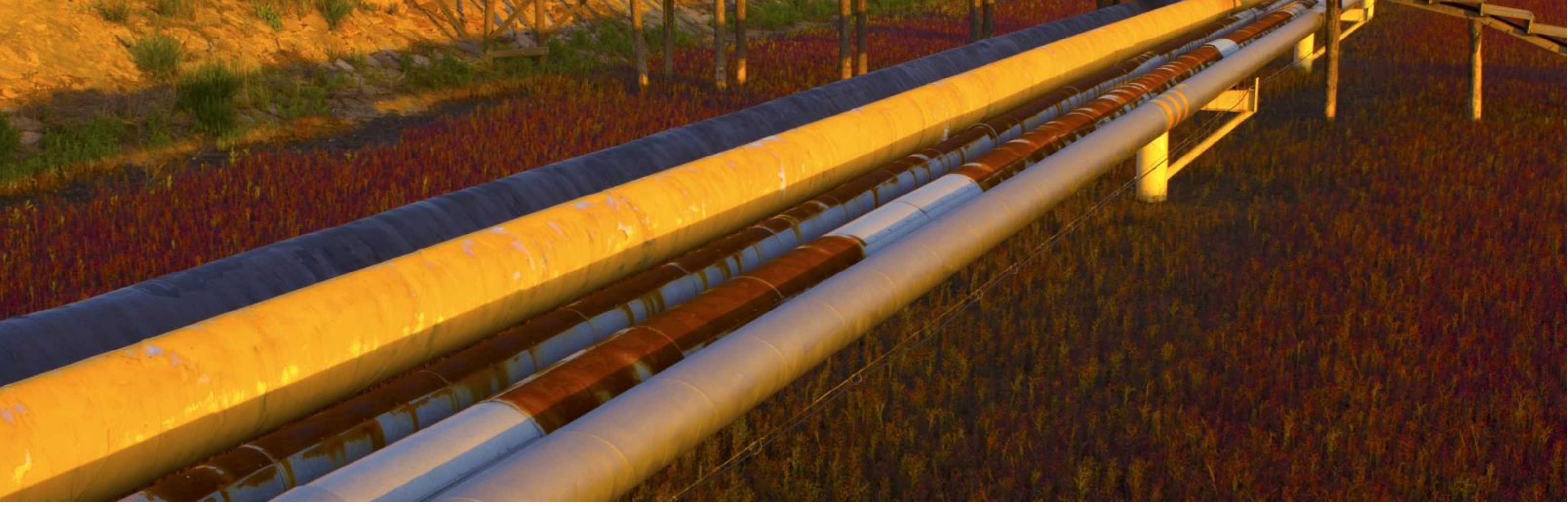

Methodology description for the cost estimation of hydrogen admission into existing natural gas infrastructure and end use

2023

CONTACT

MARCOGAZ AISBL

Rue Belliard, 40

1040 Brussels – Belgium

marcogaz@marcogaz.org

www.marcogaz.org

ABOUT MARCOGAZ

Founded in 1968, MARCOGAZ represents 29 member organisations from 20 countries. Its mission encompasses monitoring and policy advisory activities related to the 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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1. INTRODUCTION

In order to achieve climate neutrality in Europe by 2050, the use of renewable gases, and especially hydrogen (H_2) in the gas industry is becoming a necessity. In the transition towards a net-zero energy system, many aspects need to be considered to find the most sustainable, economic, and implementable way of achieving this goal. MARCOGAZ aims to alleviate some of those concerns by bringing more clarity to the actual status of the European gas infrastructure regarding its hydrogen suitability.

With this report, MARCOGAZ provides a methodology to estimate the costs of hydrogen admission into existing natural gas infrastructure or end use equipment on a national or regional level. Besides the methodology description, also specific European average values are given as reference to support stakeholders in case local data is lacking. The figures are based on experiences from several stakeholders in the gas industry and include expected technical suitability of components for the use with hydrogen. Nevertheless, as the existing situation on national or regional level might differ significantly from the European average, the European picture might not always hold on small scale. As the purpose of this document is on the methodology description, no cost estimations are included in this work. However, assumptions are given on the transformation within the borders of technical feasibility.

This methodology description starts by elaborating on the essential steps to determine the cost of repurposing the existing natural gas grid for hydrogen mixtures. For each of these steps, MARCOGAZ experts have selected five main categories regarding the use of hydrogen: transmission, underground gas storage, distribution, pressure regulation and metering, and end use. Beyond the methodology steps, this document identifies for the five infrastructure categories different asset types, with their respective specific asset volumes and the H_2 readiness of the assets. These values assist stakeholders in determining their total asset volumes and the required mitigation measure costs.

The structure of this report can be summarized in the following parts:

1. In the first part, chapter 2, a general methodology outline is given to set a framework to determine the cost estimation of hydrogen admission into existing natural gas infrastructure and end use
2. In the second part, chapters 3-7, the five categories are described individually in more detail. Here, assumptions are given for the quantification of the specific asset volumes of components that are operated in the European gas infrastructure and their respective hydrogen tolerance.
3. In the third part, chapter 8, a brief overview of the cost estimation for hydrogen admission into existing natural gas infrastructure and end use is given when the methodology is applied on an European level.
4. In the final part, chapter 9, a conclusion is presented which summarizes the main outcomes of this document.

The mitigation measures are in line with the updated version of H_2-infographic as published by MARCOGAZ in 2023 [1]. A more general comparison between various types of technology, concerning aspects like energy efficiency and energy availability, might require additional measures even for low hydrogen concentrations. These questions can only be answered on a case-by-case assessment by the operator, when deciding which technology is best suited for a specific task. These measures are therefore not considered in this publication.

2. METHODOLOGY

2.1 Scope of the methodology

In developing the methodology to determine the cost estimation of hydrogen admission into existing natural gas grids, MARCOGAZ experts worked closely together with the different European shareholders. The method, assumptions and data have been extensively discussed by MARCOGAZ experts. Following this discussion, five gas infrastructure categories are identified covering the mid- and downstream gas chain for which the cost analyses can be performed. These categories are:

- **Transmission and regional distribution networks:** All the gas systems operating with pressures higher than 25 bar. These systems are typically used to deliver gas over long distances through steel pipelines and operated by transmission system operators (TSOs).
- **Local distribution networks:** Systems operating with pressures below 25 bar, in most cases pressures up to 16 bar. This encompasses gas distribution networks on a more local scale. Note that there are some pipelines in distribution grids that are operated with pressures above 25 bars. These are covered within the first item.
- **Underground gas storage facilities:** 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:** Stations in both the gas transmission and distribution system for pressure control and gas metering.
- **End use:** Equipment related to the different specific usages of gas for residential and commercial appliances.

For these categories, the individual costs for hydrogen admission into existing gas infrastructure can be estimated using the methodology outlined below. Adding the costs of the individual categories will result in the estimated total costs of hydrogen admission in the mid- and downstream gas infrastructure. After this chapter, the individual categories are explained in more detail and assumptions on the specific assets volumes and mitigation measures are given.

2.2 General approach of the calculation

Using the general methodology, the reader can calculate the costs for the specific situation in their country or segment. The general approach to calculate the cost for hydrogen admission into existing gas infrastructure can be summarized by four steps:

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

An overview of the steps can be found in Figure 1. Before applying these steps in detail to the different categories in the next chapters, a few general remarks can be made about the individual steps.

