energy capacity, etc.) of the existing gas infrastructure are not yet being exploited.

Increasing political and public awareness of the advantages of gas infrastructure is still a challenging task. There are remaining concerns about its capability to be H_2-ready in a timely manner, and about the lack of visibility around the required adaptions for stakeholders.

MARCOGAZ aims to alleviate some of those concerns by bringing more clarity to the current status of H_2 suitability for Europe's gas infrastructure. As a result, this report focuses on defining the required mitigation steps to achieve the necessary H_2-readiness. It also looks at running a cost analysis, in order to show the costs for the transformation towards H_2-ready infrastructure. The scope of this report is divided into these major categories:

1. Quantification of the volume of assets for components that are operated in Europe's gas infrastructure and their respective H_2 tolerance.
2. Estimating the mitigation costs for the key H_2 concentrations (2, 5, 10, 15, 20, 25, 30 and 100 vol.-% H_2).
3. Updating and improving the infographic on the H_2-tolerance of the gas infrastructure and end use.

This work, including the acquired data and the results for the calculated adjustment costs, can be visualised in a user-friendly infographic attached to this report. The infographic serves as an accompanying document to explain the method and the results. It also provides insights into the data that the calculations are based on.

3 INTRODUCTION

In the process of planning a climate-neutral Europe, many aspects need to be considered to find the most sustainable, economic and implementable way of achieving this goal. Regarding all these questions, both technical issues and economic grounds need to be considered to find the most effective path to lead Europe into climate neutrality. This report aims to provide estimations about the transformation costs of Europe's gas infrastructure in order to prepare it for the transport of H_2. The costs presented in this report are based on experiences from several stakeholders in the gas industry and include expected technical suitability of components for use with H_2. Obviously, not all the assumptions and information are already confirmed for norms and standards.

This report focuses on economic aspects of the four main fields regarding the use of H_2: transport, storage, local distribution and end use (focusing on domestic appliances). The numbers given focus on the economic aspects of the transformation within the borders of technical feasibility. This report does not include a more general comparison between various types of technology for aspects like energy efficiency and energy availability. These questions need to be answered on a case-by-case basis when deciding which technology is best suited for a specific task.

When aiming to ensure the same energy throughput, additional measures are sometimes needed, even for low H_2 concentrations. These measures and their corresponding costs are not considered in this publication. They can only be provided on the basis of an individual assessment by the operators themselves. Additional TSO perspectives on individual cases are described in Annex 1.

The authors of this report aim to provide information about the probable transformation costs of the European gas grid, which includes the UK's infrastructure. This is one of the factors that must be considered by decision-makers, who face the complex task of finding the most suitable path towards a climate-neutral Europe.

4 I INFOGRAPHIC 2023

In October 2019, the first infographic[1] was created by MARCOGAZ to provide an overview of the technical readiness of the gas infrastructure and end-use equipment to handle H_2-/natural gas mixtures at each stage of the gas chain. The current state of knowledge of transmission, storage, gas pressure regulation and measurement, distribution and end use of H_2-/natural gas mixtures (up to 30 vol.-% H_2) as well as for pure H_2 were collected and appraised, drawing on the wide expertise and experience of network operators, storage operators and end-use experts. The infographic focuses on material aspects and functional principles. It does not consider the effect of increasing levels of H_2 on performance, efficiency and output. The level of knowledge and available sources on H_2 tolerance may vary across the infrastructure sectors under consideration. In rare cases, this can lead to differences in the listed H_2 tolerances for assets represented in different areas of the infrastructure. The infographic takes this into account as far as possible.

The infographic has been updated, because of the many new experiences and the research results obtained over the last few years. Several new components have therefore been added, as well as updated information on existing components. The updated infographic is depicted in Figure 1 of this report.

The following components were added to the infographic:

- The original component compressor was divided into two types: turbo compressor stations and piston compressor stations. The assessment was carried out with reference to the report 'Consequences of hydrogen in natural gas infrastructure' of CEN/TC 234[2] and the 'Conversion of compression station for hydrogen – Cost study'[3] done by MARCOGAZ.
- Valves and pipelines on the surface facility of an underground gas storage location were grouped together as the 'Surface facilities and pipelines' component[4].
- Desulphurisation for gas treatment, after underground gas storage withdrawal, was included[4].
- In addition, the combustion of gases linked to underground gas storage facilities is summarised in the two components 'Flare & Burner'[4].

The following components were significantly updated:

- Pigging station: like the (pipeline) steels typically used, it can be assumed that the material is suitable for H_2. From 10 vol.-% H_2 admixture, only the seals must be tested for suitability and adapted if necessary.
- Shut-off valve and gas relief valve are suitable for up to 30 vol.-% H_2. The basic physical principle for activating the valves remains unchanged. In addition, standard natural gas components were installed in a pressure station in the 'H_2-Netz' project[5] and in a DBI project[6] for industrial thermoprocessing plants and operated with 100 vol.-% H_2. The long-term tests have so far shown no functional restrictions and no effects on seals.
- Volume converter: for H_2 admixtures greater than 10 vol.-% H_2, it is important to assess whether it is possible to make a changeover to one of the two calculation methods, SGERG-mod- H_2 or AGA8-92DC. These are applicable for all H_2 concentrations in natural gas, according to DVGW G 685-6 'Gasbilling – Natural Gas Compressibility Factor'[7]. According to ISO 20765-2, the equation of state GERG-2008 can be used for up to 40 vol.-% H_2[8].
- Turbine gas meter: according to the results of the DNV JIP 'Suitability of Flow Meters for Renewable Gases'[9], flowmeters normally used in transmission grids (turbine and ultrasonic gas meters) can be operated with H_2 up to 30 vol.-% with an uncertainty in the measurement inside the requirement of the reference normative (OIML).

1 https://www.marcogaz.org/wp-content/uploads/2019/09/H2-Infographic.pdf
2 PD CEN/TR 17797:2022, 'Gas infrastructure – Consequences of hydrogen in the gas infrastructure and identification of related standardisation need in the scope of CEN/TC 234', June 2022.
3 Marcogaz 'Conversion of compression station for hydrogen – Cost study', 2021 (internal document).
4 Sources are given in chapter 7 Underground Gas Storage.
5 DBI Gas- und Umwelttechnik, MITNETZ Gas, HTWK Leipzig, TÜV Süd & REHAU: Experiences of the HYPOS project. H_2-Netz, https://www.mitnetz-gas.de/gr%C3%BCne-gase/wasserstoff-testfeld.
6 Pietsch, P.; Wiersig, M.; Werschy, M. 'Einfluss von Wasserstoffanteilen im Erdgas auf Bauteile der DIN EN 746-2', 2018.
7 DVGW Regelwerk, Technical Standard – Worksheet DVGW G 685-6 'Gasbilling – Natural Gas Compressibility Factor', August 2022.
8 DIN EN ISO 20765-2:2018 'Natural gas – Calculation of thermodynamic properties – Part 2: Single-phase properties (gas, liquid, and dense fluid) for extended ranges of application', February 2018.
9 DNV Joint Industry Projects, 'Suitability of Flow Meters for Renewable Gases', 2021.

- Ultrasonic gas meter: according to the results of the DNV JIP 'Suitability of Flow Meters for Renewable Gases'[9], flowmeters normally used in transmission grids (turbine and ultrasonic meters) can be operated with H_2 up to 30 vol.-% with an uncertainty in the measurement inside the requirement of the reference normative (OIML). However, although the JIP test results show measurement errors within the acceptable range defined by standards for 30 vol.-% H_2 for ultrasonic meters, the bias in some specific meter types could be significant for fiscal measurement purposes carried out on large metering stations, for which high quality (very low uncertainty) measurement is required. Consequently, some manufacturers ask their customers to contact them before using existing gas meters for applications with H_2 blends higher than 10 vol.-%. Some new gas meters have already obtained their metrological certification for applications up to 30 vol.-% H_2.
- Diaphragm gas meter: in the DVGW research project G 202010 'H_2 measurement accuracy'[10], the measurement deviations of bellows gas meters with different gases (methane, 20, 30 and 100 vol.-% H_2) were investigated. Suitability for all gases could be proven. A custody transfer measurement is not yet possible, due to the lack of a separate approval for H_2 concentrations greater than 20 vol.-%. The suitability for concentrations up to 20 vol.-% H_2 was also proven by further investigations[11].
- Ductile cast iron: in an H_2 project[12], ductile iron pipes were tested for their suitability for H_2. For this purpose, there was an examination of pipes that had already been operated with town gas and those that had only been operated with natural gas. The latter were also exposed to different H_2 concentrations (up to 100 vol.-% H_2). The mechanical parameters all complied with a manufacturing standard (EN 969) and the brittle fracture surfaces also showed no abnormalities.
- Fittings and house installation: for house installation, it is assumed that all common materials are suitable. In addition, leak tests on the fittings have not revealed any abnormalities up to 100 vol.-% H_2. The evidence was provided in the DVGW research project G 201615 'Influence of hydrogen components in natural gas on gas installation components'[13].
- Gas engine, fuel cell heating appliance, gas cooker, atmospheric burner, condensing boiler: according to the THyGA project[14], operation with up to 20 vol.-% H_2 is possible for these end applications. Even an H_2 concentration of up to 30 vol.-% can be ensured through minor adjustments.
- Forced-draught burner/steam boiler, industrial thermo-process uncontrolled: through individual assessment and, if necessary, minor or major adjustments, up to 30 vol.-% H_2 suitability can be ensured.
- Industrial thermo-process controlled: there is an H_2 suitability for up to 10 vol.-%[15].

10 Kramer, R.; Weyhe, M.; Böckler, H.-B. DVGW Forschungsprojekt G 202010 'Untersuchung des Verhaltens von Haushaltsgaszählern im Verbund mit Hausdruckregelgeräten bei Nutzung von H²-beaufschlagten Gasen', August 2022.

11 NewGasMet project A3.3.3 Effect of hydrogen admixture on the accuracy of a rotary flow meter, Version 1.0, 29th October 2021.

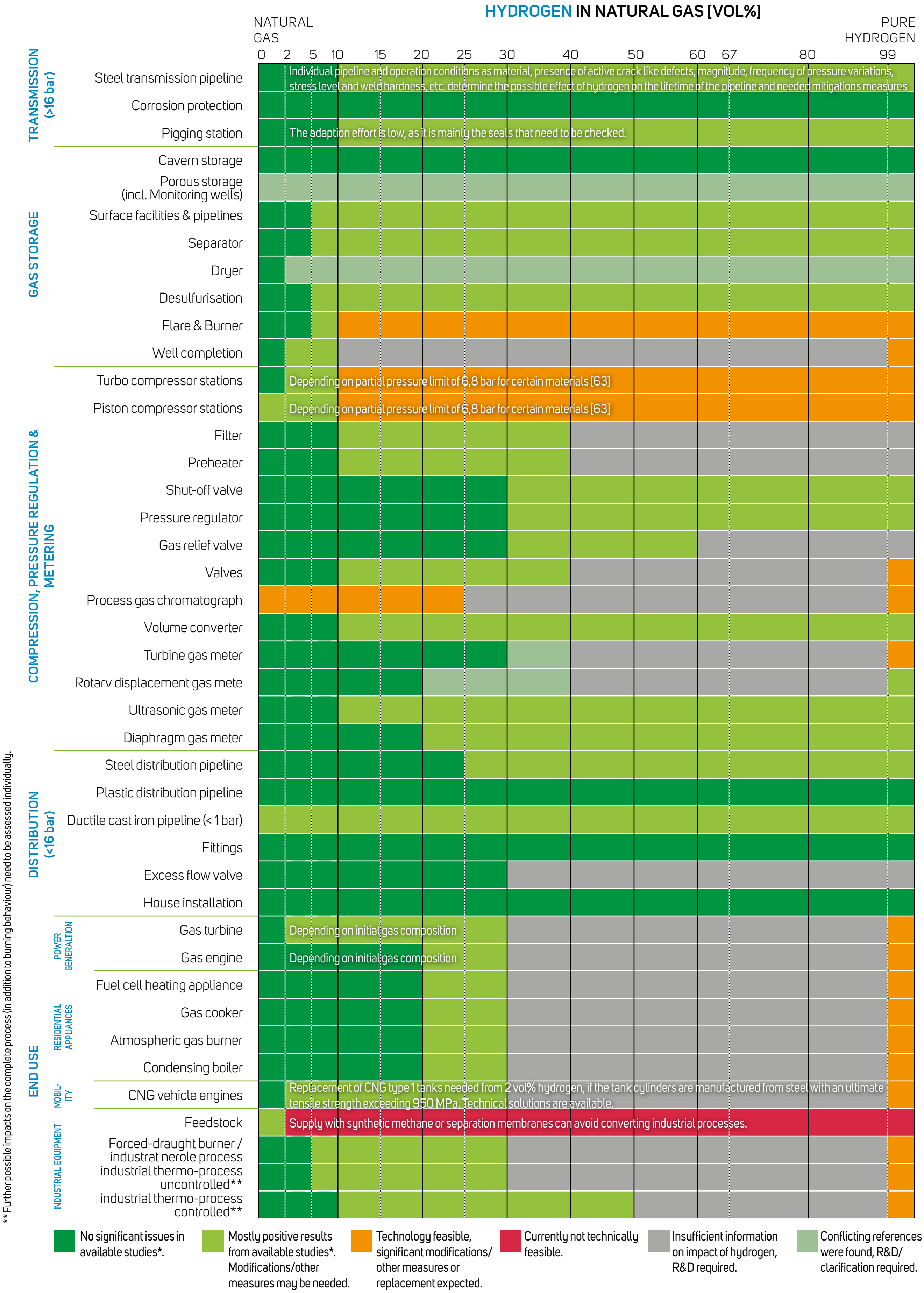
12 'Study of the possible effect of the joint conduction of natural gas/hydrogen on the mechanical resistance of gas pipelines made of ductile cast iron', Sedigas, UPC, 2022 https://www.gasrenovable.org/uploads/thinktank_documentacion/24/documento/estudio-efecto-h2-en-fd.zip

13 Gas- und Wärme-Institut, Engler-Bunte-Institut (EBI), DBI Gas- und Umwelttechnik GmbH, DVGW Forschungsprojekt G 201615 'Sicherheitskonzept TRGI - Mögliche Beeinflussung von Bauteilen der Gasinstallation durch Wasserstoffanteile im Erdgas unter Berücksichtigung der TRGI', February 2018.

14 THyGA 'Testing Hydrogen admixture for Gas Applications, WP3. Intermediate report on the test of technologies by segment – Impact of the different H_2 concentrations on safety, efficiency, emissions and correct operation'.

15 Pietsch, Ph.; Wiersig, M.: Die Einflüsse von Wasserstoff in Thermoprozessanlagen, Prozesswärme 01/22, S. 33 ff.

Figure 1: Overview of available test results and regulatory limits for hydrogen admission into the existing natural gas infrastructure and end use



This assessment is based on information from R&D projects, codes & standards, manufacturers and MARCOGAZ members expertise.
The assessment applies to segments in isolation. Any decision to inject hydrogen into a gas infrastructure is subject to case by case investigation and local regulatory approval
*According to the list of references

5 I METHOD

With the aim of generating a more complete picture of the current status of Europe's gas infrastructure, MARCOGAZ worked closely with the different European stakeholders. The resulting assumptions, data and results were discussed and proofed by the responsible committees of MARCOGAZ. This was crucial to obtain the necessary data on the volume of assets and components present throughout the gas value chain. The latter comprises these categories, which are also defined below to avoid potential confusion about the different classifications in each specific country:

- Transmission and regional distribution: all the gas systems operating with pressures higher than 25 bar. They are typically used to deliver gas over long distances.
- Local distribution networks: systems operating with pressures below 25 bar, in most cases with pressures up to 16 bar. This category encompasses gas distribution networks on a more local scale. The authors are aware that there are some pipelines in distribution grids that are operated with pressures above 25 bars: these are covered in the first group.
- Gas storage facilities: this category includes the surface- and subsurface facilities used to store gas in depleted reservoirs, aquifers or salt caverns and their respective equipment.
- Pressure regulating and metering stations: this category covers the stations in both the gas transmission and distribution system.
- End use: this category relates to the different specific usages in residential and commercial appliances (industrial applications are only partly covered[16]).

As a first step, the volumes of these assets are quantified for all the above-mentioned areas of interest. As it was not possible to make an overall audit of all the necessary assets (valves, meters, pressure regulators, etc.) along the entire European infrastructure value chain, a more feasible and strategic approach is implemented here. This entails using certain countries which have this data readily available, as a basis for this study to calculate a specific amount (weighted average, e.g. based on the corresponding pipeline length) for each area of interest. These assets are then evaluated for their H_2 suitability for the key concentration: 2, 5, 10, 15, 20, 25, 30 and 100 vol.-% H_2. Finally, the mitigation costs are estimated for the entire gas value chain, for each specific H_2 concentration scenario. The data acquired within this work and the results are included anonymously.