Quantification

As a first step, the quantification of the asset volumes has to be carried out for all the above-mentioned areas of interest. The quantification of a complete gas grid can be quite a challenging task, as 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 need to be implemented. This would entail using certain countries, which have this data readily available, as basis for this study to calculate a specific asset volume (weighted average e.g. on the basis of the corresponding pipeline length) for each area of interest. MARCOGAZ experts have analysed multiple data sets to provide European weighted average specific asset volumes (often per km). These numbers serve as reference or in case detailed data is lacking but the grid size is known. The assumptions for quantification and specific asset volumes are given in the chapters of the individual categories. From the specific asset volumes, the total asset volume can be calculated as in:

$$Total\ asset\ volume = specific\ asset\ volume \times grid\ size.$$

Evaluation

Once the quantification is done, the assets need to be evaluated in terms of their hydrogen suitability for the key concentration: 2, 5, 10,15, 20, 25, 30 and 100 vol.-% H_2. Following a hands-on oriented approach, only the technically most important hydrogen concentrations mentioned above are part of this investigation. This also means that no statements are given about hydrogen concentrations of 31 – 99 vol.-% in the gas blend. If higher concentrations would become of more interest to the industry, they could be investigated in more detail separately.

From the evaluation of H_2-readiness, mitigation measures are derived which describe in brief what action is needed to convey certain hydrogen concentrations in the existing gas infrastructure. The mitigation measures have been developed based on available literature, findings of research and demonstration projects, discussions, and consensual assumptions by MARCOGAZ expert groups. The identified mitigations measures underline the latest (2023) version of the H_2-Infographic as published by MARCOGAZ [1]. These mitigation measures apply to general asset groups in case the H_2-readiness of a specific asset model is not known. Similar as with the specific asset volumes, the expected mitigation measures for the different asset types are given in the chapters of the individual categories.

Specific costs

Next, to determine the specific costs for each asset, the expected mitigation measure per evaluated hydrogen concentration has to be translated to an estimated cost. It needs to be considered that calculating a specific price for renewal or retrofitting of a selected component is complex, especially because prices vary over Europe and depend on many variables. Therefore, prices assumptions are *not* included in this document and should be included by the expert performing the study.

Total costs

Finally, the previous steps for the different categories are consolidated to estimate the overall mitigation costs for the mid- and downstream gas value chain for a specific hydrogen concentration scenario. This can mathematically be represented by:

$$Total\ Cost\ (X\%\ H_2)[€] = C_{TP\ (X\%\ H_2)} + C_{DIS\ (X\%\ H_2)} + C_{PM\ (X\%\ H_2)} + C_{UGS\ (X\%\ H_2)} + C_{EU\ (X\%\ H_2)},$$

In which, $C_{Y\ (X\%\ H2)}$ is the cost for X vol.-% H_2 admission into the infrastructure category Y where the acronyms TP, DIS, PM, UGS and EU refer to the segments *Transmission Pipelines, Distribution, Pressure regulating and Metering stations, Underground gas storage and End use* respectively. A full spectrum can be derived by calculating the total costs for each vol.-% H_2 concentration.

To be able to perform the calculation above, first the cost ($C_{Y\,(X\%\,H2)}$) per category (Y) per hydrogen concentration (X% H_2) has to be calculated as:

$$C_{Y\,(X\%\,H_2)} = A_i * C_{Ai\,(X\%\,H_2)} + A_j * C_{Aj\,(X\%\,H_2)} + \cdots,$$

In which A_i is the volume of an asset type i, possibly derived from a specific asset number per km pipeline multiplied by the length of the grid, and $C_{Ai\,(X\%\,H2)}$ is the specific cost for the mitigation measure to allow X vol.-% hydrogen admission into asset type Ai.

The acquired and aggregated data concerning the specific assets volumes, their hydrogen compatibility as well as required mitigation measures are presented in next chapters for each operating category.

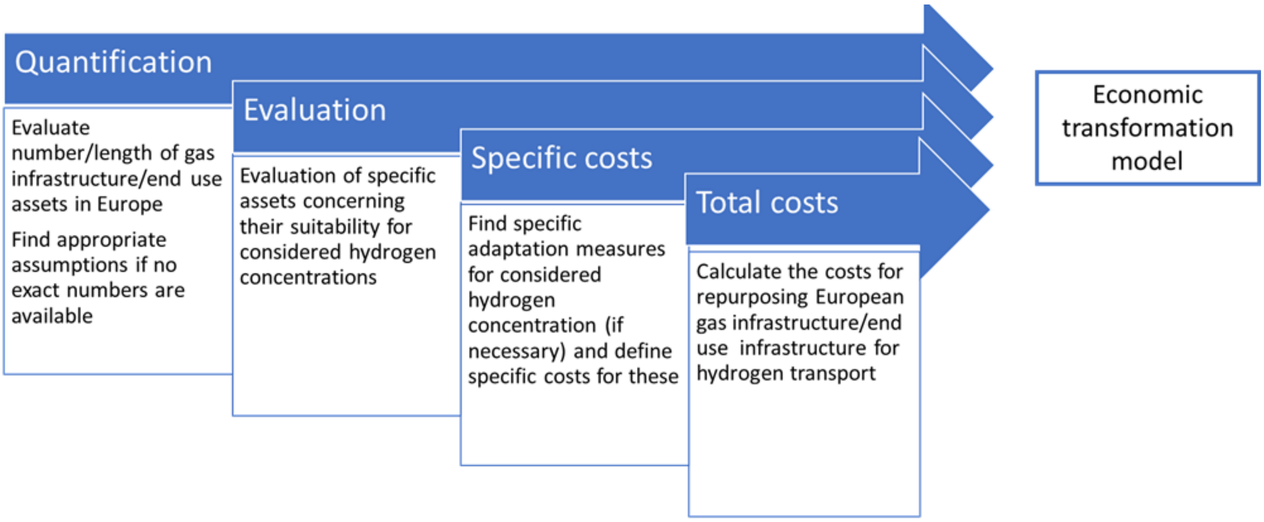

Figure 1: Economic transformation model with the four steps to calculate the estimated costs of hydrogen admission into existing natural gas infrastructure.

3. TRANSMISSION AND REGIONAL DISTRIBUTION

3.1 Introduction

In this chapter, the infrastructure category transmission and regional distribution is worked out in more detail. Firstly, the quantification of the assets within this category is evaluated and specific European average values, in unit per km, are given as a reference in case local data is lacking. In the second part of this chapter, the mitigation measures for the individual assets types in this category are outlined for the different hydrogen concentrations.

The following asset types are identified by MARCOGAZ experts in the transmission and regional distribution category: Piping, and Valves-, Pigging-, Metering- and Compressor stations. Depending on the local situation and the scope of the research, asset types might be left out or new types could be included in this category.

3.2 Quantification of specific asset volumes for transmission infrastructure

Sometimes it might be hard to quantify the assets in the category transmission and regional distribution. This subsection helps by evaluating and defining specific European average values in case national or regional data is not available.

- **Piping:** It is crucial to differentiate between older and newer steel pipelines as this determines the proposed mitigation actions and therefore adaptations costs. The motivation for the differentiation is that due to improved non-destructive testing technologies, the pipeline quality was improved during production and welding. This improved technical situation was included in the standards for pipeline production and installation in the mid 1980's, unfolding to an improved quality in the complete infrastructure that has been build afterwards. There are cases where those quality measures have been applied even earlier but this is not considered to be the typical case. 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 with an improved weld quality.