The acquired and aggregated data on the volume of assets, their H_2 compatibility as well as required mitigation measures are presented in separate chapters for each operating category. The colouring of the tables follows, as far as possible, the colour scheme in the infographic and these colours are explained in its legend.

16 Industrial applications are seen as an important future market for H_2 as an energy carrier. However, industrial applications are technologically very individual. Therefore, a case-by-case assessment is necessary for most of the industrial plants, due to their implementation of a wide range of processes, technologies and power consumption. This is not possible in this study and it would require intensive cooperation with the representatives of the respective industries. Moreover, future R&D results can support the development of a general cost estimate of the industrial end-use sector.

5.1 General approach of assumptions and calculations

The general approach of this report can be summarised in these four steps (see Figure 2):

1. Quantification of the volumes of all assets utilised in each operation category.
2. Evaluation of these assets for their H_2 suitability for the key concentrations: 2, 5, 10,15, 20, 25, 30 and 100 vol.-% H_2.
3. Elaboration of the specific costs for the defined adaption measures.
4. Calculation of the total costs for the entire gas value chain for each specific H_2 concentration.

As quantification of the complete European gas grid is a challenging task, it is not always possible to make an overall audit of all the necessary assets (valves, meters, pressure regulators, etc.). In these cases, more realistic and strategic approaches must be implemented. This includes using certain countries which have the required data readily available as a basis for this study to calculate a specific amount (weighted average) for each area of interest.

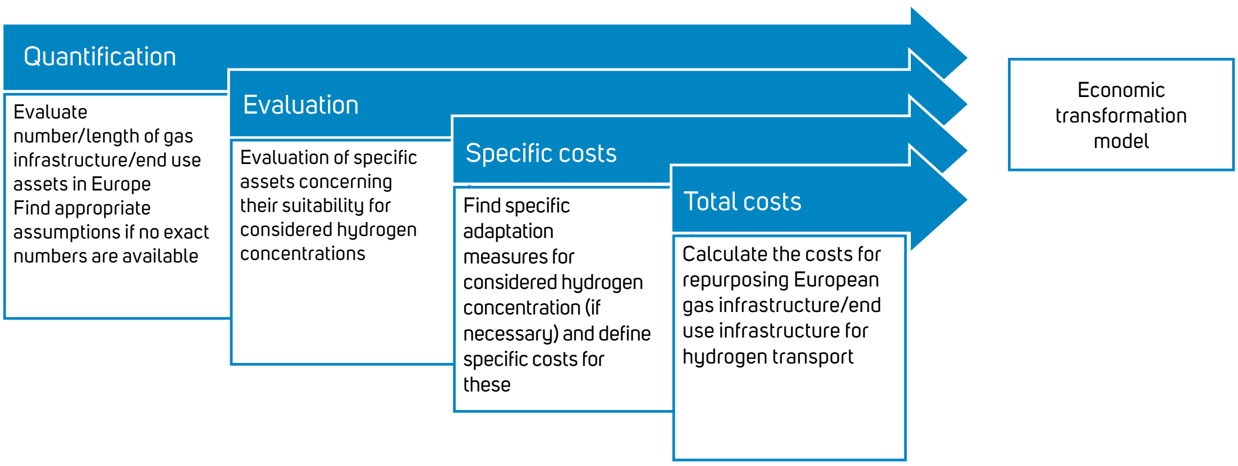
It is also important to note that calculating a specific price for the renewal or retrofitting of a selected component is complex because prices vary across Europe and depend on many variables. Therefore, average prices should be applied to as many different specific prices from different European countries as possible. Wherever possible, the price estimations cover the costs for installation of the assets.

Moreover, it is difficult to assess the extent to which H_2 is the single reason for mitigation action, compared to the elevated renewal of the infrastructure before H_2 is injected. Renewal is likely to be intensified before H_2 is injected due to a lack of experience with H_2 in the system and because safety is a high priority Therefore, assumptions and preliminary results, as well as expert assessment, have been included in the considerations.

Inflation and other cost increases have occurred during preparation of the report. In areas where specific inflation surcharges were applied in calculating transformation costs, this is stated in the text.

The most important H_2 concentrations mentioned above are included in this investigation. As a result, the report does not refer to H_2 concentrations of 31 – 99 vol.-% in the gas blend. If these concentrations eventually prove to be necessary, they would have to be investigated separately. However, this does not seem to be crucial, based on today's technical knowledge.

Figure 2: Four steps to calculate the transformation costs



6 | TRANSMISSION AND REGIONAL DISTRIBUTION

6.1 Pipeline asset volumes

Gas transmission systems are defined in this work as systems operating above 25 bar. Steel materials are therefore used in the pipelines to accommodate these high levels of pressure. It is also crucial to differentiate between older and newer pipes as this is relevant in the next step – the proposed mitigation actions and therefore adaption costs. Differentiation is implemented because of improved non-destructive testing technologies: pipe quality was improved in production facilities and in the field, when pipe sections were welded to a pipeline. This improved technical situation was included in the standards for pipeline production and installation in the mid-1980s. Consequently, the weld quality of the whole infrastructure built since then has been improved. Those quality measures were sometimes applied even earlier, but this is considered atypical. Based on this background, the following distinction has been made:

- Older pipelines: commissioned before 1984 with a lower weld quality
- Newer pipelines: commissioned after 1984 EN12732/API 1104 with an improved weld quality

The operated assets length has been estimated on the basis of the distinction developed in the ENTSOG's Hydrogen and Natural Gas Ten-Year Network Development Plan (TYNDP) and the 11th EGIG report for both groups. It was concluded that the 225,000 km of gas transmission pipelines consist of 121,000 km older and 104,000 km younger pipelines.

6.2 Station asset volumes

Station assets are defined as assets and are characterised by a structure that is more complex than a single pipeline. They can have a housing, but this is not a mandatory property. In the following section, the assumptions and estimated asset volumes are described.

6.2.1 Valve stations (in the pipeline)

It is important, when estimating the number of currently operated valve station codes and standards, to define the distance between valve stations. The regulations vary across Europe, between 10 and up to 90 km of pipeline length. A specific number for valve stations was calculated on the basis of the specific regulations and pipeline lengths of these countries:

- Belgium
- France
- Germany
- Italy
- The Netherlands

Based on this information, a length-weighted average of one valve station per 14.6 km of existing pipelines was calculated. This amounts to about 15,400 valve stations, for the total length of transmission and regional distribution pipelines in Europe.

For conveying pure H_2, it is expected that all existing valve stations will be replaced by double block and bleed stations every 20 km on average in the European gas transmission system. This estimation is based on the currently discussed requirements. The expected regulations in the EU Member States can vary significantly. In the near future, the requirements and regulations will likely become clearer.

6.2.2 Pigging stations

Following the method described in chapter 5, specific values have been calculated for these countries:

- France
- Denmark
- Italy

Based on this information, a weighted average of one pigging station for every 66 km of pipeline length was set. This amounts to about 3,400 pigging stations for the total length of transmission and regional distribution pipelines in Europe.

6.2.3 Metering stations

The estimation of metering stations (gas pressure regulation stations are covered separately) that are used, e.g. at country borders, also followed the method in chapter 5 and covered these countries:

- France
- Germany
- Italy
- The Netherlands
- United Kingdom

In addition, a second approach based on ENTSOG's transparency data has been evaluated. As the data on the platform only focus on the trans-border metering stations, large stations – except for trans-border stations – are missing. This results in fewer metering stations by comparison with the approach based on the data of the countries listed above. The initial approach, which concluded that about 870 metering stations are operated across Europe, was therefore used for further calculations. The assumption is that the metering stations are equipped with three trains, two converters (one back-up) and one Process Gas Chromatograph (PGC) for each station. It should be noted that not all the measuring stations are equipped with a PGC. However, in other parts of the grid, PGCs are installed and this leads to a realistic total amount of PGCs.

6.2.4 Compressor stations

The same method as for metering stations was used to estimate the installed compressor power. Here, the installed power, expressed per unit length of the pipeline, has been used to derive specific values. Compression infrastructure has been considered from the countries below to develop specific values:

- Germany
- Italy
- France

Based on this information, a weighted average of 0.042 MW installed compressor power per km of pipeline was determined. This amounts to about 9,500 MW installed power for the total length of transmission and regional distribution pipelines in Europe.

6.2.5 Overview of considered asset volume information

Table 1: Overview of considered asset volumes

Infrastructure item	Asset volume (rounded)	Additional information
Steel transmission pipelines	225,000 km	TYNDP 2018
Older pipe construction	121,000 km	Before 1984 EN12732, EGIG
Younger pipe construction	104,000 km	After 1984 EN12732, EGIG
Valve stations (existing)	15,400	Extrapolated based on specific values
Valve stations (needed for pure hydrogen service)	11,250	Extrapolated based on specific values
Pigging stations	3,400	Extrapolated based on specific values
Compressor station installed power incl. drive and auxiliaries combined	9,500 MW	Extrapolated based on specific values
Metering stations	870	Extrapolated based on specific value
Pressure regulating stations	-	Covered in a separate section entitled 'pressure regulation'

6.3 Mitigation measures

Mitigation measures describe, in brief, what action is needed to convey certain H_2 concentrations in the existing gas infrastructure.

The mitigation measures were elaborated on the basis of available literature, findings of research/demonstration projects, discussions and consensual assumptions of MARCOGAZ expert groups. Mitigation measures described in this chapter underpin the Infographic displayed in chapter 4.

Beyond the mitigation measures described in the following sections, further mitigation actions, including the replacement of pipeline sections, could become necessary, especially if it is necessary to maintain the same energy throughput as found in the natural gas service. Those measures could in some constellations become necessary even for low H_2 concentrations. These measures and their corresponding costs are not considered in this publication. This information can only be provided on the basis of an individual assessment by the operators themselves. Appendix 1, which was developed by ENTSOG, gives an overview of the reasons that were assessed by TSOs for any necessary replacements of pipelines: these may vary depending on the circumstances of each TSO.

For higher H_2 concentrations, transporting the same amount of energy will lead to significant adaption measures for some components (e.g. compressors). However, it is expected that the needed transport capacity will decrease in general, thanks to energy efficiency measures and shifting demand, e.g. to power and district heating.

6.3.1 Mitigation measures for pipeline assets

Steel pipelines operated statically are deemed to be suitable for H_2 applications[17, 18]. Static operation has been defined by pressure swings lower than 10% of pipeline DP. The following measures are recommended to ensure safe operation and they are considered in the subsequent assessment and cost approximation:

- For H_2 concentrations up to 10 vol.-% in the gas mixtures, a risk assessment is required for the current condition of the pipeline. (Existing ILI and MFL and for smaller diameter DCVG should be considered.)
- For higher H_2 concentrations, e.g. 10 vol.-%, ILI and subsequent repair are required if the pipelines are operated dynamically. Dynamic operation is considered for 5% of the pipeline length. This approach is considered to be conservative[19] as pressure swings in the mentioned magnitude occur mainly in pipelines directly connected to UGS or LNG regasification plants.
- It is expected that the ILI could, with suitable technologies, lead to the identification of cracks and crack-like defects. It is assumed[20] that defects for older pipelines will be more frequent (0.1/km) than for younger pipelines (0.01/km). This expectation is connected to the explanation in section 6.1.

The mitigation measures are summarised in Table 2 below. The colour indicates the readiness of the asset for the H_2 concentration in line with the legend of the infographic (Figure 1). Here, dark green in Table 2 (below) reveals that no significant mitigation measures are required.

Table 2: Mitigation measures for transmission pipelines

Mitigation measures according to hydrogen concentration								
	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100 vol.-%
Steel pipelines before 1984	Risk assessment			ILI and subsequent repair for dynamically operated pipelines needed				
Steel pipelines after 1984	Risk assessment			ILI and subsequent repair for dynamically operated pipelines needed				

17 DVGW Project SyWeSt H_2: 'Investigation of Steel Materials for Gas Pipelines and Plants for Assessment of their Suitability with Hydrogen', Dr. Michael Steiner, Dr. Ulrich Marewski, Dr. Horst Silcher, 2023.

18 Expert discussion MARCOGAZ 2021 – 2023.

19 Expert discussion MARCOGAZ 2021 – 2023.

20 Expert discussion MARCOGAZ 2021 – 2023.

6.3.2 Mitigation measures for station assets

Station assets are complex in terms of the number of components, technologies used and how products are designed. The mitigation measures shown in this sub-chapter summarise measures that apply for most of the assets in the field. However, it is expected that there will be exceptions where more, less or different measures are needed.

Valve stations[21]:

- Require their tightness to be checked due to the smaller nature of H_2 molecules, which makes these stations more prone to leaks. Replacement can be mandatory, depending on the country, for mixtures containing above 10 vol.-% H_2.
- For H_2- mixtures between 10 and 30 vol.-%, it is assumed that 10% of the valve stations will be replaced with a cost estimate of 1,500,000 to 2,200,000 EUR / valve station.
- For 100 vol.-% H_2 gases, it is assumed that all valve stations will be replaced by DBB stations every 20 km on average, with a cost estimate of 1,800,000 to 2,500,000 EUR / valve station.

Pigging stations

- No modifications are seen, as required for H_2 concentrations up to 10 vol.-%.
- Above this limit, seal replacement is expected. Some ILI technologies that are expected to be used more frequently in H_2 conveying pipelines are longer than the currently used MFL technology. This can lead to challenges with the current receiving stations, but this might be solved by ongoing technological development.

Metering stations

- Above 0.2 vol.-% H_2, PGC needs to be replaced.
- To reach a compatibility for 2 vol.-% H_2, PGC must be replaced.
- Above 10 and up to 30 vol.-% H_2, manufacturer approval of meters and converters is expected, and recalibration of ultrasonic-meters might be necessary[22].
- For 100 vol.-% H_2, replacement of meters and volume converters and further complex measures are expected to be necessary.

Compressor stations

Compressor stations are especially complex and individual facilities. This applies to the design, selected key technologies and products and components, e.g. compressors, drives and sealing systems, etc. Mitigation measures listed below are therefore of a general nature: on a case-by-case basis, it may be necessary to implement more or fewer measures in order to achieve certain H_2 concentrations.

- Up to 2 vol.-% H_2, an additional control system is considered to be necessary. This is because, due to the lower heating value of H_2 compared to natural gas, larger amounts of gas mixture must be carried through the system, leading to a higher flow rate. Furthermore, in some cases, H_2 concentration monitoring might be needed.
- Above 2 and up to 10 vol.-% H_2, modifications of the following components are considered to be necessary in many cases[23]:
  - Control System
  - Fuel gas system, including filter
  - Sealing systems (wet systems not suitable)
  - Fire detections systems
- Between 10 and 20 vol.-% H_2, complex modification, as for 10 vol.-% H_2 gases, plus retrofit of compressors, drives and possibly pressure reduction are required.
- For concentrations above 20 vol.-% H_2, replacement of the compressors and drives and significant changes on the station are required. Providing the same pressure loss in the pipelines, the additional compression energy amounts to 13% by comparison with natural gas. If the same energy flow must be maintained, the higher flow rate would amount to more than 50% additional compression energy by comparison with natural gas[24]. Replacement of the compressor stations is therefore considered if H_2 concentrations of 20 vol.-% will be exceeded.

The mitigation measures for different station types are summarised in Table 3. Here too, the colours indicate the readiness of the asset for the H_2 concentration. Two new colours are added here, in addition to dark green. Light green represents mostly positive results from studies, while some mitigation measure might be needed. Orange underscores that it is technically feasible to adjust the asset for the specific H_2 concentration, but significant mitigation measures are expected.

21 Expert assessment of Marcogaz, February 2023

22 Information from H_2GAR/ DNV, Paper 12 JIP renewable gases; results on performance of turbine and ultrasonic flow meters up to 30% Hydrogen and 20% CO2, Proceedings of the North Sea Flow Measurement Workshop, October 2021.

23 MARCOGAZ, internal report 'Conversion of compression station for hydrogen – Cost study' of Fluxys, 2022.

24 'System- und netzplanerische Aspekte der Wasserstoffeinspeisung in Erdgasnetze – Teil 1' Jens Mischner und Peter Schley, gwf-Gas|Erdgas 1-2/2015.

Table 3: Mitigation measures for station assets

	Mitigation measures according to hydrogen concentration							
	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100 vol.-%
Valve stations	Risk assessment	Tightness check		Tightness check, replacement in some countries may be mandatory				Valve stations will be replaced by DBB stations every 20 km on average
Pigging stations	No modification expected			Replacement of seals expected				
Compressor stations incl. drive and auxiliaries	Additional control system and H_2 concentration monitoring in some cases needed	Modifications are often needed to: Control system Fuel gas system Sealing systems Fire detection systems		Complex modification as for 10 vol.-% plus retrofit of compressors, drives and possibly pressure reduction required		Replacement/measures that are of comparable effort needed		
Metering stations	PGC renewal			PGC renewal + volume converter calibration manufacturer approval for turbine meters, manufacturer approval and case depending on modification of us-meters			PGC & volume converter renewal Meter replacement	

6.4 Cost assumptions

The cost assumptions build on the mitigation measures defined for the different asset types. The cost assumptions are partly direct cost figures or calculated as shares of new-build assets.