  The TYNDP and the 11th EGIG report have estimated for both groups the operated assets length in Europe [2, 3]. It was concluded that the total 225.000 km of gas transmission pipelines consist of 121.000 km (54%) older and 104.000 km (46%) younger pipelines.

- **Stations:** Station assets are defined as assets that have a character or a structure that is more complex than a single pipeline. In the following, the assumptions and estimated specific asset volumes are described by different types of stations:
    - Valve stations: Aiming to estimate a realistic amount of currently operated valve stations, codes and standards are considered that define the distance between valve stations. The regulations are varying across Europe between 10 and up to 90 km of pipeline length. A specific amount for valve stations was calculated based on the specific regulations and pipeline lengths of the countries; Belgium, France, Germany, Italy and The Netherlands. Based on this information a length-weighted average of 1 valve stations every 15 km in existing pipelines lines has been concluded.

      For conveying pure hydrogen, 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 regulation in the member states can vary significantly. It is expected that in the near future more certainty will be achieved concerning the requirements and regulations.

- Pigging stations: Data from France, Denmark en Italy is collected to determine the volume of pigging stations in the transmission network. Based on this information, a weighted average of 1 pigging station every 66 km of pipeline length has been set.

- Metering stations: The assumptions of metering stations (gas pressure regulation stations are covered separately) are derived of data from France, Germany, Italy, The Netherlands and United Kingdom. It is assumed that there are a total of 870 metering stations over the total European grid, resulting in a specific value of 0,0039 station per km. Each metering station is estimated to be equipped with three trains, two converters (one back up) and one process graph chromatograph (PGC). It should be noted that not all the measuring stations are equipped with a PGC. As in other parts of the grid some additional PGC are installed, it is assumed that one PGC per stations leads to a realistic total amount. Note that pressure regulation stations are considered in chapter 6.

- Compressor stations: The estimation of installed compressor power follows from data of Germany, Italy and France. Based on this information a specific weighted average of 0.042 MW installed compressor power per kilometre has been determined.

Overview of the considered asset volumes

An overview of the considered asset types and their specific asset volumes are given in Table 1.

Infrastructure item	Specific asset volume per km pipeline
Share of older pipe construction (before 1984 EN12732) [2,3]	54%
Younger pipe construction (after 1984 EN12732) [2,3]	46%
Valve stations (existing)	0,067 station / km
Valve stations (needed for pure hydrogen service)	0,05 station / km
Pigging stations	0,015 station / km
Metering stations	0,0039 station / km
Compressor station installed power incl. drive and auxiliaries combined	0,042 MW/ km

Table 1: Overview of the considered specific asset volumes.

3.3 Mitigation measures for transmission infrastructure with different H2 concentrations

This section elaborates on the estimated H_2-readiness and corresponding mitigation measures for assets in the category transmission and regional distribution. Beyond the mitigation measures described in the following subsections, further mitigation actions, including replacement of pipeline sections, could become necessary, especially if the same energy throughput as in the natural gas service needs to be maintained. These, non-operational required measures, could in some constellations become necessary even for low hydrogen concentrations and are not considered in this publication. This can only be provided based on an individual assessment by the operators itself.

- **Piping:** Steel pipelines that are operated statically are deemed to be suitable for hydrogen applications [4, 5]. Statical operation has been defined by pressure swings lower than 10% of pipeline design pressure. The following measures are recommended to assure a safe operation and are considered in the subsequent assessment:

    - For hydrogen concentrations up to 10 vol.-% in the gas mixture, a risk assessment is required considering the current condition of the pipeline. (Existing inline inspection (ILI), magnetic flux leakage and for smaller diameters DC voltage gradient, should be considered).

    - For higher hydrogen concentrations as of 10 vol.-%, inline inspection 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 as pressure swings in the mentioned magnitude occur mainly in pipelines directly connected to UGS or LNG regasification plants [5].

    - It is expected that inline inspection with suitable technologies (e.g. EMAT) leads to the identification of cracks and crack like defects. It is assumed that defects for older pipelines are expected to be more frequent (0,1/km) than for younger pipelines (0,01/km) [5].

The mitigation measures are summarized in Table 2 below. Note the colour indicates the readiness of the asset regarding the hydrogen concentration. In this case, dark green reveals that no significant mitigation measures are required.

	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				

Table 2: Mitigation measures for transmission pipelines.

- **Stations:** Station assets are complex concerning the number of components, technologies that are used, as well as their designed. The mitigation measures shown in this subsection summarise measures that apply for the majority of the assets in the field. However exceptions where more, less or different measures are needed are expected. For the different station types, the following measures are identified:

    - Valve Stations:
        - Require tightness checks due to the different nature of hydrogen molecules in respect to natural gas. Replacement can be mandatory depending on the country for mixtures above 10 vol.-% H_2 [6].
        - For mixtures between 10 and 30 vol.-% H_2, it is expected that 10 % of the valve stations has to be replaced [6].
        - For 100 vol.-% H_2, it is assumed is that all valve stations will be replaced by double block and bleed stations.

    - Pigging stations:
        - No modifications are foreseen as required for mixtures up to 10 vol.-% H_2 for piggings stations.
        - Above the limit of 10 vol.-% H_2, seal replacement is expected for pigging stations.

- Metering stations:
    - Above concentration of 2 vol.-% H_2, process gas chromatographs need to be replaced.
    - Concentrations above 10 and up to 30 vol.-% H_2, manufacturer approval of meters and converters is expected, and recalibration of us-meters might be needed [7].
    - For 100 vol.-% H_2 mixtures, replacement of meters and volume converters and further complex measures are expected to be necessary.

- Compressor stations: Compressor stations are complex and unique facilities, especially regarding the design and key technologies. Mitigation measure listed below are therefore of general nature and based on a case-by-case approach more/less measures could become necessary to achieve certain hydrogen concentrations.
    - For blends up to 2 vol.-% H_2, an additional control system is considered to be necessary. As the (volumetric) heating value of hydrogen is lower compared to natural gas, a higher flow rate is needed to provide the same amount of energy through the system. Furthermore, in some cases, a H_2 concentration monitoring system might be needed.
    - Above 2 and up to 10 vol.-% H_2 concentration, modifications of the following components are considered to be necessary in many cases [8]: control systems, fuel gas systems incl. filters, sealing systems (wet systems not suitable) and fire detections systems.
    - Mixtures with concentration between 10 and 20 vol.-% H_2, in addition to the previous listed measures, also complex modifications as retrofit of compressors, drives and possibly pressure reduction is 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 % in comparison to natural gas. If the same energy flow needs to be maintained, the higher flow rate would amount to more than 50% additional compression energy in comparison to natural gas [9]. Therefore replacement of the compressor stations is considered when hydrogen concentrations of 20 vol.-% will be exceeded.

The mitigation measures for different station types are summarized in Table 3**Error! Reference source not found.** below. Again, note that the colours indicate the readiness of the asset regarding the hydrogen concentration. Now, two new colours are added in addition to dark green. Light green represents mostly positive results from studies, some mitigation measure might be needed. Orange represent that it is technically feasible to adjust the asset for the specific hydrogen concentration, but significant mitigation measures are expected.

	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 20km 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 regarding: Control System Fuel gas system Sealing systems Fire detections 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	

Table 3: Mitigation measures for station assets.