6.4.1 Cost assumptions for pipeline assets

Up to 10 vol.-% H_2, no modification costs are considered for pipeline assets but costs (200 EUR/km of pipeline) are foreseen for updating documentation, general evaluation and studies assessing possible effects for H_2 injection into the existing infrastructure.

For concentrations from 10-30 vol.-% H_2, costs for ILI of 23,000 EUR/km (using new technologies like EMAT for crack-like defect identification) are estimated on the basis of operator and pilot project experiences in MARCOGAZ. This cost has been applied for the pipeline length that is assumed to be operated dynamically, as described in 6.3.1.

Repair costs are estimated to be 50,000 EUR per repair (see also Table 4).

For pure H_2 in the infrastructure retrofitting, cost as a bundle of measures has been applied on the basis of the experiences in MARCOGAZ. This combined cost approach has been applied for pure H_2 only and also includes station assets such as:

- Replacement of gas quality chromatograph
- Replacement of other equipment (e.g. metering)
- Replacement of 10% of the pipeline length
- Permits and studies costs

Retrofitting costs for pipelines built before 1984 are set at 20% of a new-build pipeline and, for pipelines built after 1984, retrofitting costs are set at 15%.

Cost for building one metre of new pipeline is set at 1,370 EUR[25] for pipelines built before 1984 (400 mm diameter in average) and at 1,530 EUR for pipelines built after 1984 (500 mm on average). The diameter displayed has been calculated using the EGIG database[26].

Table 4: Specific average adaption costs for gas transmission pipelines

	Adaption costs according to the hydrogen concentration								
	0 vol.-%	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100 vol.-%
Steel pipelines before 1984	0 EUR				23,000 EUR/km + 50,000 EUR/repair				274,000 EUR/km
Steel pipelines after 1984	0 EUR				23,000 EUR/km + 50,000 EUR/repair				229,000 EUR/km

25 Net development plan gas, 'Netzentwicklungsplan Gas 2020-2023', May 2021.

26 11th EGIG report, 2020, https://www.egig.eu/reports.

6.4.2 Cost assumptions for station assets

In this section, the cost assumptions that are applied to calculate the transformation costs of station assets are summarised in Table 5 and, where necessary, the background is explained.

Valve stations

- For mixtures between 5 and 10 vol.-% H_2, a tightness test is expected to be performed. Tightness tests will be compulsory for methane too, as a result of the new regulation on methane emissions. No additional costs for valve stations for concentrations up to 10 vol.-% H_2 are therefore considered.
- For 10 up to 30 vol.-% H_2, it is assumed that 10% of the valve stations will be replaced, leading to average costs of 1.85 Mil. EUR / replaced valve station
- For 100 vol.-% H_2, it is assumed that all valve stations will be replaced by DBB stations every 20 km on average, with a cost estimate of 2.15 Mil. EUR / valve station.

Pigging stations

- Replacement of sealing is estimated to cost 6,000 EUR per pigging station.

Metering stations

- For renewal of PGC up to 10 vol.-% H_2, 50,000 EUR are expected and above 10 vol.-% H_2 150,000 EUR, as the auxiliary systems must be modified too (e.g. change of carrier gas). Each metering station is considered to have a PGC, which is a very conservative assumption. It is expected that only every third or fourth facility is equipped with a PGC. Due to a lack of data, this conservative assumption has been made.
- Above 10 and up to 30 vol-% H_2, volume converter calibration/update are considered to be possible for 50% of the operated devices. For older devices, renewal is foreseen. Average costs of 5,000 EUR have been applied.
- For ultrasonic meter, above 10 and up to 30 vol.-% H_2, an average cost for recalibration of 3,000 EUR is estimated.
- Replacement of metres for 100 vol.-% H_2 is covered by the pipeline retrofitting costs and not considered separately.

Compressor stations

The costs for the needed modification to accommodate different H_2 concentrations are estimated on the basis of an investigation of Fluxys (see footnote 23) and assumptions discussed by MARCOGAZ experts.

The replacement cost for compressor stations is estimated on the basis of the EHB report[27] as an average from 'medium' and 'high' cost approximation for replacement costs: this amounts to 5.5 Mil. EUR/MW.

Table 5: Cost assumptions for station assets

Adaption cost in EUR according to hydrogen concentration/station, MW installed for compressor stations								
	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100 vol.-%
Valve stations	0	0		1,850,000				2,150,000
Pigging stations	0			6,000				
Compressor stations including drive and auxiliaries	6,600	132,000	352,000	880,000	968,000	5,500,000	5,500,000	5,500,000
Metering stations	50,000			158,000				Covered in pipeline retrofit

27 European Hydrogen Backbone (2020) 'HOW A DEDICATED HYDROGEN INFRASTRUCTURE CAN BE CREATED', Table 5, page 20.

7 UNDERGROUND GAS STORAGE FACILITIES (UGS)

Underground Gas Storage facilities (UGS) are the facilities used to store gas for future utilisation, including all the equipment required for injection and gas treatment. For this study, three main types of UGS facilities were distinguished: Cavern-UGS, Depleted Oil- and Gas Fields, and Aquifers.

The assessment of UGS facilities was undertaken in three steps:

1. Analysis of existing UGS facilities in Europe and determination of main parameters and asset amounts.
2. Analysis of main components: H_2-tolerance and adaption measures.
3. Cost assessment for reaching higher H_2-tolerances for adjustment of an existing natural gas UGS facility and for building a new H_2-UGS facility

The main difficulty in this part of the project was to determine the quantities of the main components of the UGS facilities in Europe. A further challenge was to narrow them down to a format that allows for a representative cost assessment for all European UGS facilities.

UGS facilities vary significantly, in terms of type size and storage volume as well as operating conditions. Accordingly, a wide variety of equipment is used and, currently, in several cases, no clear statements on H_2 suitability could be made. However, several field projects are currently being carried out and real practical experience will be gained in the near future. These experiences might also change the current knowledge of H_2 suitability for several components.

Europe has a total of 205 UGS facilities, divided into three main types (see Table 6). All of them have unique parameters and different types and amounts of components installed. For this work, a bottom-up approach was used, supplemented by more detailed information from reference projects. This was discussed and agreed upon with MARCOGAZ experts. The workflow to determine the amounts and types of components are outlined below:

1. Analysis of the 'Gas Storage Europe'[28] database. Compilation of the main parameters of each UGS, i.e. storage volumes and maximum withdraw and injection rates. Analysis of depths and number of wells was also done, if secondary sources were available. Mainly used here: IGU WGC 2018[29].
2. Determination of main parameters for each UGS.
3. Determination of amounts of main equipment for each UGS, using the assumptions and approaches described in Table 8.
4. Determination of average values for each UGS type, for main parameters and the amounts of equipment.
5. Determination of a weighted average value for all main parameters and equipment, using the average values for each UGS type and the number of UGS facilities for each type.

Applying the workflow above, a 'generic UGS' was generated. This covers cavern UGS, depleted field UGS, as well as aquifer UGS. This approach can be considered representative because, ultimately, all the necessary main equipment and their overall shares and quantities are covered. However, this approach also has some limitations as it produces unrealistic combinations of equipment in a single UGS (e.g. different types of gas treatment and different types of compressor drives[30], whereas in reality only a single system would be used).

28 https://www.gie.eu/index.php/gie-publications/databases/storage-database.

29 European UGS facilities in operation. Based on WOC 2 UGS Report SG 2.1. Presented at 27th IGU WGC 2018, Washington DC. Actuality: 2016/17. Not freely available source.

30 Usage of different compressor types is, however, common. There are several UGS facilities using both piston compressors and turbo compressors, e.g. Rehden in Germany.

7.1 Main parameters of UGS facilities

In this sub-chapter, the European UGS facilities, their number and their main characteristics are determined. The starting point for the analysis was the 'Gas Storage Europe'[31] database. The following table summarises the number of UGS facilities considered:

Table 6: Summary of UGS facilities according to type

Type	Salt Cavern	Aquifers	Depleted Fields	Total
Number	68	36	101	205

In the next step, the main characteristics/parameters for each UGS were assessed and average values for each type calculated subsequently. Then, a weighted average value for a standard representative European UGS facility was formed, using the number of each type in relation to the total existing UGS facilities.

These values are important as they determine the amounts of the main component of the UGS facilities (see Table 8):

- Depths are used to determine the length of tubings and LCCS.
- Working gas volume is required to determine the number of wells.
- Maximum withdraw rate is required to stipulate the amount of components on the withdrawal side of the UGS.
- Maximum injection rate is required to stipulate the amount of components on the injection side of the UGS, mainly number and type of compressors.
- Max. Pressure at the LCCS is important for calculating the power consumption of a compressor.

Table 7: Summary of main parameters of UGS facilities according to type

Parameter	Unit	Cavern UGS	Aquifer UGS	Depleted Field UGS	Weighted Average
Depth Top	M	1,040.30		12,44.51	958.22
Depth Bottom	M	1,324.13	706.43	1,427.67	1,266.67
WGV	Mil. Nm^3	220.56	150.98	529.88	360.74
TGV	Mil. Nm^3	662.13	368.13	1,160.52	856.05
Max. Withdrawal Rate	1,000 Nm^3/h	516.03	325.25	654.76	550.88
Max. Injection Rate	1,000 Nm^3/h	263.02	192.40	476.92	356.00
Max. Pressure at LCCS	Bar	185.00	78.79	149.03	148.63
Min. Pressure at LCCS[32]	Bar	60.00			19.90
Temperature	°C	47.50	27.17	54.91	47.58
No. Wells	-	9	31	28	22

31 https://www.gie.eu/index.php/gie-publications/databases/storage-database.

32 For cavern UGS, a regular value fitting for the cavern depth had been applied by DBI. For the other types, no minimum pressures could be determined from GSE. Thus, the weighted average value is automatically calculated as very low. However, this value has no impact on the subsequent cost assessment.

7.2 Analysis of UGS facilities: quantity of main components

As a next step, the main components for gas operation were assessed according to the facilities' main parameters. The specific amounts were determined, as is explained below and in Table 8:

- For some components like gas chromatographs, fixed values are assumed.
- For components like amounts of compressors and gas treatment units, assumptions for calculations are made, e.g. the amount of compressors is determined according to maximum injection capacity:
  - Maximum injection rate of a UGS facility:
    - » Above 200,000 Nm3/h max. injection capacity:
      - › Maximum injection capacity divided by 150,000 Nm3/h = amount of turbo compressors. Value rounded.
    - » Below 200,000 Nm3/h max. injection capacity:
      - › Maximum injection capacity divided by 50,000 Nm3/h = amount of piston compressors. Value rounded.
    - » 1 compressor for redundancy each.
  - Above calculation was done for each UGS facility in Europe, using the general information from GIE.
  - Calculation of the sum of all piston and turbo compressors and calculation of the weighted average value, using the amount of each UGS type in Europe.
- For components with differing types, e.g. varying gas treatment units, it was important to determine not only the overall amount of the component itself but also the share of certain types (e.g. TEG drying and adsorption drying). Here, IGU WGC 2018 was the main source, alongside the reference project 'Wasserstoff speichern – soviel ist sicher. Transformationspfade für Gasspeicher'[33].
- For several components, e.g. subsurface tubings, it is currently not possible to make a funded determination about the degree of H_2-tolerance since this is unknown for the API grades typically used for subsurface equipment. Future and ongoing research projects/results might change this assessment.
  - However, there are some practical experiences in the field, showing that regular API-steels can be used under certain conditions and/or up to limited shares of H_2 blended into natural gas[34].
  - Some API steels are reported to be H_2-suitable, such as e.g. X-52. However, they are rather untypical.

For several components, e.g. pipelines in the surface facility (SF) components, it was important to differentiate between two cases:

- H_2-suitable
- Not H_2-suitable

That is because, for these components, varying types and materials are available on the market and a survey among UGS operators in Germany[35] concluded that partially H_2-suitable material is used and is partially not suitable material. The respective shares were extrapolated to the European UGS facilities.

The following table summarises the main components and the assumptions about calculation principles for number assessment.

33 Bültemeier et al. (2022): 'Wasserstoff speichern – so viel ist sicher. Transformationspfade für Gasspeicher.' Available online: https://erdgasspeicher.de/wasserstoff-speichern-soviel-ist-sicher/.

34 https://www.underground-sun-storage.at/fileadmin/bilder/SUNSTORAGE/Publikationen/UndergroundSunStorage_Publizierbarer_Endbericht_3.1_web.pdf.

35 Bültemeier et al. (2022): 'Wasserstoff speichern – so viel ist sicher. Transformationspfade für Gasspeicher.' Available online: https://erdgasspeicher.de/wasserstoff-speichern-soviel-ist-sicher/.

Table 8: Summary of assumptions and calculation principles for assessment of number of main components

Main Component and Type	Calculation / Assumption	Amount for representative type-UGS
Compressors » Turbo Compressors » Piston Compressors	» Calculated according to max. injection rate of UGS facility. Turbo-comp. with 150,000 Nm3/h and Piston comp. with 50,000 Nm3/h. 1 compressor in addition for redundancy. Calculated for each European UGS facility. » Above 200,000 Nm3/h max. injection capacity utilisation of Turbo-compressors, otherwise Piston. » 2-stages compression	» 4 turbo » 4 piston
Drive engine » Electric engine » Gas engine » Gas turbine	» One drive engine per compressor. » Numbers for different drive engines were applied from a reference project and extrapolated to the European UGS infrastructure[36].	» 3 electrical engines » 4 gas engines » 1 gas turbine
Cooler	» One per compression stage, i.e. two per compressor.	16
Separator	» Calculated according to max. withdrawal rate (3 separators for 1,500,000 Nm3/h; rule of three[37]) + 1 for redundancy.	2
Gas Dryer » Absorption » Adsorption » JT-Dryer	» Calculation of total number of dryers according to max. withdrawal rate (3 units for 1,500,000 Nm3/h[38]; rule of three) + 1 for redundancy. » Analysis of shares of absorption drying, adsorption drying and JT-drying according to IGU WGC 2018 database and Type of UGS. » Calculation of amount of units per UGS according to type and shares; formation of an average value for all European UGS facilities.	» 5 absorption » 1 adsorption » 1 JT
Pressure and flow regulations	» Analogy from a reference project: › Cavern-UGS: 1 per every 2.25 wells › Aquifer-UGS: 1 per every 6.2 wells › Depleted Field UGS: 1 per every 1.56 wells » Final values are rounded up, and then the weighted average value is generated.	11
Turbine gas meter	» Calculation of total number of flow meters: › 2 per well, i.e. 44 › 1 per compressor, i.e. 8 › 1 per cooler, i.e. 16 › 1 per separator, i.e. 2 › 1 per gas drying unit, i.e. 7 › 1 per field pipeline, multiplied by 1.5[39], i.e. 33 › 1 per desulphurisation unit, i.e. 2 › 1 per flare, i.e. 4 » 2/3 of all normal gas meters are Turbine type. Analogy from a reference project.	77
Coriolis gas meter	» 1/3 of all normal gas meters are Coriolis type. Analogy from a reference project.	39
Ultrasonic gas meter	» Calculated according to max. withdrawal rate (3 ultrasonic meters for 1,500,000 Nm3/h[40]; rule of three) + 1 for redundancy, used for fiscal measurement.	2

36 https://www.bveg.de/wp-content/uploads/2022/06/20220610_DBI-Studie_Wasserstoff-speichern-soviel-ist-sicher_Transformationsp-fade-fuer-Gasspeicher.pdf.
37 The assumption that three separators are used in a UGS facility with an overall maximum withdrawal capacity of 1,500,000 Nm3/h is directly applied from a reference project.
38 As in footnote 36.
39 For every well, there is a field pipeline. Some might directly go into the surface facility, but others might be initially combined to a larger common field pipeline first. Factor 1.5 is DBI's own assumption.
40 As in footnote 36.

Main Component and Type	Calculation / Assumption	Amount for representative type-UGS
Diaphragm gas meter	» Set to 0	0
Process gas chromatograph	» 2 per UGS facility	2
Pipeline Surface Facility, length	» Analogy from a reference project[41]: › Cavern UGS: 645 m 100% H_2-suitable pipes; 1,257 m not H_2-suitable pipes › Aquifer UGS: 0 m 100% H_2-suitable pipes; 1,799 m not H_2-suitable pipes › Depleted Field UGS: 0 m 100% H_2-suitable pipes; 6,311 m not H_2-suitable pipes	» 214 m H_2-suitable » 3,842 m not H_2-suitable » Above numbers are the weighted average from the values of different UGS-types.
Fittings Surface Facility, amount	» Analogy from a reference project: › Cavern-UGS: 67 100% H_2-suitable; 145 not H_2-suitable › Aquifer-UGS: 7 100% H_2-suitable; 112 not H_2-suitable o › Depleted Field UGS: 25 100% H_2-suitable; 391 not H_2-suitable	» 36 H_2-suitable » 260 not H_2-suitable » Above numbers are the weighted average from the values of different UGS-types.
Field pipelines (surface facilities - wells), length	» Analogy from a reference project: › Cavern-UGS: 4,245 m 100% H_2-suitable pipes; 14,415 m not H_2-suitable pipes › Aquifer-UGS: 0 m 100% H_2-suitable pipes; 4,678 m not H_2-suitable pipes › Depleted Field UGS: 0 m 100% H_2-suitable pipes; 4,225 m not H_2-suitable pipes	» 1,408 m H_2-suitable » 7,685 m not H_2-suitable » Above numbers are the weighted average from the values of different UGS-types.
Glycol vessels: fresh, condensate, old	» Each type 3 times, i.e. 3 x 3 = 9 (updated according to IGU WGC 2018 database).	9
Desulphurisation	» Assumption that 1/3 of the UGS facilities need a desulphurisation. » Amount determined as 1/3 of total number of gas dryers, value rounded.	2
Flare	» Fixed value for each UGS type according to average withdrawal capacity: 4 for caverns, 2 for aquifers, 4 for depleted fields. » Calculation of weighted average amount.	4
Burners	» 2	2
No. Wells	» Determined according to UGS type, reference project and WGV, in case no values in IGU WGC 2018 given › Cavern-UGS: 9 › Aquifer-UGS: 31 › Depleted Field UGS: 28 » Calculation of weighted average value.	22
Cumulative LCCS length	» Calculated as number of wells x depth bottom.	21,081 m
Packer	» 1 per well.	22
Tubing length	» Calculated as number of wells x depth bottom. » Assumption that no tubing is H_2-suitable.	21,081 m
Sand filter (in case porous UGS)	» Cavern-UGS: 0. » Aquifers and depleted Field UGS: 1 per well.	19
Wellhead	» 1 per well. » Assumption that no WH is H_2-suitable.	22
SSV	» 1 per well.	22

The above-described approach for the works had been discussed with MARCOGAZ experts on storage.

41 Bültemeier et al. (2022): 'Wasserstoff speichern – so viel ist sicher. Transformationspfade für Gasspeicher.' Available online: https://erd-gasspeicher.de/wasserstoff-speichern-soviel-ist-sicher/.

7.3 Analysis of UGS facilities: H_2-tolerance and adjustment measures

The following Tables summarise the necessary adjustment measures (Table 9) and the overview of suitability vs. different shares of H_2-blending (Table 10).

Table 9: Summary of adjustment measures for UGS components

Component	Comment / measures
Compressors	**Piston compressors:** must be checked for material suitability, eventually change of lubricants. Function of piston compressors is not hindered by hydrogen (-blends). **Turbo compressors:** according to Adam et al.[42], operation for hydrogen blends up to 10 vol.-% is possible without any adjustments. Up to 40 vol.-% hydrogen blends require adjustments in the compressor, higher shares of hydrogen require a complete replacement. The power consumption of both piston and turbo compressors increases significantly[43] when blending hydrogen to a degree of ca. 25 vol.-%, before it gradually decreases and reaches a lower level at 100% hydrogen than with natural gas[44]. Material suitability is a general pre-requisite for any compressor.
Compressor drives	**Gas engines:** suitability is similar to the gas engines in the chapter on end use/gas applications, showing very minor mitigation measures up to 20 vol.-% H_2 while beyond this threshold and up to pure H_2, retrofitting is needed and possible for some cases. **Gas turbines:** suitability is similar to turbo compressors, but with a need for modification already at 5 vol.-% H_2 blends. Reason here is the significantly increased power consumption of the compressor beyond 5 vol.-% H_2 that the engine must provide. **Electrical engines:** completely suitable since this type of engine does not operate with the medium of hydrogen itself. Power output might be a limiting factor, in particular at ca. 15 vol.-%: this can be mitigated by reduced rates (see also footnote 21).
Coolers	Generally suitable, as long as the material is suitable. Up to a level of 25 vol.-% H_2 blending, increased cooling power (at the same discharge and cooling temperatures) is expected. For 100% hydrogen, power requirement is lower than for natural gas.
Separators	Generally suitable, as long as the material is suitable. Similar to pipeline materials, a share of up to 5 vol.-% H_2 is considered not critical, up to 10 vol.-% material suitability must be examined in detail, and, for higher H_2-concentrations, adaptions are required (e.g. inner coating).
Gas Drying	Above 5 vol.-% of hydrogen blending, material suitability must be evaluated and adjustment measures might become necessary. The functionality of the dryers is not affected by the hydrogen concentration. Deciding point is the moisture: up to 40 mg/Nm3 hydrogen, TEG (i.e. absorption drying) is suitable, beyond that only adsorption can be used[45].
Desulphurisation	Material suitability must be ensured in terms of functionality, the amount of H_2 is decisive. Operating principle is the same as absorption drying.

42 P. Adam, F. Heunemann, C. von dem Bussche, S. Engelshove und T. Thiemann, Hydrogen infrastructure - the pillar of energy transition: The practical conversion of long-distance gas networks to hydrogen operation, 2020.

43 It is estimated that, for the same inlet and discharge pressure and at the same volumetric flow rate, a ca. 50% increased power consumption is required at ca. 25 vol.-% hydrogen blending. This effect can be mitigated by reducing the volumetric flow rate. In contrast to grids, UGS compressors are not required to operate constantly/continuously throughout the year, but only temporarily until the UGS facility is fully filled with the storage medium. Thus, a reduced volumetric flow rate to decrease the power demand does not result in malfunction of the compressor but only in a prolonged injection time. This is DBI's own assessment: for reference, see our practical training programme on underground hydrogen storage.

44 It is estimated that, for the same inlet and discharge pressure and at the same volumetric flow rate, only 60% of the compression power required for natural gas is required. This is DBI's own assessment: for reference, see our practical training programme on underground hydrogen storage.

45 DNV JIP 'Suitability of Flow Meters for Renewable Gases' (2021).

Component	Comment / measures
Flow Metering	Flowmeters normally used in transmission grids (turbine and ultrasonic meters) can be operated with H_2 up to 30 vol.-%. The bias in some specific meter types could be significant for fiscal measurement purposes carried out on large metering stations, for which high quality (very low uncertainty) measurement is required. For this reason, some manufacturers ask their customers to contact them before using existing gas meters for applications with H_2 blends higher than 10 vol.-%. Some new gas meters have already obtained their metrological certification for applications up to 30 vol.-% H_2[46].
Pipeline (SF and Field Pipelines) and Fittings	Here, differentiation as H_2-suitable and not H_2-suitable is made (refer also to paragraph above Table 8). For not suitable material, a tolerance of 5 vol.-% hydrogen blending is made similar to the gas grids. Examples for 100% hydrogen suitable materials are: P460 NL, P460 QH, L360 NB, L415 (ISO 3183) / X60 (API 5L)[47]. Besides the material itself, pressure levels and flow velocities must be considered. Both are adjustable via flow rate regulation.
Glycol vessels	Generally suitable, as long as the material is suitable. Similar to pipeline materials, a share of up to 5 vol.-% hydrogen is considered not critical. Beyond that, material suitability must be examined in detail, and adaptions are required (e.g. inner coating).
Flares and Burners	Up to 5 vol.-% of hydrogen blending, no adjustment is considered to be necessary. Beyond that, material suitability must be examined and EX-zones re-calculated. Furthermore, the fuel gas consumption for burners is increased according to calorific value.
Tubings, Packers, SSVs	Here, differentiation as H_2-suitable and not H_2-suitable is made (refer also to paragraph above Table 8). For not suitable material, a tolerance of 5 vol.-% H_2 blending is made just like the gas grids. A detailed examination might result in the proof of suitability for regular API grades and standard equipment. Nonetheless, currently no supplier offers this. Field experiences show, however, that at least up to 20 vol.-% H_2 blends, standard API materials (e.g. J55, K55) are suitable.
Wellhead	Here, differentiation as H_2-suitable and not H_2-suitable is made (refer also to paragraph above Table 8). For wellheads, the justification for this differentiation is that there are suppliers available on the market who declare their equipment to be H_2-suitable[48]. But such components are not installed at every UGS facility. A survey among UGS operators in Germany concluded that such H_2-suitable wellheads are not widely installed yet.

The next table offers a more detailed summary of the actual H_2-tolerances of each main component and necessary adaption measures to reach higher H_2-tolerance.

46 Bültemeier et al. (2022): 'Wasserstoff speichern – so viel ist sicher. Transformationspfade für Gasspeicher.' Available online: https://erd-gasspeicher.de/wasserstoff-speichern-soviel-ist-sicher/.

47 Bültemeier et al. (2022): 'Wasserstoff speichern – so viel ist sicher. Transformationspfade für Gasspeicher.' Available online: https://erd-gasspeicher.de/wasserstoff-speichern-soviel-ist-sicher/. Final workshop with INES on 25 August 2022.

48 https://h2.hartmann-valves.com/

Table 10: Summary of H_2-tolerances of main components and adaption measures

<table>
<tr><th rowspan="2">Main Component</th><th rowspan="2">H_2-Tolerance (vol.-%)</th><th colspan="9">Specific Adaption Measures to reach levels of H_2-tolerance</th></tr>
<tr><th>0 %</th><th>2 vol.-%</th><th>5 vol.-%</th><th>10 vol.-%</th><th>15 vol.-%</th><th>20 vol.-%</th><th>25 vol.-%</th><th>30 vol.-%</th><th>100 %</th></tr>
<tr><td>Turbo compressor</td><td>10</td><td colspan="4">No adaption required</td><td colspan="2">Adjustments required, a detailed evaluation of the respective component must be carried out, taking into account the individual conditions / modes of operation</td><td colspan="2">Adjustments required, a detailed evaluation of the respective component must be carried out, taking into account the individual conditions / modes of operation</td><td>Replacement required</td></tr>
<tr><td>Piston compressor</td><td>5</td><td colspan="3">No adaption required</td><td colspan="6">Check for material compatibility, adjust lubricant and pressure if necessary</td></tr>
<tr><td>Electric motor</td><td>100</td><td colspan="9">No adaption required</td></tr>
<tr><td>Gas engine</td><td>20</td><td colspan="6">No adaption required</td><td colspan="3">Check for material compatibility and combustion behaviour</td></tr>
<tr><td>Gas turbine</td><td>2</td><td colspan="2">No adaption required</td><td colspan="6">Modification of the gas turbines is required</td><td>Replacement required</td></tr>
<tr><td>Cooler</td><td>20</td><td colspan="6">No adaption required</td><td>Adaption is required / check for material compati-bility</td><td colspan="2">Adaption or complete replacement is required</td></tr>
<tr><td>Separator</td><td>5</td><td>No adaption required</td><td colspan="2">No adaption required</td><td>Check for material compati-bility</td><td colspan="5">Adaption is required</td></tr>
<tr><td>Absorption Gas Dryer</td><td>5</td><td colspan="2">No adaption required</td><td colspan="7">Check for material compatibility, eventually adaption</td></tr>
<tr><td>Adsorption Gas Dryer</td><td>5</td><td colspan="2">No adaption required</td><td colspan="7">Check for material compatibility, eventually adaption</td></tr>
<tr><td>JT Gas Dryer</td><td>N/A</td><td colspan="9">N/A</td></tr>
<tr><td>Pressure regulator</td><td>30</td><td colspan="8">No adaption required</td><td>Testing of material compatibility and function-ality / (ca-pacity test) is required</td></tr>
<tr><td>Turbine gas meter</td><td>30</td><td colspan="8">No adaption required</td><td>Replacement required</td></tr>
<tr><td>Coriolis gas meter</td><td>5</td><td colspan="3">No adaption required</td><td colspan="6">Individual evaluation of the measuring range and material compatibility is required</td></tr>
<tr><td>Ultrasonic gas meter</td><td>10</td><td colspan="2">No adaption required</td><td>Individual evalua-tion of the meas-uring range and material compat-ibility is required</td><td colspan="6">Replacement required</td></tr>
<tr><td>Diaphragm gas meter</td><td>N/A</td><td colspan="9">N/A</td></tr>
<tr><td>Process gas chromatograph</td><td>0.2</td><td>No adaption required</td><td colspan="8">Replacement required</td></tr>
<tr><td>Pipeline, 100% H_2-compatible</td><td>100</td><td colspan="9">No adaption required</td></tr>
<tr><td>Pipeline, not H_2-compatible</td><td>5</td><td colspan="3">No adaption required</td><td colspan="6">Pressure stages, flow velocities, material suitability and stresses must be observed</td></tr>
</table>

<table>
<tr><th rowspan="2">Main Component</th><th rowspan="2">H_2-Tolerance (vol.-%)</th><th colspan="9">Specific Adaption Measures to reach levels of H_2-tolerance</th></tr>
<tr><th>0 %</th><th>2 vol.-%</th><th>5 vol.-%</th><th>10 vol.-%</th><th>15 vol.-%</th><th>20 vol.-%</th><th>25 vol.-%</th><th>30 vol.-%</th><th>100 %</th></tr>
<tr><td>**Fittings, H_2-compatible**</td><td>100</td><td colspan="9">No adaption required.</td></tr>
<tr><td>**Fittings, not H_2-compatible**</td><td>5</td><td colspan="3">No adaption required</td><td colspan="6">Pressure stages, flow velocities, material suitability and stresses must be observed</td></tr>
<tr><td>**Field pipeline, H_2-compatible**</td><td>100</td><td colspan="9">No adaption required</td></tr>
<tr><td>**Field pipeline, not H_2-compatible**</td><td>5</td><td colspan="3">No adaption required</td><td colspan="6">Check for material compatibility or use recommendation of the NACE and EIGA Standard</td></tr>
<tr><td>**Glycol vessels**</td><td>5</td><td colspan="3">No adaption required</td><td colspan="6">Check for material compatibility or use recommendation of the NACE and EIGA Standard</td></tr>
<tr><td>**Flare**</td><td>5</td><td colspan="3">No adaption required</td><td>Check for material compatibility, define or adjust EX-zones</td><td colspan="5">Check for material compatibility, define or adjust EX-zones, new flare to be installed</td></tr>
<tr><td>**Burners**</td><td>5</td><td colspan="3">No adaption required</td><td>Burners must be adapted / check for material compatibility, EX-zones to be re-assessed</td><td colspan="5">Burners must be adapted / replaced, fuel gas demand increased according to calorific value, EX-zones to be re-assessed</td></tr>
<tr><td>**Desulphurisation**</td><td>5</td><td colspan="3">No adaption required</td><td colspan="6">Check for material compatibility, eventually adaption</td></tr>
<tr><td>**LCCS**</td><td>100</td><td colspan="9">No adaption required.</td></tr>
<tr><td>**Packer**</td><td>2</td><td colspan="2">No adaption required</td><td colspan="4">Check material for long-term degradation safety, check Elastomer compatibility and eventually replacement</td><td colspan="3">Replacement is required[49]</td></tr>
<tr><td>**Tubing - H_2-compatible**</td><td>100</td><td colspan="9">No adaption required.</td></tr>
<tr><td>**Tubing - not H_2-compatible**</td><td>2</td><td colspan="2">No adaption required</td><td colspan="4">Check material for long-term degradation safety, eventually replacement</td><td colspan="3">Replacement is required</td></tr>
<tr><td>**New inner liner as secondary barrier for protection of casing**</td><td>100</td><td colspan="9">No adaption required, new installation which must be H_2-compatible</td></tr>
<tr><td>**Sand filter (in case porous UGS)**</td><td>100</td><td colspan="9">No adaption required</td></tr>
<tr><td>**Wellhead, H_2-compatible**</td><td>100</td><td colspan="9">No adaption required</td></tr>
<tr><td>**Wellhead, not H_2-compatible**</td><td>2</td><td colspan="2">No adaption required</td><td colspan="4">Proof of suitability/monitoring required. Eventually replacement</td><td colspan="3">Replacement is required</td></tr>
<tr><td>**SSV**</td><td>2</td><td colspan="2">No adaption required</td><td colspan="4">Check material for long-term degradation safety, eventually replacement</td><td colspan="3">Replacement is required</td></tr>
</table>

49 Currently, no H_2-suitability for any packer is guaranteed by any supplier. Thus, conservatively, a required replacement is stipulated. Some current research projects deal with aspects of this and future results might result in a given packer suitability for certain types and/or certain H_2-concentrations. If so, the evaluation of the amount of packers to be replaced might be updated.

7.4 Cost assessment of adaption and replacement of main UGS components

This sub-chapter summarises the assumed cost for a new 100% H_2-suitable component and the share of cost of a new component as adaption/adjustment cost, when certain levels of H_2 blends in natural gas must be achieved.

For the cost assessment, the following cases were distinguished:

- H_2 suitability is given (up to a certain share): no additional cost.
- Adjustment measures, re-evaluations, etc. are required:
- a general assumption is made that adjustment costs account for 20% of the cost of the component itself. This assumption was applied in a reference project and discussed intensively with industry experts, among them UGS operators[50].
- No H_2 suitability/required exchange of a component at a certain level of H_2 blend: the full price for a new component must be paid.