4. UNDERGROUND GAS STORAGE

4.1 Introduction

Underground Gas Storage facilities (UGS) refer to the facilities used to store gas for future utilization, including all the equipment required for injection and gas treatment. Three main types of UGS facilities have been distinguished, namely salt caverns, depleted oil- and gas fields and aquifers.

UGS facilities vary significantly throughout Europe, not only in terms of type, but also regarding size and storage volume, as well as operating conditions. Accordingly, a wide variety of equipment is used, and currently in several cases no distinct proclamations on hydrogen suitability can be provided. However, currently there are a series of real projects in the field being carried out, and real practical experience will be gained in near future. These experiences are expected to improve the current knowledge of hydrogen suitability for several components.

Similar to the assessment of the transmission category, the existing UGS facilities in Europe have been analysed to determine the main parameters and specific asset amounts to come up with a so-called European generic UGS. Subsequently, the main components have been analysed for their H_2-tolerance and adoption measures.

4.2 Quantification of an European generic UGS

A total of 205 UGS facilities exist in Europe, distinguished into three main types (see Table 4), and all of them with unique parameters and different types and amounts of components installed. To be able to quantify a so-called generic UGS, a bottom-up approach was used, supplemented with more detailed information from reference projects. The workflow to determine the amounts and types of components are outlined below:

1. Analysis of the data base “Gas Storage Europe” [10]. Compilation of main parameters of *each* UGS, i.e. storage volumes and maximum withdraw and injection rates. Further, analysis of depths and number of wells, if there are secondary sources available. Mainly used here: IGU WGC 2018 [11].
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 6).
4. Determination of average values for each UGS-type, for both main parameters and 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 so-called generic UGS was generated, covering cavern-UGS, depleted field-UGS and aquifer-UGS alike. This approach can be considered representative, since in the end all necessary main equipment and their overall shares and quantities are covered. However, this approach also has some limitations in that regard that it produces unrealistic combinations of equipment in a single UGS (e.g. different types of gas treatment and different types of compressor drives[1], whereas in reality only a single system would be used).

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[1] Usage of different compressor types on the other hand is indeed common, there are several UGS facilities using both piston compressors and turbo compressors, e.g. Rehden in Germany.

4.2.1 Main parameters of UGS

In this sub-chapter, the main parameters of the European UGS facilities are determined. These values are important to determine the amounts of the main component of the UGS facilities (as in Table 6). Starting point for the analysis was the data base "Gas Storage Europe" [10]. First of all, Table 4 summarizes the number of considered UGS facilities:

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

Table 4: Summary of UGS facilities according to type.

In the next step, the main characteristics/parameters for each UGS were assessed and subsequently, average values for each type calculated. 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. The parameters considered are:

- Depths are used to determine the length of the tubing 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 calculation of power consumption of a compressor.

Parameter	Unit	Cavern-UGS	Aquifer-UGS	Depleted Field UGS	Weighted Average
Depth Top	m	1,040.30		1,244.51	958.22
Depth Bottom	m	1,324.13	706.43	1,427.67	1,266.67
WGV	Mio. Nm^3	220.56	150.98	529.88	360.74
TGV	Mio. Nm^3	662.13	368.13	1160.52	856.05
Max. Withdrawal Rate	1000 Nm^3/h	516.03	325.25	654.76	550.88
Max. Injection Rate	1000 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[2]	bar	60.00			19.90
Temperature	°C	47.50	27.17	54.91	47.58
No. Wells	-	9	31	28	22

Table 5: Summary of main parameters of UGS facilities according to type.

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[2] 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 automatically gets very low. However, this value has no impact on the subsequent cost assessment.

4.2.2 Analysis of UGS facilities: specific asset volume of main components

As a next step, the main components for gas operation were assessed according to the facilities' main parameters. For several components a distinction into two cases needed to be made regarding their H_2-suiability.

A few remarks on the assumptions to derive a reference-UGS:

- 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. amount of compressors is determined according to maximum injection capacity:
  - Maximum injection rate of an UGS facility:
    - Above 200,000 Nm3/h max. injection capacity:
      - Maximum injection capacity divided by 150,000 Nm3/h leads to the amount of turbo compressors. Value rounded.
    - Below 200,000 Nm3/h max. injection capacity:
      - Maximum injection capacity divided by 50,000 Nm3/h leads to the amount of piston compressors. Value rounded.
    - Above 200,000 Nm3/h max. injection capacity:
      - Maximum injection capacity divided by 150,000 Nm3/h leads to the amount of turbo compressors. Value rounded.
    - Below 200,000 Nm3/h max. injection capacity:
      - Maximum injection capacity divided by 50,000 Nm3/h leads to the amount of piston compressors. Value rounded.
    - 1 compressor for redundancy has been added of each.
  - The above calculation was done for each UGS facility in Europe, using the general information from GIE.
  - Then the weighted average amount of compressors was, using the calculated amount of each UGs-type in Europe.
- For components with differing types, such as 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) [11, 12].
- For a number of components like subsurface tubings, there could no funded determination be found about the degree of H_2-tolerance, since this is unknown for the API grades typically used for subsurface equipment. Future and currently 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 hydrogen blended into natural gas [13].
- Some API-steels are reported to be H_2-suitable, such as e.g. X-52. However, they are rather untypical.

For several components such as pipelines in the surface facility (SF) components a distinction into two cases needed to be made:

- H_2-suitable
- Not H_2-suitable

Reason is that for these components varying types and materials are available at the market, and a survey among UGS-operators in Germany [12] concluded that partially H_2-suitable material is used and partially not H_2-suitable material. The respective shares had been extrapolated to the European UGS facilities.

The following, Table 6, summarizes the main components and the assumptions with respect to the calculation principles for the specific number of a representative type-UGS.

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 Nm/h and Piston comp. with 50,000 Nm^3/h. 1 compressor in addition for redundancy. Calculated for each European UGS facility. • Above 200,000 Nm^3/h max. injection capacity utilization 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 [12].	• 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 Nm^3/h; rule of three[3]) + 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 Nm^3/h; rule of three[3]) + 1 for redundancy; • Analysis of shares of absorption drying, adsorption drying and JT-drying according to IGU WGC 2018 data base 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 meter as follows:
	  ○ 2 per well, i.e. 44
	  ○ 1 per compressor, i.e. 8
	  ○ 1 per cooler, i.e. 16
		• 77

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[3] The assumption that 3 separators are used in a UGS facility with an overall maximum withdraw capacity of 1,500,000 Nm^3/h is directly applied from a reference project.

Main Component and Type	Calculation / Assumption	Amount for representative type-UGS
	○ 1 per separator, i.e. 2 ○ 1 per gas drying unit, i.e. 7 ○ 1 per field pipeline, multiplied with 1.5[4], i.e. 33 ○ 1 per desulphurization 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.	
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 ultra-sonic meters for 1,500,000 Nm³/h; rule of three³) + 1 for redundancy, used for fiscal measurement	• 2
Diaphragm gas meter	• Set to 0.	• 0
Process gas chromatograph	• 2 per UGS facility	• 2
Piping Surface Facility, lenght	• Analogy from a reference project [12]: ○ 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 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 ○ 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 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 different UGS-types.
Glykol vessels: fresh, condensate, old	• Each type 3 times, i.e. 3 x 3 = 9 [11]	• 9
Desulphurization	• Assumption that 1/3 of the UGS facilities need a desulphurization.	• 2

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[4] For every well, there is a field pipeline. Some might directly go into the surface facility, but others might be preliminary combined to a larger common field pipeline first. Factor 1.5 is DBI's own assumption.

Main Component and Type	Calculation / Assumption	Amount for representative type-UGS
	• Amount determined as 1/3 of total number of gas dryers, value rounded.	
Flare	• Fixed value for each UGS type according to average Withdraw 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 [11] are 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 Filed UGS: 1 per well	• 19
Wellhead	• 1 per well • Assumption that no WH is H_2-suitable	• 22
SSV	• 1 per well	• 22

Table 6: Summary of assumptions and calculation principles for assessment of number of main components.

4.3 Mitigation measures for UGS facilities with different H2 concentrations

The next step for the category UGS facilities is determining the H2-readiness of the identified components. Table 7 summarizes the actual H2-tolerances of each main component in more detail and gives the necessary adoption measures to reach higher H2-tolerance. Annex I, Table 17, gives a more detailed description of the identified mitigation measures.

Main Component	H_2-Tolerance vol.-%	Specific Adoption Measures to reach levels of H_2-tolerance								
		0 %	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100 %
Turbo compressor	10	No Adoption required.				Adjustments required, a detailed evaluation of the respective component must be carried out, taking into account the individual conditions / modes of operation		Adjustments required, a detailed evaluation of the respective component must be carried out, taking into account the individual conditions / modes of operation		Replacement required.
Piston compressor	5	No Adoption required.				Check for material compatibility, adjust lubricant and pressure if necessary.				
Electric engine	100	No Adoption required.								
Gas engine	10	No Adoption required.				Check for material compatibility, Check for required gas demand for fuelling, if is not given.				
Gas turbine	2	No Adoption required.		Modification on the gas turbines are required.						Replacement required.
Cooler	20	No Adoption required.						Adaptation is required. Check for material compatibility	Adaptation or complete replacement is required.	
Separator	5	No Adoption required.			Check for material compatibility, eventually adaptation.	Absorption Gas Dryer				
Absorption & adsorption Gas Dryer	5	No Adoption required.		Check for material compatibility, eventually adaptation.						
JT Gas Dryer	N/A	N/A								
Pressure regulator	30	No Adoption required.								Testing of material compatibility and functionality / (capacity test) is required.
Turbine gas meter	30	No Adoption required.								Replacement required.
Coriolis gas meter	5	No Adoption required.			Individual evaluation of the measuring range and material compatibility is required.					

Main Component	H_2-Tolerance vol.-%	Specific Adoption Measures to reach levels of H_2-tolerance								
		0 %	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100 %
Ultrasonic gas meter	10	No Adoption required.		Individual evaluation of the measuring range and material compatibility is required.	Replacement required.					
Diaphragm gas meter	N/A	N/A								
Process gas chromatograph	0.2	No Adoption required.	Replacement required.							
Piping, 100 % H_2-compatible	100	No Adoption required.								
Piping, not H_2-compatible	5	No Adoption required.			Piping, not H_2-compatible					
Fittings, H_2-compatible	100	No Adoption required.								
Fittings, not H_2-compatible	5	No Adoption required.			Fittings, not H_2-compatible					
Field pipeline, H_2-compatible	100	No Adoption required.								
Field pipeline, not H_2-compatible	5	No Adoption required.			Field pipeline, not H_2-compatible					
Glykol vessels	5	No Adoption required.			Check for material compatibility or use recommendation of the NACE and EIGA Standard.					
Flare	5	No Adoption required.			Check for material compatibility, define or adjust Ex-Zones	Check for material compatibility, define or adjust Ex-Zones, new flare to be installed.				
Burners	5	No Adoption required.			Burners must be adapted / check for material	Burners must be adapted / replaced, fuel gas demand increased according to calorific value, Ex-areas to be re-assessed.				

Main Component	H_2-Tolerance vol.-%	Specific Adoption Measures to reach levels of H_2-tolerance								
		0 %	2 vol.-%	5 vol.-%	10 vol.-%	15 vol.-%	20 vol.-%	25 vol.-%	30 vol.-%	100 %
					compatibility, Ex-areas to be re-assessed					
Desulfurization	5	No Adoption required.			Check for material compatibility, eventually adaptation	Desulfurization				
LCCS	100	No Adoption required.								
Packer	2	No Adoption required.		Check material for long-term degradation safety, check Elastomer compatibility and eventually replacement.				Replacement is required[5].		
Tubing - H_2-compatible	100	No Adoption required.								
Tubing - not H_2-compatible	2	No Adoption required.		Check material for long-term degradation safety, eventually replacement.				Replacement is required.		
New inner Liner as secondary barrier for protection of Casing	100	No adaption required, new installation which must be H_2-compatible.								
Sand filter (for porous UGS)	100	No Adoption required.								
Wellhead, H_2-compatible	100	No Adoption required.								
Wellhead, not H_2-compatible	2	No Adoption required.		Proof of suitability/monitoring required. Eventually replacement.				Replacement is required.		
SSV	2	No Adoption required.		Check material for long-term degradation safety, eventually replacement.				Replacement is required.		

Table 7: Summary of H2-tolerances of main components and adoption measures.

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[5] Currently, no H_2-suitability for any packer is guaranteed by any supplier. Thus, conservatively a required replacement is stipulated. Some actual research projects are dealing with aspects of this and future results might result in a given packer suitability for certain types and H_2-concentrations. Here, the evaluation of the to-be replaced amount of packers might be updated.

5. DISTRIBUTION

5.1 Introduction

Gas distribution systems are defined as systems operating below 25 bars within the scope of this report. 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 2, for the first two steps, concerning the quantification and evaluation, an online survey was implemented where stakeholders of the gas distribution systems were asked to share relevant data with MARCOGAZ.

Similar to the quantification step in the transmission category, the number of specific assets are calculated from the data of the asset volumes and corresponding grid length of the grid operators. In this way, a specific number of each component could be calculated per kilometre grid length to serve as a reference for the researcher.

Next, the answers about the evaluations of the components coming from the different stakeholders were compared to ensure consensus on the required mitigation measures, which was then presented to and confirmed by MARCOGAZ experts.

5.2 Quantification of specific asset volumes for distribution infrastructure

Based on the survey and the following studies; *MARCOSTAT Report on European Gas Safety Gas Distribution (EGAS B) 2018, MARCOSTAT Report on European Gas Safety Gas Distribution (EGAS B) 2019* [14], and *the Marcogaz survey on Methane Emissions 2017* [15], an overview of the European gas distribution grid was collected. For countries where specific data was lacking, an averaged benchmark calculation was used. From these results, the ratio of piping materials (steel, plastic, cast iron, other) was derived as giving in Table 8**Error! Reference source not found.**.

COUNTRY EU 28 + Ukraine	Total (km)	Total Plastic (%)	Total Steel (%)	Cast Iron (%)	Others (%)
TOTAL	2245993	54%	43%	2%	1%

Table 8: Share of piping materials for gas distribution grids in Europe.

The approximated specific number of valves in lines, diaphragm gas meters and house pressure regulators are shown in Table 9, including the number of data points, each result is based on. The number of house pressure regulators was calculated with the data gained from the survey on the one hand and data given in a report of the German federal environmental agency on the other hand [16].

Asset type	Specific amount (units / km)	Data points
Valves in Lines	0.89	7
Diaphragm gas meters	54	8 [16]
House pressure regulators	9	6

Table 9: Specific asset volumes for distribution (excluding pipelines).