It is important to note that the 20% adjustment cost only needs to be paid for one selected H_2 concentration. An operator would first identify the required level of H_2(-blending) and apply the necessary measures.

Furthermore, if, besides adjustments, there is a need for replacement (at a certain level of H_2 blends), it is more cost-efficient to replace the component directly rather than to carry out adjustment measures first and later replace the component to reach a higher degree of H_2 tolerance.

Table 11: Summary of cost of new equipment and shares of cost for adaption measures to reach certain H_2-tolerances

Main Component	Cost Unit	Value	0 %	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100 %
Turbo compressor	EUR	6,280,000	No additional cost				20%	20%	20%	20%	100%
Piston compressor	EUR	6,280,000	No additional cost			20%	20%	20%	20%	20%	20%
Electric motor	EUR	6,280,000	No additional cost								
Gas engine	EUR	6,280,000	No additional cost					20%	20%	20%	20%
Gas turbine	EUR	6,280,000	No additional cost		20%	20%	20%	20%	20%	20%	100%
Cooler	EUR	1,130,000	No additional cost						20%	20%	20%
Separator	EUR	2,130,000	No additional cost			20%	20%	20%	20%	20%	20%
Absorption Gas Dryer	EUR	9,500,000	No additional cost		20%	20%	20%	20%	20%	20%	20%
Adsorption Gas Dryer	EUR	2,650,000	No additional cost		20%	20%	20%	20%	20%	20%	20%
JT Gas Dryer	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pressure regulator	EUR	105,000	No additional cost								20%
Turbine gas meter[51]	EUR	54,900	No additional cost								100%
Coriolis gas meter[52]	EUR	109,800	No additional cost			20%	20%	20%	20%	20%	20%
Ultrasonic gas meter[53]	EUR	109,800	No additional cost				20%	20%	20%	20%	100%
Diaphragm gas meter	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Process gas chromatograph	EUR	150,000	No additional cost	100%	100%	100%	100%	100%	100%	100%	100%
Pipeline, 100% H_2-compatible	EUR/m	291	No additional cost								
Pipeline, not H_2-compatible	EUR/m	291	No additional cost			20%	20%	20%	20%	20%	20%
Fittings, H_2-compatible	EUR	2617	No additional cost								

50 Bültemeier et al. (2022): 'Wasserstoff speichern – so viel ist sicher. Transformationspfade für Gasspeicher.' Available online: https://erdgasspeicher.de/wasserstoff-speichern-soviel-ist-sicher/.

51 Price is estimated as 50% of ultrasonic gas meters.

52 Price is estimated to be the same as ultrasonic gas meters.

53 Price is the average for pipe diameter DN 200 mm and DN 400 mm, ANSI 900. Source: Since 900 psi is too low for UGS facilities, the prices were multiplied by 2 (DBI Honeywell, 2020).

Main Component	Cost Unit	Value	0 %	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100 %
Fittings, not H_2-compatible	EUR	2617	No additional cost			20%	20%	20%	20%	20%	20%
Field pipeline, H_2-compatible	EUR/m	500	No additional cost								
Field pipeline, not H_2-compatible	EUR/m	500	No additional cost			20%	20%	20%	20%	20%	20%
Glycol vessels	EUR	260,000	No additional cost			20%	20%	20%	20%	20%	20%
Flare	EUR	160,000	No additional cost			20%	100%	100%	100%	100%	100%
Burners	EUR	390,000	No additional cost			20%	100%	100%	100%	100%	100%
Desulphurisation	EUR	530,000	No additional cost			20%	20%	20%	20%	20%	20%
LCCS			No additional cost								
Packer	EUR	180,000	No additional cost		20%	20%	20%	20%	100%	100%	100%
Tubing - H_2-compatible	EUR/m	370	No additional cost								
Tubing - not H_2-compatible	EUR/m	370	No additional cost		20%	20%	20%	20%	100%	100%	100%
New inner liner as secondary barrier for protection of casing	EUR/m	370	100%	100%	100%	100%	100%	100%	100%	100%	100%
Sand filter (in case porous UGS)	N/A	N/A	No additional cost								
Wellhead, H_2-compatible	EUR	370,000	No additional cost								
Wellhead, not H_2-compatible	EUR	370,000	No additional cost		20%	20%	20%	20%	100%	100%	100%
SV	EUR	290,000	No additional cost		20%	20%	20%	20%	100%	100%	100%

8 DISTRIBUTION

8.1 Approach and survey

Within the scope of this report, gas distribution systems are defined as systems operating below 25 bars. It is worth pointing out that the pressure ranges for these specific systems differ depending on the country, but they generally do not exceed 16 bars.

Following the procedure described in chapter 5.1, the first three steps for gathering data are the quantification, evaluation and elaboration of specific costs. An online survey was implemented where stakeholders of gas distribution systems could share relevant data with the project engineers. The survey was shared with members and partners of MARCOGAZ all over Europe and the responses were aggregated by members of the DBI GUT GmbH in Germany.

It is worth mentioning that responses from a Ukrainian gas distribution network operator are also part of the aggregated dataset. Despite the critical situation in Ukraine, the operator was able to provide detailed and highly valuable information, which helped to improve the overall calculations of this report.

In the first step, the quantification, the number of specific assets (e.g. diaphragm gas meters) were linked to the corresponding grid length of each grid operator that provided data. In this way, a specific number of each component could be calculated per kilometre grid length. By including information about the length of the whole European gas distribution grid, a total number of each component could be calculated.

$$\text{Total Number}_{\text{Component}} = \text{Specific Number}_{\text{Component}} \times \text{Total grid length}$$

Next, the answers about the evaluations of the components from the different stakeholders were compared. This led to a consensus, which was presented to and confirmed by the group. In the third step, the elaboration of specific renewal or retrofitting prices, the average of the different responses to the survey was calculated and put into the model. In the last step, the overall costs for making the European gas distribution grid H_2-ready could be approximated.

It should be mentioned that calculating a specific price for renewing or retrofitting a selected component is a complicated task. This is because the price varies across Europe and depends on many variables itself. Therefore, average prices have been calculated using as many different specific prices from different European countries as possible. Where only a few numbers were available, a discussion with the work group was necessary, so that a consensus on a realistic price could be reached.

Another important factor in the following calculations is the current level of inflation, which is hard to predict for the upcoming months and years. That is why it is necessary to point out that all economic numbers in the chapter about local distribution grids presented in this report are based on the prices from early 2023.

The survey was completed and sent back to the group by a total of eight participants, representing gas distribution infrastructure from six European countries, including Ukraine. This did not provide enough data to run the required calculations. Consequently, several assumptions had to be made and extra data were needed to plug some of the gaps that were left open due to the limited number of responses to the survey.

However, it is important to highlight that the calculations are still based on a thin availability of data. So the overall results can only be understood as an approximation of the real transformation costs. This report can give an idea about the magnitude of reliable numbers, but it cannot provide these itself.

8.2 Distribution pipeline asset volumes

To fill the gaps about the grid lengths of the European gas distribution gas infrastructure, the results of other studies were included in these calculations. These studies are the MARCOSTAT Report on European Gas Safety Gas Distribution (EGAS B) 2018, the MARCOSTAT Report on European Gas Safety Gas Distribution (EGAS B) 2019, and the MARCOGAZ survey on Methane Emissions 2017. In these studies, the length of the distribution gas grid of each European country is listed, including information about the pipeline materials (steel, plastic, cast iron, other). The three studies were combined with the collected data from the present survey. The results are shown in Table 12.

Table 12: Lengths of gas distribution grids in Europe

COUNTRY EU 28 + Ukraine	Total (km)	Total Plastic (km)	Total Steel (km)	Total Cast Iron (km)	Others (km)
Austria	43,400	30,497	11,423	2	1,478
Belgium	76,334	57,609	17,000	16	1,709
Czech Republic	74,821	43,396	31,425	0	0
Denmark	18,229	15,677	2,552	0	0
Germany	498,500	268,193	218,343	11,964	0
Ireland	11,913	11,794	119	0	0
Italy	262,360	73,329	184,872	2,948	1,211
The Netherlands	125,326	100,261	18,799	3,760	2,507
Poland	170,900	68,360	102,540	0	0
Portugal	19,022	16,721	2,283	19	0
Slovakia	33,301	14,519	18,782	0	0
Spain	74,629	63,980	9,515	1,134	0
France	208,105	146,533	54,469	5,821	1,282
Finland	1,911	1,808	83	20	0
Slovenia(1)	4,342	2,464	1,700	108	70
UK	126,335	81,657	7,242	17,362	20,074
Greece	6,080	4,663	1,281	136	0
Romania	17,218	8,958	8,260	0	0
Cyprus	0	0			
Latvia(1)	5,501	3,122	2,153	137	89
Estonia(1)	2,151	1,220	842	54	35
Lithuania(1)	8,300	4,710	3,249	207	134
Croatia(1)	18,386	10,435	7,197	458	296
Malta(1)	0	0			
Sweden(1)	2,720	1,543	1,065	68	44
Bulgaria(1)	248	141	97	6	4
Luxembourg(1)	1,962	1,113	768	49	32
Hungary(1)	83,999	47,672	32,879	2,094	1,354
RGC Ukraine	350,000	126,781	223,219	0	
TOTAL	**2,245,993**	**1,207,156**	**962,156**	**46,362**	**30,318**

(1) For all pipeline lengths where no material lengths were available, the known average material distribution was assumed.

8.3 Valves, meters and house pressure regulators asset volumes

The approximated number of valves in lines, diaphragm gas meters and house pressure regulators were calculated using the approach shown in the formula in chapter 8.1. The results of these calculations are shown in Table 13, including the number of data points that each result is based on. The total number of house pressure regulators was calculated with the data gathered from the survey and from data given in a report of the German federal environmental agency.

Table 13: Volumes of various assets

	Specific number (units / km)	Data points	Total (units)
Valves in Lines	0.89	7	2,001,725
Diaphragm gas meters	54	8[54]	121,742,674
House pressure regulators	9	6	20,185,279

8.4 Mitigation measures for distribution pipeline assets

Regarding the distribution pipeline assets, some assumptions had to be made, enabling calculations based on a slightly simplified approach. These assumptions are:

- **Plastic distribution pipelines:** only a small part of the grid is used at pressures above 16 bar and an even smaller part is operated with regular pressure swings, so that the pressure dependency can be neglected. Damage to the pipelines because of H_2 embrittlement is not expected, because of the low pressure and the lack of cyclic loading.
- **Steel distribution pipelines:** parts of the gas distribution grid are old and in sensitive condition, so that local replacement of the pipeline assets is necessary anyway. Regarding the use of H_2, it is assumed that, for pure H_2, 10% of the steel distribution pipelines must be replaced due to risk assessments. However, the costs for this replacement cannot be accounted for by H_2 only and are considered with half of the costs in the calculation.
- **Cast iron distribution pipelines:** cast iron pipelines can be either made of ductile cast iron or grey cast iron. Preliminary research results, and the use of pipelines made of this metal for conveying town gas in this material, underline the assumption that ductile cast iron can be safely used with H_2. This is also supported by research results (e.g. from Sedigas 2023). Grey cast iron is subject to renewal, as it is prone to brittle fraction under certain conditions. Therefore, it is recommended that several countries should replace this material anyway. This can be justified if shares of corresponding costs are H_2-related. In this report, costs for replacing grey cast iron are accounted for by H_2 addition to the gas infrastructure. The estimated percentage of grey cast iron in the European distribution gas grid is less than 5%.
- **Service lines:** according to the German rule G600, no mitigation measures are necessary up to 20 vol.-% H_2 in the gas blend. At higher concentrations, the following adaptions become necessary:
  - **Diaphragm gas meters:** replacement necessary.
  - **Gas flow monitors:** no adaption required.
  - **All other components** (e.g. thermal shut-off devices): no adaption required if the gas pressure is increased, which solves dimensioning issues.

  ❯ In the cost model, only the diaphragm gas meters are considered as cost relevant.

An overview about the necessary mitigation measures for distribution pipeline assets is provided in Table 14.

Table 14: Mitigation measures for distribution pipeline assets

<table>
<tr><th colspan="9">Hydrogen concentration / vol.-%</th></tr>
<tr><th></th><th>2</th><th>5</th><th>10</th><th>15</th><th>20</th><th>25</th><th>30</th><th>100</th></tr>
<tr><td>Steel distribution pipelines</td><td colspan="7">No adaption required</td><td>Replacement of pipelines can be necessary depending on the specific conditions.</td></tr>
<tr><td>Plastic distribution pipelines</td><td colspan="8">No adaption required</td></tr>
<tr><td>Cast iron distribution pipelines</td><td colspan="8">Replacement of grey cast iron pipelines as action independent of hydrogen injection</td></tr>
<tr><td>Service lines</td><td colspan="5">No adaption required</td><td colspan="3">Replacement of diaphragm gas meters</td></tr>
</table>

54 The number of diaphragm gas meters is based on data from the survey and the number for Germany given in the National Inventory Report for the German Greenhouse Gas Inventory 1990 – 2020.

8.5 Mitigation measures for valves, meters and house pressure regulators

For the various components of the gas distribution grid that are not pipelines and are not part of the gas pressure regulation and metering stations (GPRMS), several assumptions had to be made in order to work with the given data. As in other areas of the gas infrastructure, we face the situation that components are considered to be suitable. But dedicated investigation and testing are not finalised or in initiation phase. Moreover, it is difficult to assess to what extent H_2 is the reason for mitigation action, as opposed to the continuous renewal of the infrastructure. Renewal is likely to be intensified before H_2 is injected, due to the lack of experiences with H_2 in the system and because safety is paramount. Therefore, the considerations include assumptions and preliminary results, as well as expert assessment.

- **Valves in lines:** based on demonstration projects[55], where natural gas components are operated continuously with pure H_2 and testing is performed[56], it is expected that valves specified for natural gas are also suitable for H_2. However, risk assessments could lead to the situation that valve assets close to the end of their lifetime will be replaced if H_2 is injected, even though they are considered to be in at least temporary acceptable condition for natural gas. The corresponding costs cannot be considered to be initiated by H_2 injection only. Therefore, it is assumed that, at H_2 concentrations of 25 vol.-% and higher, 7.5% of the valves in lines will be replaced.
- **Excess flow valves:** not considered in these calculations, due to missing asset volume data.
- **Meters:** only diaphragm gas meters are considered explicitly. Diaphragm gas meters are considered to be suitable up to 20 vol.-% H_2[57, 58]. All other types of meters (turbine gas meters, ultrasonic gas meters, etc.) are only considered within the calculations about GPRMS. Costs for metrology-admissions are not considered in these calculations, due to missing data.
- **House entry combination:** this is not considered in the cost estimation, as no H_2-induced mitigation measures are expected. If the house entry combination including valve appears to be in an acceptable condition for natural gas, this will likely be the case for H_2 too.
- **House pressure regulators:** it is assumed that house pressure regulators will be replaced above 25 vol.-% H_2. However, research shows that these components can most likely be used at higher concentrations too. Replacement above 25 vol.-% H_2 is considered for 7.5% of the installed house pressure regulators, because, for example, receiving manufacturer approval especially for older types could prove difficult in comparison to replacement.
- **Valves in stations, shut-off valves, gas relief valves, filters, process gas chromatographs (PGC), volume converters and pressure regulators:** these components are considered only within the scope of GPRMS, due to the need for simplification.

Table 15: Mitigation measures for valves, meters and house pressure regulators

	Hydrogen concentration / vol.-%							
	2	5	10	15	20	25	30	100
Valves in lines	No adaption required					Partial replacement		
Diaphragm gas meters	No adaption required					Individual assessment/ replacement		
House pressure regulators	No adaption required						7.5% replacement	

55 https://www.mitnetz-gas.de/gr%C3%BCne-gase/wasserstoff-testfeld.
56 Preliminary findings of currently running testing at DBI laboratory.
57 Honeywell, suppliers declaration, Declaration-no. and Revision: Elster H_2 BGZ r02.
58 Marcogaz survey results show suitability of minimum 15 vol.% as expert guess, manufacturer information consider 25 vol.-% as limit for accurate measurement.

8.6 Cost assumptions

To calculate the overall costs for getting the European gas distribution grid H_2-ready, the adaption or replacement costs for each component had to be elaborated. These costs are given either per kilometre grid (pipelines) or per unit (all other components) and are referred to as specific adaption costs. The costs for pipeline assets, meters, valves in lines and house pressure regulators are given in Table 16 and are independent of the H_2 concentration. In the event that not all of the components in the gas grid must be replaced, this is solved by using the replacement factors mentioned in the previous subchapters.

Ten percent of steel pipelines for pure H_2 service are expected to be renewed, based on risk assessment. Half of this amount is considered in the cost estimation to be H_2-induced, as a rough approximation.