Some remarks have to made about the asset types in the distribution category. First of all, components overlap with the Gas Pressure Reduction and Metering Stations category and are only listed in the next chapter to avoid repetition. Examples of such components are different types of valves, meters, filters, process gas chromatographs, volume converters and pressure regulators. Furthermore, also assumptions are made in the case data is lacking (excess flow valves) or for simplification reasons if the impact of the component is not expected to be significant (house entry combinations).

5.3 Mitigation measures for distribution infrastructure with different H_2 concentrations

5.31 Piping assets

Regarding the piping assets for distribution, some assumptions had to be taken, so that calculations were possible based on a slightly simplified approach. These assumptions are as follows:

- **Steel 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 of the pipelines because of hydrogen embrittlement is not expected because of the low pressure and the lack of cyclic loading. Furthermore, parts of the gas distribution grid are old and in sensitive condition, so that local replacement of the piping assets is necessary anyway. Regarding the use of hydrogen, it is assumed that for pure hydrogen 10% of the steel distribution pipelines need to be replaced due to risk assessments.
- **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 for conveying town gas in this material underline the assumption that cast iron can be safely used with hydrogen. This is also supported by research results (e.g. from Sedigas 2023 [17]). Nevertheless, Grey cast iron is subject to renewal as it is prone to brittle fraction under certain conditions. Therefore, it is recommended in several countries to replace this material anyway and it is open to debate if this should be related to the introduction of hydrogen. 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 [18], no mitigation measures are necessary up to 20 vol.-% H_2 in the gas blend. At higher concentrations, replacement of the diaphragm gas meters becomes necessary.

An overview about the necessary mitigation measures for distribution piping assets is provided in Table 10.

	Hydrogen concentration / vol.-%							
	2	**5**	**10**	**15**	**20**	**25**	**30**	**100**
Steel distribution pipelines	No adaptation required							Replacement of pipelines can be necessary depending on the specific conditions.
Plastic distribution pipelines	No adaptation required							
Cast iron distribution pipelines	Replacement of grey cast iron pipelines as action independent of hydrogen injection							
Service lines	No adaptation required					Replacement of diaphragm gas meters		

Table 10: Mitigation measures for distribution piping assets.

5.32 Valves, meters and house pressure regulators.

Again, some assumption are made to process the available data for the valves, meters and house pressure regulators. First of all, some components are considered and judged on their hydrogen readiness, although dedicated investigation and testing is not completely finalised yet. So beyond that this makes it is difficult to assess the H2-readiness, it is also difficult to determine till what extend the introduction of hydrogen is responsible for the mitigation action in comparison to the continuous renewal of the infrastructure. The renewal process is expected to be intensified before hydrogen is injected as experiences with hydrogen in the system are rare and safety is at the first place. The following remarks can be made on the identified asset types:

- **Valves in lines:** Based on demonstration projects [19], where natural gas components are operated continuously and tested with pure hydrogen[6], 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 that are close to the end of their lifetime will be replaced if hydrogen is injected even though they are considered to be in at least temporary acceptable condition for natural gas. The corresponding measures can therefore not fully be considered to be initiated by hydrogen injection only. Therefore, it is assumed that at mixtures of 25 vol.-% H_2 and higher, 7.5% of the valves in lines will be replaced.
- **Diaphragm gas meters:** Diaphragm gas meters are considered to be suitable up to 20 vol.-% H_2[7] [20].
- **House pressure regulators:** It is assumed that house pressure regulators have to be replaced above 25 vol.-% H_2. However, research shows that these components can most likely be used at higher concentrations as well. Therefore, replacement above 25 vol.-% H_2 is considered for 7.5% of the installed house pressure regulators as e.g. receiving manufacturer approval especially for older types could be a difficult task in comparison to replacement.

An overview of the mitigation measures is given in Table 11.

	Hydrogen concentration / vol.-%							
	2	**5**	**10**	**15**	**20**	**25**	**30**	**100**
Valves in lines	No adaptation required					Partial replacement		
Diaphragm gas meters	No adaptation required					Individual assessment/ replacement		
House pressure regulators	No adaptation required						7,5% replacement	

Table 11: Mitigation measures for valves, meters and house pressure regulators.

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[6] Preliminary findings of currently running testing at DBI laboratory.

[7] Marcogaz survey results show suitability of minimum 15 vol.% as expert guess, manufacturer information consider 25 vol.-%% as limit for accurate measurement.

6. PRESSURE REGULATION AND METERING STATIONS

6.1 Introduction

Gas pressure regulating and metering stations (GPRMS) are an essential part of gas transport systems as they allow 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.

6.2 Quantification of specific asset volumes for pressure regulation and metering stations

The GPRMS have been divided into four categories according to the pressure regime they are operated at. Each category contains a set of components that was specified by stakeholder and MARCOGAZ experts. Table 12 shows the calculated number of GPRMS for each pressure stage as well as the number of data points it is derived from. The volumes for GPRMS up to 40 bars have been derived from the survey of the distribution category. GPRMS with pressures up to 100 bars are more common in the gas transmission. It is worth mentioning that this pressure division is not strictly applicable to all European countries, but it is considered a feasible approach to distinguish between facilities with different complexity.

Pressure regime	Specific number (units / km)	Data points
GRRMS p <= 5 bar	0.0658	9
GRRMS 5 bar < p < 16 bar	0.0243	7
GRRMS 16 bar < p < 40 bar	0.0356	7
GRRMS 40 bar < p < 100 bar	0.029	5

Table 12: Specific volumes of GPRMS per pressure group.

Within the four pressure groups, the asset volumes have been identified as given in Table 13.

GPRMS group:	p <= 5 bar	5 < p < 16 bar	16 < p < 40 bar	40 < p < 100 bar*
Number of filters	2	2	2	x
Number of pressure regulator (incl. shut-off valve)	2	2	2 (shut-off valve separately)	x (shut-off valve separately)
Number of meters	1	1	2	x
Number of converters	1	1	2	x
Number of preheaters	-	-	2	x
Number of water safety shut-off valves	-	-	4	x
Number of separate safety shut-off valves	-	-	4	x
Number of process graph chromatographs (PGC)	-	-	0.1 (one per ten stations)	1

Table 13: Volumes of assets per facility in the GPRMS pressure group.

*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 and sometimes multiplied many times over in their total according to the number of different outlets.

6.3 Mitigation measures

For each of the pressure groups, mitigation measures for the GPRMS are again identified depending on the hydrogen concentration. The results are shown in Table 14**Error! Reference source not found.**. A few remarks can be made on the identified measures:

- From H_2 admission of 2 vol.-% and more, PGC removal is needed if a PGC is installed.
- For concentrations up to 10 vol.-% H_2, it is assumed that no adoption is necessary unless a PGC is installed. This assumption is based on the fact that the changes to the physical properties of the gas mixture are minor and that the volume flow increase is minor, if the same energy through put is maintained.
- For concentration 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.-% [21]. These results consider an energy flow 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 of more complex nature, some modification next to PGC and metering/converters are expected also for concentrations above 10 and up to 30 vol.-% H_2.
- Depending on the composition of other component in a natural gas – H_2 mixture with a H_2 concentration between 25 and 30 vol.-%, the explosion protection group is changing from IIa to IIb. It is assumed that by implementing further organizational measures, the potentially occurring risks can be minimized to such an extent that the replacement of the electrical equipment is not necessary.
- For 100 vol.-% H_2 mixtures; the renewal of filters, meters and possibly safety devices such as shut off valves are needed especially if the same energy throughput is envisaged leading to significant higher volume flows.
  For stations above 16 bar, additional measures are expected such as the removal of preheating systems, adoption of measuring lines due to a higher throughput and the installation of longer inlet section before metering systems.
  Finally for pure hydrogen, the explosion protection group IIc needs to be applied. It is assumed that by implementing further organizational measures, the potentially occurring risks can be minimized to such an extent that the replacement of the electrical equipment is not necessary. If this is not possible, technical changes are required concerning the selection/replacement of electrical equipment. Also, the adjustment of blow-out lines and other measures might be additionally needed. It is therefore an important task to develop organizational measures that avoid a change of the electrical equipment.

Table 14 summarizes the adjustments that may become necessary in relation to the different conversion variants.

	Hydrogen concentration / vol.-%							
	2	**5**	**10**	**15**	**20**	**25**	**30**	**100**
GPRMS p <= 5 bar	No adaptation required			Manufacturer and metrological approval of meters needed.				Renewal of meters, filters, maybe safety devices
GPRMS 5 - 16bar	No adaptation 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

Table 14: Mitigation measures for GPRMS.

7. END USE

7.1 Introduction

In this final chapter, end use equipment is assessed to set a reference for the asset volumes and required mitigation measures at different hydrogen concentrations. Due to the wide variety of end use equipment, this chapter is divided into two subsections which asses the asset volume and mitigation measures directly. The following two subcategories are identified:

- **Domestic and commercial end use:** This mainly covers space heating and cooking.
- **Industrial end use and power generation:** This refers to installations that are used to generate heat for steam generation or for product treatment (e.g. melting, drying, heat treatment) and installation which use gas mixtures as feed stock.

7.2 Quantification and mitigation measures for domestic and commercial end use

In order to determine the specific asset volume, the THyGA-research project [22] has be used to summarize the number of different end use categories for domestic and commercial purposes such as heating and cooking. Table 15 shows the accumulated results of research into hydrogen tolerances for domestic and commercial appliances. The specific asset volumes are found from dividing the total European amount by the total grid size (TSO (225,000 km) + DSO (2,245,993 km) grid = 2,470,993 km) [2, 3, 14, 15]. The assets are divided into four categories, namely:

- 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

In general, it is expected that most appliances can cope with 20 vol.-% H_2 in natural gas. When further increasing the hydrogen concentration to 20-30 vol.-% H_2 range, the equipment is expected to stay operating, although a few premixed or atmospheric appliances may experience flashback problems. These appliances may therefore need to be adapted. For 100 vol.-% H_2, it is very likely that the existing appliances will require replacement. Therefore, new designs will be needed to replace current generations of appliances when operated with pure hydrogen.

			ADAPTATION MEASURES FOR DIFFERENT HYDROGEN SHARES[22]			
Type	**Volume per km [22]**	**Average Age**	**2 - 10 %**	**15 - 20 %**	**20 - 30 %**	**100 %**
Atmospheric (including all cookers)	37.72	20	No measures needed	No measures needed for most of installed appliances	Flash back risk increasing	New design needed
Premix / Partial premixed	54.52	20	No measures needed	No measures needed for most of installed appliances	Flash back risk increasing	New design needed
Radiant	0.81	20	Missing data/ not enough available knowledge			New design needed
Not burner based (eg. fuel cells heating appliances)	0.051					Varies from retrofit to new design

Table 15: Specific asset volume and adaptation measures for domestic and commercial appliances for different hydrogen levels.

7.3 Quantification and mitigation measures for industrial end use and power generation

Within the subcategory *industrial end use and power generation* there is 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 this large number of different plants and product types, with again a large diversity of plant layouts and process steps, it is currently not possible to oversee the necessary adaptations for industrial plants as a whole. Nevertheless, this subsection gives an overview of the most significant mitigation measures that could be identified by MARCOGAZ experts.

For lower hydrogen contents (up to 20 vol.-% H_2) in industry, it is expected that it is be possible to adapt or implement combustion control systems. It may also be necessary to adjust other factors of individual production steps. For higher hydrogen contents, it may be inevitable to retrofit the entire plant or even each individual production step [23].

For power generation equipment, the following statements refer to adaptability in general:

- Most gas turbines are adaptable to higher hydrogen blends. The percentages can vary between 5 and 20 vol.-% H_2, depending on age and manufacturer. Newer gas turbines are reported to be capable of up to 40% hydrogen with a combustion chamber upgrade [24].
- For 100 vol.-% H_2, it is expected that new gas turbines are required [24].
- Adaptation 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.
- Retrofitting gas engines to run on gas mixture up to 100 vol.-% H_2 is only possible in some cases. However, this requires the fuel injection system to be converted to direct injection without premix chambers [25, 26].
- 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, and sometimes even more. These typically require changes in combustion control and air/fuel ratios [23, 27].
- For 100% applications, new burner designs and changes in combustion and flame control are required [23].

8. COST ESTIMATION OF HYDROGEN ADMISSION APPLIED ON EUROPEAN LEVEL

In this chapter, a brief overview is given of the estimated costs when the methodology is applied on European level. In doing so, the European averages values, as introduced in this document, are used and extrapolated with the size of the existing European gas infrastructure. Cost estimations for the mitigation measures are included for the key hydrogen concentration from which the total cost for hydrogen admission into existing natural gas infrastructure and end use could be derived. The results are compared (in %) to the estimated cost of constructing a new hydrogen gas grid in Europe. The outcomes are given in Table 16 and Figure 2.

Total adaption costs compared to new build H_2 infrastructure in % per category.	**2 vol.-%**	**5 vol.-%**	**10 vol.-%**	**15 vol.-%**	**20 vol.-%**	**25 vol.-%**	**30 vol.-%**	**100 vol.-%**	**New build H_2 infrastructure**
Gas transmission	0.03	0.28	0.71	2.4	2.6	11.5	11.5	27.7	100
UGS	0.1	7.1	10.8	13.4	15.5	25.8	25.8	38.3	100
GPRMS	2.2	2.2	2.2	3.9	3.9	3.9	3.9	33.2	100
Gas distribution	0.07	0.07	0.07	0.07	0.07	4.8	4.8	6.4	100
End Use (domestic and commercial)	0.0	0.0	0.0	0.0	0.0	14.8	14.8	100.0	100
Total gas-infrastructure 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	0.2	0.5	0.7	1.4	1.5	9.8	9.8	40.5	100

Table 16: Relative cost for hydrogen admission into existing natural gas infrastructure and end use on European level compared to construction of new build infrastructure.