Steel pipeline to be replaced will at least partly be designed and installed as plastic pipelines. Therefore, costs for new plastic pipelines are also shown in Table 16.

For diaphragm gas meters, larger meters are likely to be needed to cover the increased volume flow. Furthermore, thanks to increased efficiency of end-use devices and lower energy demand, the volume flow increase is expected to not be linear. Moreover, cost reduction is expected if the larger meters are needed in high quantities.

For the service lines, the costs include only changing the diaphragm meter, which is 250 EUR for the component itself and 50 EUR for the installation.

Costs for replacing valves in lines depend very much on the diameter, material, design pressure and the surrounding conditions, e.g. depth, covering, location, etc. Hence, a cost estimation must be applied that reflects the costs, in light of the complete population of valves on average. Given that the majority of valves are operated below 4 bar in plastic pipes with a medium to small diameter, costs have been applied that cover this situation. For high pressure steel pipelines, significant higher costs will be incurred, but these assets are rare by comparison with the majority of operated valves.

Table 16: Specific average adaption costs for gas distribution components

Component	Specific costs
Steel distribution pipeline	150-350 EUR/m
Plastic distribution pipeline	90 EUR/m
Cast iron distribution pipeline	Will be replaced by plastic pipelines
Service lines	300 EUR/unit
Diaphragm gas meters	250 + 50 Installation EUR/unit
Valves in lines	1,500-2,000 EUR/unit
House pressure regulators	70 + 50 installation EUR/unit

9 I PRESSURE REGULATING AND METERING STATIONS

Gas pressure regulating and metering stations (GPRMS or GPRS) are an essential part of gas transport systems. These stations make it possible for transport and distribution network operators to keep track of, manage and account for the natural gas moving through their networks. A gas metering station's primary function is to measure the flow of gas so that gas sellers may distribute and charge for consumption and distribution firms can manage the network.

9.1 GPRMS asset volumes

The following Table 17 shows the calculated number of GPRMS in terms of their pressure stages as well as the number of data points that the result is based on. For the calculations, the same approach was used as when calculating for the valves, meters and house pressure regulators.

The volumes for GPRMS up to 40 bars have been derived from the survey, which is explained in chapter 8.1. For the GPRMS operated above 40 bars, input from MARCOGAZ experts has been used. This was because the data given in the survey could, in this case, not be weighted to the corresponding grid length. Furthermore, the GPRMS with pressures up to 100 bars are more common in the gas transmission.

Table 17: Volumes of GPRMS

	Specific number (units / km)	Data points	Total (units)
GRRMS p <= 5 bar	0.0658	9	147,700
GRRMS 5 bar < p < 16 bar	0.0243	7	54,666
GRRMS 16 bar < p < 40 bar	0.0356	7	80,062
GRRMS 40 bar < p < 100 bar	0.029	5	6,626

9.2 Mitigation measures for GPRMS

The gas pressure regulation and metering stations have been divided into four categories, according to the pressure that they are being used at. Each category contains a set of components that was specified by a member of the DBI GUT GmbH and presented to MARCOGAZ experts. This system does not apply to all EU Member States but it is considered a feasible approach to distinguish between facilities of different complexity. Mitigation measures for each category, depending on the H_2 concentration, are shown in Table 18. The four categories have been defined as follows:

GPRMS p <= 5 bar

- 2 x Filter
- 2 x Pressure regulator (contains safety shut-off valve)
- 1 x Meter
- 1 x Converter

GPRMS 5 bar < p < 16 bar

- 2 x Filter
- 2 x Pressure regulator (contains safety shut-off valve)
- 1 x Meter
- 1 x Converter

GPRMS 16 bar < p < 40 bar

- 2 x Filter
- * 2 x Preheater
- 4 x Water safety shut-off valve
- 2 x Pressure regulator
- 2 x Meter
- 2 x Converter
- 4 x Separate safety shut-off valve
- 1 x PGC in every ten's facility

GPRMS 40 bar < p < 100 bar*

- Filter
- Preheater
- Water safety shut-off valve
- Pressure regulator
- Meter
- Converter
- Separate safety shut-off valve
- PGC in every facility

*These are complex plants with several outlets and/or consumers with various pressure and volume parameters. As a rule, all the above-mentioned fittings and devices are included in this system, sometimes multiplied many times over according to the number of different outlets.

Regarding the mitigation measures, the following can be seen:

- For H_2 admission of 2 vol.-% and more, PGC replacement is needed if a PGC is installed.
- For concentrations up to 10 vol.-% H_2, it is assumed that no adaption is necessary unless a PGC is installed. This assumption is based on the fact that the physical properties of the gas mixture are minor as well as the volume flow increase that occurs, if the same energy throughput is maintained.
- For concentrations above 10 and up to 30 vol.-% H_2, the expected activities are focusing on approval and in some cases modification/recalibration of the metering devices. The capacity throughput of the regulators is about 94% and filter load about 130% in comparison to natural gas at H_2 admission of 25 vol.-%[59]. These results consider an energy flow to be equal to pure natural gas service. As demand is expected to decrease over time and as the effects are considered to be moderate, no explicit need for modification of the facilities is expected. This may be different for individual cases and can lead to additional costs. For stations above 16 bar, which are more complex in nature, some modification next to PGC and metering/converters is also expected for concentrations above 10 and up to 30 vol.-% H_2. Depending on the composition of the natural gas, H_2 is added between 25 and 30 vol.-% and the explosion protection (ATEX) group changes from IIA to IIB. It is assumed that, by implementing further organisational measures, any potentially occurring risks can be minimised to such an extent that replacement of the electrical equipment is not necessary.
- For 100 vol.-% H_2, the renewal of filters, meters and less common safety devices such as shut-off valves are needed, especially if the same energy throughput is envisaged and leads to significantly higher volume flows. For stations above 16 bar, additional measures – e.g. removal of preheating systems, adaption of measuring lines due to higher throughput – may lead to the installation of a longer inlet section before metering, etc. are expected. For pure H_2, the explosion protection (ATEX) group IIC must be applied. It is assumed that, by implementing further organisational measures, any potentially occurring risks can be minimised to such an extent that replacement of the electrical equipment is not necessary. If this is not possible, technical changes are required on the selection/replacement of electrical equipment, and, if necessary, adjustments must be made to blow-out lines and other measures. It is therefore important to develop organisational measures that avoid a change of electrical equipment.

The following table summarises the adjustments that may become necessary in the different conversion variants.

59 Jens Mischner und Peter Schley, System- und netzplanerische Aspekte der Wasserstoffeinspeisung in Erdgasnetze – Teil 2, gwf 1-2/2015, page 159/160.

Table 18: Mitigation measures for GPRMS

	Hydrogen concentration / vol.-%							
	2	5	10	15	20	25	30	100
GPRMS p <= 5 bar	No adaption required			Manufacturer and metrological approval of meters needed.				Renewal of meters, filters, maybe safety devices
GPRMS 5 – 16 bar	No adaption required			Manufacturer and metrological approval of meters needed.				Renewal of meters, filters, maybe safety devices
GPRMS 16 - 40 bar	PGC renewal			PGC renewal, manufacturer and metrological approval of meters and volume converters, partly modification.				Renewal of: PGC, meters, volume converter, filters and preheater removal, further complex modifications incl. safety expected
GPRMS 40 - 80 bar	PGC renewal			PGC renewal, manufacturer and metrological approval of meters and volume converters, partly modification.				Renewal of: PGC, meters, volume converter, filters and preheater removal, further complex modifications incl. safety expected

9.3 Cost assumptions for GPRMS

The specific costs for GPRMS are listed in Table 19 and depend on the H_2 concentration (0-10 vol.-%, 15-30 vol.-% and 100 vol.-%). These specific costs have been calculated using prices for replacing the components listed previously. To include the current inflation and uncertainties about cost assumptions, each of the known prices has been increased by 25%. This is intended to guarantee fairly realistic prices at a time when adaption/replacement costs change on a daily basis.

Furthermore, the following assumptions were taken for elaborating the specific costs for GPRMS. They must be considered when looking at the numbers given in Table 19, respectively, where the detailed cost assumptions are shown:

- The conversion from natural gas to H_2 is a change in gas quality and thus leads to a potential substantial change in national standards, e.g. DVGW AB G491. This would result in the need for a new inspection by a quality officer. These inspections have not been considered in the following calculation.
- The calculation is based on German norms, standards and experience from already realised projects.
- Only major changes were considered (no wear parts).
- Materials used for pipes and connections were not considered.
- The calculations are based on the plant types listed in the table, according to their pressure stages and the assumed plant capacities; odorisation facilities have not been taken into account, as they have (despite the injection nozzle) no contact with H_2.

For H_2 concentrations above 10 up to 30 vol.-% H_2, for facilities up to 40 bar, a comparable modification cost per facility is considered as for 100 vol.-% H_2. However, for the latter case, all the facilities up to 40 bar are considered to be modified. But for concentrations up to 30 vol.-%, it is assumed that the considered modifications are applied to 10% of the operated facilities. Here for example, where the same energy throughput is urgently needed and the margin for filters is not sufficient, meters get no approval by the manufacturer. Consequently, the metering equipment and converters cannot be easily updated.

For stations above 40 bar, especially for pure H_2, complex modification is expected: this is explained in section 9.2. For those modifications, 25% of renewal costs are expected at minimum.

Table 19: Specific adaption costs for GPRMS in gas distribution

GPRS	2 – 10 vol.-% H_2	15 – 30 vol.-% H_2	100 vol.-% H_2
P <= 5 bar	0 EUR	20,000 EUR	20,000 EUR
5 bar < p < 16 bar	0 EUR	25,000 EUR	25,000 EUR
16 bar < p < 40 bar	250,000 EUR	350,000 EUR	400,000 EUR
40 bar < p < 80 bar	250,000 EUR	500,000 EUR	3,000,000 EUR[60]

60 NEP Gas

10 END USE

10.1 Asset Volumes, adaption measures and adaption costs of domestic and commercial end use

The following numbers are based on the THyGA-research project[61] and summarise the number of different end-use categories for domestic and commercial purposes, e.g. heating and cooking. Additionally, the following tables show the accumulated results of research into H_2 tolerances and costs for domestic and commercial appliances. They are divided into four categories:

- Atmospheric burners (mainly cooking appliances, gas fireplaces, barbecues).
- Premixed/partially premixed burners (e.g. heating appliances).
- Radiant burners (e.g. dark radiators for heating purposes).
- Other (e.g. fuel cells).

The basic findings are that most appliances can cope with 20 vol.-% H_2 in natural gas. In the 20 to 30 vol.-% H_2 range, most appliances will still work, but a few premixed or atmospheric appliances may experience flashback problems. These appliances may therefore need to be adapted. The adaption costs basically comprise the labour to adapt the appliances and the cost of retrofit kits (e.g. new valves or nozzles). These costs can vary from 200 EUR to 300 EUR per appliance.

Most appliances are not suitable for pure H_2, so new designs will be needed to replace current generations of appliances. New cooking appliances are expected to have a similar price range to natural gas appliances, which would vary between 100 EUR and 1,000 EUR or even more (fireplaces, commercial kitchen stoves) depending on size and purpose.

New heating appliances are calculated at costs comparable to current generations plus 20%, which results in 3,000 EUR per appliance.

The adaption costs for radiant heaters can also vary, depending on the power and purpose and they could be very different. For this reason, an estimate of 8,000 EUR per appliance was used for the calculation.

The cost for other appliances has also been calculated at 8,000 EUR per appliance, if replacement is required.

It should be highlighted that these findings refer exclusively to residential and commercial gas utilisation and allow only for limited transfer to other end-use sectors, e.g. industry or power generation. While these two sectors are today responsible for the majority of gas consumption in the EU, they are structurally and technologically very different from residential and commercial gas utilisation. Due to the extreme heterogeneity and the need for separate evaluation for different plants and sectors, it was outside the scope of this report to provide cost estimates for industrial plants and power generation.

61 Source: THyGA: Testing Hydrogen admixture for Gas Applications, WP3. Intermediate report on the test of technologies by segment – Impact of the different H_2 concentrations on safety, efficiency, emissions and correct operation.

Table 20: Number of operated and adaption measures for domestic and commercial appliances for different hydrogen levels

ADAPTION MEASURES FOR DIFFERENT HYDROGEN SHARES[62]						
Type	Amount[63]	Average Age	2-10 vol.-% H_2	15-20 vol.-% H_2	20-30 vol.-% H_2	100 vol.-% H_2
Atmospheric (including all cookers)	93,205,000	20	No measures needed	No measures needed for most of installed appliances	Flashback risk increasing	New design needed
Premix / Partial premixed	134,714,000	20	No measures needed	No measures needed for most of installed appliances	Flashback risk increasing	New design needed
Radiant	2,000,000	20	Missing data/not enough available knowledge			New design needed
Not burner based (e.g. fuel cells heating appliances)	125,000					Varies from retrofit to new design

Table 21: Adaption costs for domestic and commercial appliances for different hydrogen levels

Type	Amount	0-20 vol.-% H_2	20-30 vol.-% H_2	100 vol.-% H_2
Atmospheric (including all cookers)	93,205,000	No technical adaption costs	Some technologies will not be able to cope with 30 vol.-% H_2	According to manufacturers, 100% H_2 will require a replacement of the existing appliances
Premix / Partial premixed	134,714,000	Minor costs for verification and execution needed	For some technologies, technical adaption may help to increase the tolerance	Cost estimation 3,000 EUR per appliance (heater), 500 EUR (cooker), 8,000 EUR (other)[64]
Radiant	2,000,000	Cost for new appliances H_2 ready and expected to match present costs	Cost is expected to be about 200/300 EUR for component replacements	
Not burner based (e.g. fuel cells heating appliances)	125,000			

62 Source: THyGA: Testing Hydrogen admixture for Gas Applications, WP3. Intermediate report on the test of technologies by segment – Impact of the different H_2 concentrations on safety, efficiency, emissions and correct operation.
63 Source: THyGA: Testing Hydrogen admixture for Gas Applications, WP3. Intermediate report on the test of technologies by segment – Impact of the different H_2 concentrations on safety, efficiency, emissions and correct operation.
64 Source: interviews with manufacturers of gas appliances.

Table 22: Estimated costs for the adaption of domestic and commercial appliances for the European market depending on the hydrogen level

<table>
<tr><th>Type</th><th>Amount</th><th>0-20 vol.-% H_2</th><th>20-30 vol.-% H_2</th><th>100 vol.-% H_2</th></tr>
<tr><td>Atmospheric (including all cookers)</td><td>93,205,000</td><td rowspan="4">No direct costs for adaption</td><td rowspan="4">70 bn EUR</td><td rowspan="4">470 bn EUR</td></tr>
<tr><td>Premix / Partial premixed</td><td>134,714,000</td></tr>
<tr><td>Radiant</td><td>2,000,000</td></tr>
<tr><td>Not burner based (e.g. fuel cells heating appliances)</td><td>125,000</td></tr>
</table>

Table 23: Transformation costs in comparison to new build appliances for NG and H_2

	0-20 vol.-% H_2	20-30 vol.-% H_2	100 vol.-% H_2	NG new built	H” new built
H_2	0%	10%	100%	80%	100%
NG				100%	125%

Overall, the estimation for adaption costs resulted in:

- No direct costs for adaption up to 20 vol.-% H_2 in NG.
- 70 billion EUR for retrofit and adaption measures between 20 and 30 vol.-% H_2 in NG.
- 470 billion EUR for a complete replacement of all current domestic and commercial NG-appliances.

10.2 Asset Volumes, adaption measures and adaption costs of industrial use and power generation

In contrast to domestic and commercial end use, which mainly covers space heating and cooking, industrial installations are used to generate heat for steam generation, heat for product treatment (e.g. melting, drying, and heat treatment) and feed stock.

This results in a wide range of components, processes, products and performance levels, and a large number of small and medium-sized manufacturers as well as large corporations. Due to the large number of different plant and product types, as well as the diversity of plant layouts and process steps, it is currently not possible to provide an overview of the necessary adaptions for industrial plants as a whole.

For lower H_2 concentrations of up to 20 vol.-% H_2, it should only be possible to adapt or implement combustion control systems. It may also be necessary to adjust other factors of individual production steps. For higher H_2 concentrations, it may be essential to retrofit the entire plant or even each individual production step[65].

There are several plant layouts, product varieties, and an unreasonable number of producers. As a result, this study cannot provide a valid estimation of retrofit costs for industrial equipment.

For power generation equipment, it was not possible to obtain valid figures for installed gas turbines or gas engines in the field. Therefore, the following statements refer to adaptability and not costs:

- Most gas turbines are adaptable to higher H_2 blends. The percentages can vary between 5 and 20% H_2, depending on age and manufacturer. Newer gas turbines are reported to be capable of handling up to 40 vol.-% H_2 with a combustion chamber upgrade[66].
- For 100% H_2, new turbines are required[67].
- Adaption to gas engines for up to 20 vol.-% H_2 is easily possible for almost all manufacturers, mainly with software updates. In some cases, retrofitting is necessary. The cost of this adaption can be up to 20% of the investment cost[68, 69].
- Retrofitting gas engines to run on up to 100% H_2 is possible in some cases: this requires the fuel injection system to be converted to direct injection without premix chambers[70, 71].
- Gas-fired boilers for steam or hot water production are mainly equipped with forced draught burners. These can, in most cases, be adapted to 20 vol.-% H_2, sometimes more, but typically require changes in combustion control and air/fuel ratios[72, 73].
- For 100% applications, new burner designs and changes in combustion and flame control are required[74].

65 Pietsch, Ph.; Wiersig, M.: The influences of hydrogen in thermoprocessing plants, Prozesswärme 01/22, p. 33 ff.
66 https://www.euturbines.eu/wp-content/uploads/2021/09/EUTurbines-H2-ready-Definition-September-2021-1.pdf.
67 https://www.euturbines.eu/wp-content/uploads/2021/09/EUTurbines-H2-ready-Definition-September-2021-1.pdf.
68 Use of hydrogen in gas engines over 100 kW, Frank Grewe, 2G, Grüne KWK – Dekarbonisierung hocheffizienter KWK-Anlagen, 15.03.2023 Magdeburg.
69 Use of hydrogen in gas engines over 1 MW, Dr. Marco Schultze, Caterpillar Energy Solutions GmbH, Grüne KWK – Dekarbonisierung hocheffizienter KWK-Anlagen, 15.03.2023 Magdeburg.
70 Use of hydrogen in gas engines over 100 kW, Frank Grewe, 2G, Grüne KWK – Dekarbonisierung hocheffizienter KWK-Anlagen, 15.03.2023 Magdeburg.
71 Use of hydrogen in gas engines over 1 MW, Dr. Marco Schultze, Caterpillar Energy Solutions GmbH, Grüne KWK – Dekarbonisierung hocheffizienter KWK-Anlagen, 15.03.2023 Magdeburg.
72 Pietsch, Ph.; Wiersig, M.: The influences of hydrogen in thermoprocessing plants, Prozesswärme 01/22, p. 33 ff.
73 Joint research project reCoCon – Green Combustion Control. Teilprojekt 2 in der Leittechnologie 'TTgoesH2', Förderkennzeichen: 32 LBG, Projektträger / Fördermittelgeber: AiF / BMWi (IGF).
74 Pietsch, Ph.; Wiersig, M.: The influences of hydrogen in thermoprocessing plants, Prozesswärme 01/22, p. 33 ff.

11 RESULTS

Based on the asset volumes, the specific costs – for modification/retrofitting the gas infrastructure assets, the costs for making the infrastructure and end use ready for certain H_2 concentrations – have been approximated and summarised as follows.

11.1 Transmission

In Table 24, the total transformation costs for all assets in the gas transmission grid are summarised. These results have been calculated by using the data and assumptions presented in chapter 6. To understand the following numbers, it is crucial to bear in mind the underlying assumptions, which readers of this report are recommended to read through carefully. In Table 25, detailed cost information is displayed.

Key findings are:

- Up to 10 vol.-% H_2, transformation costs below 1% of CAPEX for a new-build infrastructure.
- Up to 30 vol.-% H_2, transformation costs below 15% of CAPEX for new-build infrastructure.
- Total costs for retrofitting the existing transmission infrastructure for 100 vol.-% H_2 are below 30% of CAPEX for new-build infrastructure.
- Compressor and valve stations are the predominant cost driver up to 30 vol.-% H_2. When pure H_2 is conveyed, pipeline costs are expected to be the major cost item.

Table 24: Summarised gas transmission transformation costs in comparison to new-build H_2-infrastructure

	Adaption cost (in bn EUR and %) according to hydrogen concentration								
	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100 vol.-%	New-build H_2 infrastructure
Total adaption costs in bn EUR	0.2	1.3	3.4	11.7	12.5	55.5	55.5	133.4	482.2
Total adaption costs compared to new-build H_2 IS in %	0.03	0.28	0.71	2.4	2.6	11.5	11.5	27.7	100

Table 25: Detailed transformation costs of transmission gas grid assets in bn EUR

	Amount [-] / Length [km]	2 vol.-% H_2	5 vol.-% H_2	10 vol.-% H_2	15 vol.-% H_2	20 vol.-% H_2	25 vol.-% H_2	30 vol.-% H_2	100 vol.-% H_2	Inspection/ Replacement factor
Steel pipelines before 1984	121,000	0	0	0	0.17	0.17	0.17	0.17	33	0.05
Steel pipelines after 1984	104,000	0	0	0	0.12	0.12	0.12	0.12	23.87	0.05
Valve stations	15,400	0	0	0	2.85	2.85	2.85	2.85	24.19	0.1/1
Pigging stations	3,400	0	0	0	0.020	0.020	0.020	0.020	0.020	-
Compressor stations	9,500	0.06	1.25	3.34	8.35	9.18	52.17	52.17	52.17	-
Metering stations	870	0.04	0.04	0.04	0.14	0.14	0.14	0.14	Covered in pipe retrofit	-
Total costs	0.15	1.34	3.43	11.70	12.53	55.52	55.52	133.44	-	

11.2 Underground gas storage

The subsequent tables summarise the results of the cost assessment for conversion of UGS facilities and construction of new ones. The provided costs are determined by multiplying the amount of a certain component (Table 8) of a UGS facility with the respective share of cost to reach a certain H_2-tolerance (Table 11) and with the number of UGS facilities in Europe (Table 6).

The main cost drivers are the compressors, compressor drive engines[75] and the gas treatment. This applies to both the retrofitting of existing facilities and construction of new ones. This is due to the high cost for the single pieces of equipment and the required amounts, as well as the requirement for total replacement of turbo compressors (which make up a share of 50% of all installed compressors) for 100% H_2 storage. The cost of replacing subsurface installations is rather modest, compared to the cost for adaptions and replacement in the surface facilities.

The cost associated with the need for replacement in the subsurface installations (i.e. wells) is subject to changes. This is because new research projects are being carried[76] out or are planned. This issue affects mainly the suitability of tubings, packers and SSVs. If higher H_2-tolerances for 'classical' equipment/material grades are identified (compared to the current state of knowledge), this would result in a significantly lower amount of to-be-replaced components.

Generally:

- Up to 10 vol.-% of H_2 blending: the adjustment cost is 12% resp. 16%[77] of the CAPEX for building a new UGS facility.
- Up to 30 vol.-% of H_2 blending: the adjustment cost is 26% resp. 29%[78] of the CAPEX for building a new UGS facility.
- Total costs for retrofitting the existing UGS facilities are approximately 40% of the CAPEX for building a new facility.

Table 26 includes the summary. Table 27 includes the total cost for adjustment and replacement, compared to building a new designated H_2-UGS facility.

The given costs are valid for the average type-UGS (specified in Table 7) and the main components specified in Table 8. The actual cost for a specific UGS must be scaled according to:

- Number of wells
- Injection and withdrawal capacity
- Operating pressure
- UGS-type

In terms of UGS-type, it should be recalled that construction of a new UGS facility, and conversion of an existing facility, are more expensive for cavern UGS than for porous UGS. Because for cavern UGS, the following additional and not-component related steps for conversion/construction must be undertaken:

- Construction of new UGS
  - Leaching
  - First-Gas-Filling
  - Snubbing
- Conversion of an existing natural gas UGS
  - Snubbing
  - Flooding
  - First Gas Filling with H_2
  - Snubbing.

The costs for the above-mentioned steps are not provided in the following tables for cost assessment. This is because the cost analysis was provided for the technical equipment only, and the generated average UGS on which the cost assessment is based, are initially an average of cavern- and porous UGS facilities. Thus, providing the cost for leaching, etc. would make no sense.

75 With the exception of electrical engines, which are considered 100% H2-suitable and therefore result in zero cost for adjustments/retrofitting.

76 E.g. DGMK-project 866, 'Hystories', Gasunie-project in Zuidvending and others.

77 Difference in numbers stems from the separation into two different cases: 1) using the existing LCCS, and 2) installation of a new H2-suitable protective liner.

78 As in previous footnote.

Table 26: Summarised underground gas storage transformation costs in comparison to new build H_2-infrastructure

Unit		Total cost for retrofit to reach certain levels of H_2-tolerance (bn EUR)								Total cost for replacement	Total cost for building same amount of new H_2 UGS facilities
		2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100%		
Total costs for UGS (without new inner liner)	bn EUR	0.06	3.5	5.3	6.5	7.6	12.6	12.6	18.8	13.1	48.9
	Share of cost for new-build facility (%)[79]	0.12	7.07	12.88	15.48	15.48	25.81	25.81	38.34	26.74	100
Total costs for UGS (with new inner liner)	bn EUR	1.7	5.1	6.9	8.1	9.2	14.2	14.2	20.4	13.1	48.9
	Share of cost for new-build facility (%)[80]	3.40	10.34	16.15	18.75	18.75	29.08	29.08	41.61	26.74	100

Table 27: Detailed transformation costs of existing UGS facilities in MilEUR

Main Component	Total cost for retrofit to reach certain levels of H_2-tolerance (Mil. EUR)								Total cost for replacement (Mil. EUR)	Total cost for building same amount of new H_2 UGS facilities (Mil. EUR)
	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100%		
Turbo compressor	0	0	0	1,030	1,030	1,030	1,030	5,150	5,150	5,150
Piston compressor	0	0	1,030	1,030	1,030	1,030	1,030	1,030	0	5,150
Electric engine	0	0	0	0	0	0	0	0	0	3,862
Gas engine	0	0	0	0	1,030	1,030	1,030	1,030	0	5,150
Gas turbine	0	264.7	264.7	264.7	264.7	264.7	264.7	1,323.6	1,323.6	1,323.6
Cooler	0	0	0	0	0	741.3	741.3	741.3	0	3,706.4
Separator	0	0	174.7	174.7	174.7	174.7	174.7	174.7	0	873.3
Absorption Gas Dryer	0	1,947	1,947	1,947	1,947	1,947	1,947	1,947	0	9,737.5
Adsorption Gas Dryer	0	108.7	108.7	108.7	108.7	108.7	108.7	108.7	0	543
JT Gas Dryer	0	0	0	0	0	0	0	0	0	543[81]
Pressure regulator	0	0	0	0	0	0	0	47.4	0	237
Turbine gas meter	0	0	0	0	0	0	0	866.6	866.6	866.6
Coriolis gas meter	0	0	175.6	175.6	175.6	175.6	175.6	175.6	0	877.9
Ultrasonic gas meter	0	0	0	9	9	9	9	45	0	45

79 Note that the percentages for adjustment cost to reach higher hydrogen tolerances are not cumulative: please refer to chapter 7.4.
80 Note that the percentages for adjustment cost to reach higher hydrogen tolerances are not cumulative: please refer to chapter 7.4.
81 Due to lack of data, a simplified assumption was made that cost for JT-drying equals the cost for adsorption drying.

Main Component	Total cost for retrofit to reach certain levels of H_2-tolerance (Mil. EUR)								Total cost for replacement (Mil. EUR)	Total cost for building same amount of new H_2 UGS facilities (Mil. EUR)
	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100%		
Diaphragm gas meter	0	0	0	0	0	0	0	0	0	262.4[82]
Process gas chromatograph	61.5	61.5	61.5	61.5	61.5	61.5	61.5	61.5	61.5	61.5
Pipeline, 100% H_2-compatible	0	0	0	0	0	0	0	0	0	229.2
Pipeline, not H_2-compatible	0	0	46	46	46	46	46	46	0	0
Fittings, H_2-compatible	0	0	0	0	0	0	0	0	0	139.7
Fittings, not H_2-compatible	0	0	28	28	28	28	28	28	0	0
Field pipeline, H_2-compatible	0	0	0	0	0	0	0	0	0	788
Field pipeline, not H_2-compatible	0	0	157.5	157.5	157.5	157.5	157.5	157.5	0	0
Glycol vessels	0	0	96	96	96	96	96	96	0	479.7
Flare	0	0	26.2	131	131	131	131	131	131	131
Burners	0	0	32	160	160	160	160	160	160	160
Desulphurisation	0	0	43.5	43.5	43.5	43.5	43.5	43.5	0	217.3
LCCS[83]	0	0	0	0	0	0	0	0	0	1,919
Packer	0	162.4	162.4	162.4	162.4	812	812	812	812	812
Tubing, H_2-compatible	0	0	0	0	0	0	0	0	0	1,599
Tubing, not H_2-compatible	0	319.8	319.8	319.8	319.8	1,598.9	1,598.9	1,598.9	1,598.9	0
New inner liner as secondary barrier for protection of casing	1,599	1,599	1,599	1,599	1,599	1,599	1,599	1,599	0	0
Sand filter (in case porous UGS)	0	0	0	0	0	0	0	0		
Wellhead, H_2-compatible	0	0	0	0	0	0	0	0	0	1,669
Wellhead, not H_2-compatible	0	333.7	333.7	333.7	333.7	1,669	1,669	1,669	1,669	0
SSV	0	261.6	261.6	261.6	261.6	1,308	1,308	1,308	1,308	1,308

82 Due to lack of data, a simplified assumption was made that cost for diaphragm gas meters equals the cost for ultrasonic gas meters.
83 The LCCS is not cost-relevant for retrofitting, but for new wells. Thus, as a cost assessment, tubing costs were multiplied by 1.2; since LCCS has a slightly higher diameter, please refer to API completion schemes.

Main Component	Total cost for retrofit to reach certain levels of H_2-tolerance (Mil. EUR)								Total cost for replacement (Mil. EUR)	Total cost for building same amount of new H_2 UGS facilities (Mil. EUR)
	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100%		
Total transformation costs for underground gas storages depending on H_2 concentration (without new inner liner)	61.5	3,459.8	5,268.9	6,540.7	7,570.7	12,621.9	12,621.9	18,750.4	13,079.8	48,909.3
Total transformation costs for underground gas storages depending on H_2 concentration (with new inner liner)	1,660.5	5,058.8	6,867.9	8,139.7	9,169.7	14,220.8	14,220.8	20,349.4	13,079.8	48,909.3

Table 26 and Table 27 summarise the cost for adjustment measures for reaching certain levels of H_2-tolerance:

- Columns '2 vol.-%' – '100%' include the cost for reaching certain levels of H_2 tolerance (starting from a mere NG facility) in line with the required adjustment measures according to Table 10.
- The 'Total cost for replacement' column includes the cost, should it be necessary, to replace an entire component with a new one. This cost can be zero for certain components (e.g. coolers) since entire replacement is not necessary for some components.
    - Thus, the sum of 'total cost for replacement' ends up being lower than the values in the column '100%' and partially in '30 vol.-%'.
- The 'Total cost for building same amount of new H_2 UGS facilities' column includes the cost for building an entire new facility.

An operator might choose to reach, in stepwise fashion, certain levels of H_2 tolerance. In this case, the cost from the columns '2 vol.-%' – '100%' would be cumulative. However, if an operator decides to immediately adjust the facility for 100% H_2 tolerance, some costs can be saved.

Retrofitting an existing facility is more cost-efficient than building a new facility.

11.3 Distribution

In Table 29, the total transformation costs for all assets for the gas distribution grid are summarised. These results have been calculated by using the data and assumptions presented in chapter 8. To understand the following numbers, it is crucial to bear in mind the underlying assumptions, which readers of this report are recommended to read through carefully.

Key findings are:

- Up to 20 vol.-% H_2, transformation costs are far below 1% of CAPEX for a new-build infrastructure.
- Up to 30 vol.-% H_2, transformation costs are below 5% of CAPEX for new-build infrastructure.
- Total costs for retrofitting the existing distribution infrastructure for 100 vol.-% H_2 are below 10% of CAPEX for new-build infrastructure.
- Up to 30 vol.-% H_2, the service lines (major H_2-induced replacement in the diaphragm gas meter) and further diaphragm gas meters in the distribution system.
- For 100 vol.-% H_2, the share of 5% steel pipelines that are considered to be renewed is also a significant cost item.

Table 28: Summarised gas distribution transformation costs in comparison to new-build H_2-infrastructure

Distribution	Adaption cost (in bn EUR and %) according to hydrogen concentration								
	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100 vol.-%	New build H_2
Total adaption costs in bn EUR	0.4	0.4	0.4	0.4	0.4	28.3	28.3	37.9	594.4
Total adaption costs compared to new-build H_2 IS in %	0.07	0.07	0.07	0.07	0.07	4.8	4.8	6.4	100

Table 29: Detailed transformation costs of distribution gas grid assets in Mil. EUR

	Amount [-] / Length [km]	2 vol.-% H_2	5 vol.-% H_2	10 vol.-% H_2	15 vol.-% H_2	20 vol.-% H_2	25 vol.-% H_2	30 vol.-% H_2	100 vol.-% H_2	Replacement factor
Steel distribution pipelines	962,156	0	0	0	0	0	0	0	9,419.8	0.05
Plastic distribution pipelines	1,207,156	0	0	0	0	0	0	0	0	-
Cast iron pipeline	46,362	399.6	399.6	399.6	399.6	399.6	399.6	399.6	399.6	0.05
Service lines	59,675,523	0	0	0	0	0	17,902.7	17,902.7	17,902.7	-
Valves in lines	2,001,725	0	0	0	0	0	262.7	262.7	262.7	0.075
Diaphragm meters	121,742,674	0	0	0	0	0	9,739.4	9,739.4	9,739.4	-
House pressure regulators	20,185,279	0	0	0	0	0	0	0	181.7	0.075
Total costs		399.6	399.6	399.6	399.6	399.6	28,304.4	28,304.4	37,905.9	-

11.4 Gas pressure regulating and metering stations

In Table 30, the total transformation costs for GPRMS are summarised. These results have been calculated by using the data and assumptions presented in chapter 8. To understand the following numbers, it is crucial to bear in mind the underlying assumptions, which readers of this report are recommended to read through carefully:

Key findings are:

- Up to 10 vol.-% H_2, transformation costs are far below 5% of CAPEX for new-build infrastructure.
- Up to 30 vol.-% H_2, transformation costs are close to 5% of CAPEX for new-build infrastructure.
- Total costs for retrofitting the existing GPRMS for pure H_2 are in the range of 30% of CAPEX for new-build infrastructure.

Table 30: Summarised GPRMS transformation costs in comparison to new-build H_2-infrastructure

GPRMS	Adaption cost (in bn EUR and %) according to hydrogen concentration								
	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100 vol.-%	New-build H_2
Total adaption costs in bn EUR	3.7	3.7	3.7	6.5	6.5	6.5	6.5	56.2	169.4
Total adaption costs compared to new-build H_2 IS in %	2.2	2.2	2.2	3.9	3.9	3.9	3.9	33.2	100

Table 31: Detailed transformation costs of GPRMS assets in Mil. EUR

	Amount [-] / Length [km]	0 vol.-% H_2	2 vol.-% H_2	5 vol.-% H_2	10 vol.-% H_2	15 vol.-% H_2	20 vol.-% H_2	25 vol.-% H_2	30 vol.-% H_2	100 vol.-% H_2	Replace-ment factor
GPRMS p <= 5 bar	147,700	0	0	0	0	295.4	295.4	295.4	295.4	295.0	0.1
GPRMS 5 bar < p < 16 bar	54,666	0	0	0	0	136.7	136.7	136.7	136.7	1,366.6	0.1
GPRMS 16 bar < p < 40 bar	80,062	0	2,001.5	2,001.5	2,001.5	2,802.2	2,802.2	2,802.2	2,802.2	32,024.6	0.1
GPRMS 40 bar < p < 100 bar	6,626	0	1,656.6	1,656.6	1,656.6	3,313.2	3,313.2	3,313.2	3,313.2	19,879.4	1
Total costs		0	3,658.2	3,658.2	3,658.2	6,547.5	6,547.5	6,547.5	6,547.5	56,224.7	-

11.5 Gas end use

The mitigation measures based on the available literature for the end uses are summarised in these findings:

- The majority of cookers and boilers are suitable for concentrations up to 20 vol.-% H_2, beyond which the risk of flashback increases for premixed burners. New designs are required for 100% H_2.
- Engines could easily cope with up to 20 vol.-% H_2, but few manufacturers offer kits for up to 30 vol.-% H_2 or even 100% H_2. The adaption costs for 20 to 30 vol.-% H_2 are estimated by manufacturers at 20% of the investment costs.
- For industrial equipment, the upper limits of H_2 tolerance are highly dependent on the burners installed, the combustion control and the product, so an estimate is not currently possible.
- Boilers for heating networks or industrial processes are limited by the tolerances of the installed diffusion burners.

There are many different plant layouts, different types of products and an unmanageable number of manufacturers. This leads to the conclusion that a reliable calculation of retrofit costs for industrial equipment is not possible for this study.

Most domestic and commercial appliances are not suitable for pure H_2, so new designs will be needed to replace current generations of appliances. New cooking appliances are expected to have a similar price range to natural gas appliances, which would vary between 100 EUR and 1,000 EUR or even more (fireplaces, commercial kitchen stoves) depending on size and purpose.

New heating appliances are calculated at costs comparable to current generations plus 20%, which results in 3,000 EUR per appliance.

The adaption costs for radiant heaters can also vary, depending on the power and purpose, and these could be very different. For this reason, an estimate of 8,000 EUR per appliance was used for the calculation.

Table 32: Estimated costs for a transformation of domestic and commercial end use in bn EUR

Type	Amount	0-20 vol.-% H_2	20-30 vol.-% H_2	100 vol.-% H_2
Atmospheric (including all cookers)	93,205,000	No direct costs for adaption	70 bn EUR	470 bn EUR
Premix / Partial premixed	134,714,000			
Radiant	2,000,000			
Not burner based (e.g. fuel cells heating appliances)	125,000			

The cost for other appliances has also been calculated at EUR 8,000 EUR per appliance, if replacement is required.

Overall, the estimation for adaption costs resulted in:

- No direct costs for adaption up to 20% H_2 in NG.
- 70 billion EUR for retrofit and adaption measures between 20 and 30% H_2 in NG.
- 470 billion EUR for a complete replacement of all current domestic and commercial NG appliances.

11.6 Results summary

In the following Table 33, cost approximation for transforming the gas infrastructure and end use is summarised. The results are differentiated for the areas considered:

- Gas transmission.
- Gas distribution.
- Gas pressure regulation.
- Underground storage.
- End use (residential and commercial but no industrial appliances).

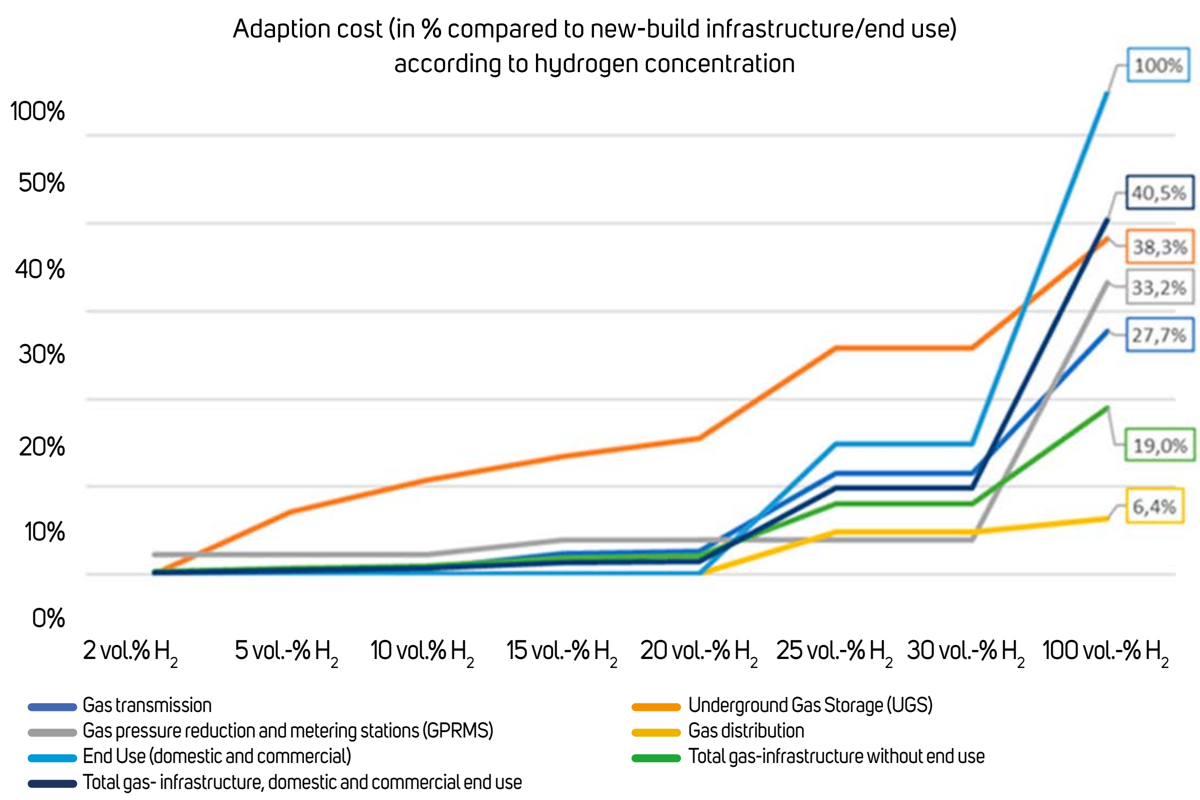
Beyond this, the approximation of total costs is shown as absolute values and in comparison to costs that are expected to arise if a new dedicated H_2 infrastructure is developed.

The key findings are:

1. Up to 10 vol.-% H_2, the transformation cost is less than 1% of CAPEX for new-build infrastructure*.
2. Up to 30 vol.-% H_2, the transformation cost is equal to 10% of CAPEX for new-build infrastructure*.
3. For pure H_2 service, the transformation cost is less than 20% of CAPEX for new-build infrastructure.
4. In addition to the indicated financial advantages of transforming the existing infrastructure, this will lead to the faster establishment of H_2-ready infrastructure with fewer negative effects on the environment and a lower carbon footprint.[84, 85]

The results, as a percentage of the estimated cost of constructing a new hydrogen gas grid in Europe, are given in Figure 3 and Table 33.

Figure 3: Collecting relevant data using an online survey



84 IEA Energy Technology Perspectives 2023, January 2023, page 348.
85 Short study 'Hydrogen Network Central Germany', 2022, page 9 (German).
* incl. residential and commercial appliances

Table 33: Transformation costs in comparison to new-build infrastructure for NG and H_2

		Adaption cost in % according to hydrogen concentration								
		2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100 vol.-%	New-build H_2 infra-structure
Gas-transmission	Total adaption costs compared to new-build H2 IS in %	0.03	0.28	0.71	2.4	2.6	11.5	11.5	27.7	100
UGS	Total adaption costs compared to new-build H2 IS in %	0.1	7.1	10.8	13.4	15.5	25.8	25.8	38.3	100
GPRMS	Total adaption costs compared to new-build H2 IS in %	2.2	2.2	2.2	3.9	3.9	3.9	3.9	33.2	100
Gas-distribution	Total adaption costs compared to new-build H2 IS in %	0.07	0.07	0.07	0.07	0.07	4.8	4.8	6.4	100
End use (domestic and commercial)	Total adaption costs compared to new-build H2 IS in %	0.0	0.0	0.0	0.0	0.0	14.8	14,8	100.0	100
Total gas-infrastructure	Total adaption costs compared to new-build H2 IS in % without end use	0.3	0.7	1.0	1.9	2.1	8.0	8.0	19.0	100
Total gas-infrastructure, domestic and commercial end use	Total adaption costs compared to new-build H2 IS in %	0.2	0.5	0.7	1.4	1.5	9.8	9.8	40.5	100

12 I CONCLUSIONS

Transformation of Europe's existing gas infrastructure can be achieved cheaply and quickly. In particular, H_2 blending up to 10% by volume leads to very low transformation costs (<1% of the cost of building a new H? infrastructure). Blending is therefore a very attractive option, in order to initiate an international H? trade and support the required value chains.

The low transformation costs, even for pure H_2 (<20% of the cost of building a new hydrogen infrastructure), create financial scope for transforming energy systems in general. This is important as, in many areas (e.g. expansion of power grid, insulation of building stock, etc.), massive and cost-intensive measures are required that will burden European countries and their societies.

The data situation on gas asset volumes in Europe must be improved. However, this report's chosen method, assumptions and expert estimates provide a solid basis for estimating the transformation costs of the gas infrastructure and these can be improved further in future investigations.

Before H_2 is injected into the gas infrastructure, the transformation effort has to be assessed individually (see Appendix 1). This must be done at the infrastructure operator level. For the injection of low H_2 concentrations as currently foreseen, e.g. in the EASEE gas guidelines, no or only marginal adaption measures are expected in the vast majority of gas infrastructure elements. There are very few known exceptions where this general conclusion does not apply, and greater efforts and corresponding costs are expected on the basis of the current state of knowledge.

The authors emphasise that the results of this study show very clearly that the use of Europe's existing gas infrastructure for H_2 natural gas/H_2 mixtures is extremely attractive in macroeconomic terms. It will also accelerate the transformation of the energy system. This potential contribution to reaching climate goals should be used in the best possible way.

ATTACHMENT

Annex 1: ENTSOG Statement for Marcogaz Blends Study INT2493-23

entsog
european network
of transmission system operators
for gas

ENTSOG recommendations for retrofitting / repurposing gas grids for transport of hydrogen (supplementary to the Marcogaz Blends Study)

ENTSOG welcomes this Marcogaz study assessing the costs of retrofitting / repurposing gas infrastructure for the transport of hydrogen blends and 100% hydrogen.

The gas Transmission System Operators' (TSOs) knowledge of the effect on their assets of introducing hydrogen blends has significantly increased over the past number of years, and this Marcogaz study is a very important additional source of information in this regard. Indeed, ENTSOG continues to develop exercises to inform on the hydrogen injection possibilities into the transmission system, including internal assessments among ENTSOG members to further analyse the tolerance for different levels of hydrogen concentration in the gas grid system, as well as its feasibility and verification.

ENTSOG hereby provides suggestions for relevant considerations when retrofitting /repurposing gas grids for the transport of hydrogen. These recommendations are included to complement Marcogaz report.

- A gas transmission grid consists of many different elements. While the Marcogaz study assessed the most relevant of these aspects, additional measures needed even for low hydrogen concentrations (like pipeline replacements and their corresponding costs) are not considered. Feedback from TSOs suggest that even for low hydrogen concentrations some parts of the pipelines should also be replaced.

- TSOs have to date concluded that the estimated total CAPEX for retrofitting / repurposing gas grids for the transport of hydrogen is mainly dependent on the share of pipelines that need to be replaced. Some TSOs estimate that up to 30% of the pipeline total length may need to be replaced based on the current industry knowledge and standards. However, the situation is not uniform in EU. These replacements shares can be dependent on:

  - **The requirement to maintain a minimum energy delivery.**
    The energy transportation capacity of hydrogen can be slightly smaller compared to high-calorific natural gas. Therefore, for strict energy delivery requirements, pipelines would have to be replaced.

  - **The applicable technical rules in each Member State (MS) that are not yet available in all cases.**
    Some TSOs already have carried out activities to assess their pipelines' condition to inform on retrofitting / repurposing. Other TSOs are currently carrying out, or are planning, such assessments. Amongst those TSOs that have completed their assessments, the share of pipelines that require replacement at TSO level is varying between 0% and 30%. Even in the cases of TSOs foreseeing replacements, only specific individual pipeline strips are envisaged to be changed).

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- **The formal suitability (based on standards) of pipelines is subject to the applicable rules that differ between MSs.**
  Standards in place differ from MS to MS, meaning that, in certain cases pipeline replacements could be required even though there may be alternative findings that deem it not necessary. Based on the typically cited technical code ASME B31.12, the majority of TSOs assume that up to 10% hydrogen will not require any modifications in their pipelines, or any other metallic element of the network like valves, pig-traps, metering stations, etc. Other TSOs choose to disregard the ASME B31.12 limit of 10% hydrogen, focusing on the presence of cracks and the frequency and amplitude of pressure changes.

- **The economic life of the pipelines established by MSs regulation.**
  Some pipelines reaching economic maturity may need to be replaced even if their continued use would have been for natural gas (without any content of hydrogen). In this regard, it is questionable if the costs of these assets should be allocated to hydrogen blending, since they would have been occurred in any case.

- An additional factor is the estimated milestones of technical readiness and planning that may also be a source of costs, and that may differ from country to country. The majority of TSOs cannot however provide a concise view on these estimations, as a clear regulatory framework to allow for the remuneration of respective investigations is currently not in place.

- Furthermore, pipelines in place over distances in various grid sections would need to be replaced or retrofitted, requiring a detailed coordination and timing of implementing such measures within a TSO network and often even between the TSOs of different MS, to maintain security of supply and efficiency – the status for different TSOs could differ. It is noteworthy that for pipelines to be reusable considering the current industry knowledge and standards, pipeline requalification processes should still be undertaken, and testing might be needed.

The Marcogaz study – relevant for pipeline retrofitting/repurposing to transport hydrogen – may need, in some circumstances (even for lower blending level), to be complemented with further considerations to provide a complete costs assessment. Further evaluations of the pipelines replacement needs are required to have a full and accurate assessment of the TSO costs incurred to retrofit its system to any scenario of blends, or for repurposing into a hydrogen backbone. Additionally, one should consider that in the cases of higher hydrogen content, the higher the costs will be due to larger replacements needs for some TSOs. For other TSOs, where replacements are not needed to the same extent, the effect of replacements in costs will not be so relevant.

ENTSOG would like to thank Marcogaz for this timely assessment, and for the opportunity to contribute to the overall analysis.

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