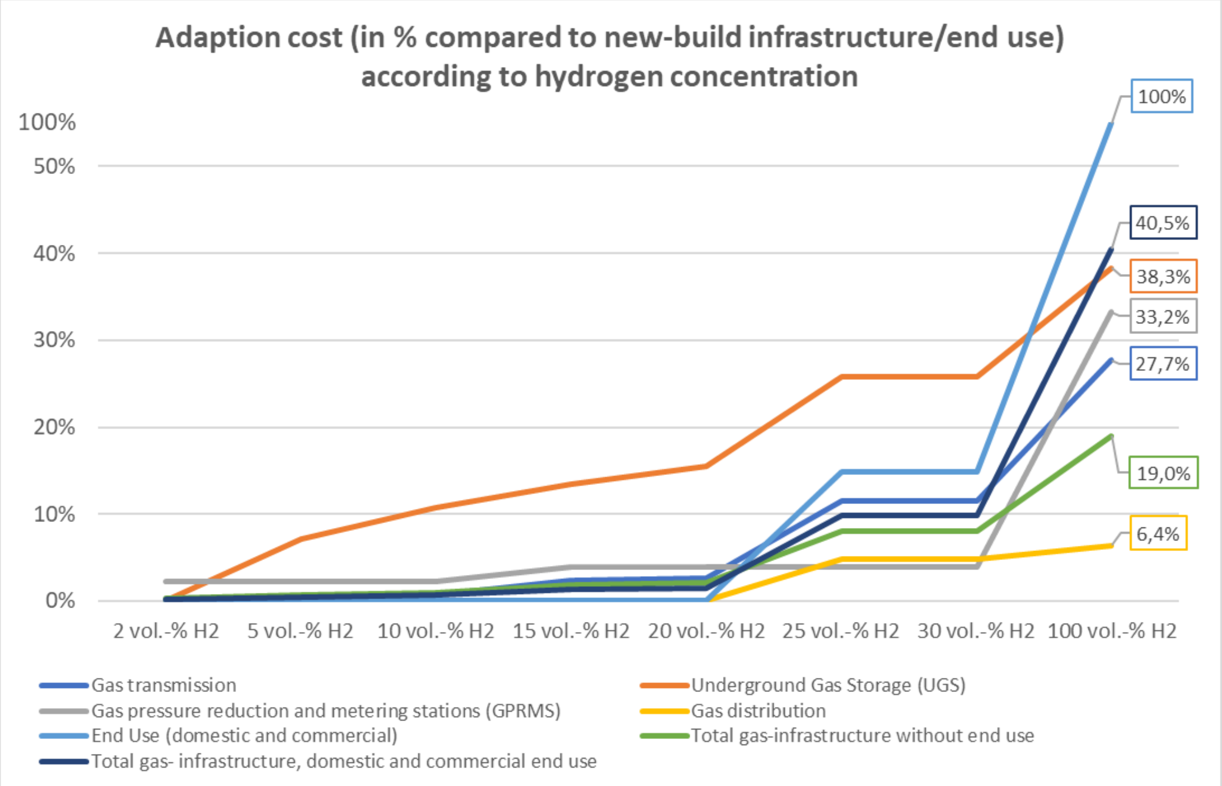

Figure 2: Relative cost for hydrogen admission into existing natural gas infrastructure and end use on European level compared to construction of new build infrastructure.

From the results, the following statements can be derived on the transformation cost for hydrogen admission into existing natural gas infrastructure and end use on European level:

- For the admission of gas mixtures up to 10 vol.-% H_2, the total transformation cost is less than 1% of CAPEX for a new build infrastructure.
- For the admission of gas mixtures up to 30 vol.-% H_2, the total transformation cost is less than 10% of CAPEX for a new build infrastructure.
- For the admission of pure H_2, the transformation cost is less than 20% of CAPEX for new build H_2 infrastructure when residential and commercial appliances are not included.

9. CONCLUSION

In this document, a methodology description has been given to estimate the cost of hydrogen admission into existing natural gas infrastructure and end use equipment. With this methodology, MARCOGAZ aims to support stakeholders in efforts of hydrogen admission into existing infrastructure, and thereby remove barriers for the introduction of a renewable energy carriers in Europe. To generate a clear picture, gas infrastructure and end use equipment were evaluated for their H_2-tolarence at the key concentration: 2, 5, 10, 15, 20, 25, 30 and 100 vol.-% H_2 and the corresponding adaptation measures were given. The presented method and figures have been thoroughly discussed by industry stakeholders and MARCOGAZ experts.

A general approach was introduced, revealing four steps to determine the overall cost. The steps are given in logical order. Starting with the quantification of the asset volume, followed by the evaluation of the asset volume where the hydrogen readiness and required mitigation measures are identified for the different asset types. In the third step, the specific costs for the mitigation measures are determined and finally, the overall costs can be calculated in the fourth step from the previous three steps.

From this work, it follows that the segments in the mid- and downstream gas industry can be divided in five categories to determine the overall costs. The categories are: Transmission, Distribution, Underground Gas Storage Facility, Pressure Regulating and Metering Stations, and finally, End Use. The first two steps of the general approach, quantification and evaluation, are described in more detail in separate chapters of this document.

Although this work provides a strong framework and includes information on the size and readiness of gas infrastructure, the methodology description does not include any figures related to the costs of the introduction of hydrogen. The cost estimation is a complex process as prices depend on many variables and can vary largely within Europe. Therefore, no assumptions on costs are given in this specific work.

Nevertheless, in the final part of this work, the relative costs (in % compared to the cost of new construction) are briefly shown when the methodology is applied on European level. This revealed that the cost for hydrogen admission into existing natural gas infrastructure is depended on the vol.-% H_2 concentration and that even for pure H_2 admission, the cost are below 20% of the cost for the development of a new grid when end use equipment is not included. The results are based on values given in this work and an average cost approximation on European level is used. The situation in single countries might therefore be different. Beside that these results show the financial advantages of transforming the existing infrastructure, this will also lead to a faster establishing of a H_2 ready infrastructure with less negative effects on the environment and lower carbon footprint.

The transformation of the existing gas infrastructure is expected to be realized quickly. For the injection of low hydrogen concentrations as currently foreseen e.g. in the EASEE gas guidelines, no or only marginal adaptation measures are expected in the vast majority of gas infrastructure elements. In particular, hydrogen blending up to 10% by volume leads seems a realistic option from the limited required mitigation measures. Hydrogen blending is therefore a very attractive option to initiate an international H_2 trade and supports the required value chains.

As a final remark, an improvement of the data situation on gas asset volumes in Europe might contribute to more clarity on the readiness of the European gas grid for hydrogen admission . Nevertheless, the chosen methodology, assumptions and estimates by stakeholder and MARCOGAZ experts provide a solid basis for estimating the transformation costs of the gas infrastructure.

ANNEX I: DETAILLED MITIGATION MEASURES FOR UGS

Table 17 gives a more detailed overview of the identified mitigation measures for UGS asset.

Component	Comment / measures
Compressors	**Piston compressors**: need to 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. [28], 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[8] 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[9]. Material suitability a general pre-requisite for any compressor.
Compressor drives	**Gas engines**: suitability in analogy to piston compressors. **Gas turbines**: suitability in analogy to turbo compressors, but with a need for modification already at 5 vol.-% hydrogen blends. Reason here is the significantly increased power consumption of the compressor beyond 5 vol.-% hydrogen, that the engine must provide. **Electrical engines**: completely suitable, since this type of engines does not operate with the medium hydrogen itself. Power output might be a limiting factor, in particular at ca. 15 vol.-%, what can be mitigated by reduced rates (see also footnote 1).
Coolers	Generally suitable as long as the material is suitable. Up to a level of 25 vol.-% hydrogen 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. In analogy to pipeline materials, a share of up to 5 vol.-% hydrogen is considered not critical, up to 10 vol.-% material suitability needs to be examined in detail, and for higher H_2-concentrations adoptions are required (e.g. inner coating).
Gas Drying	Above 5 vol.-% of hydrogen blending, material suitability needs to be evaluated and adjustment measures might become necessary. The functionality of the dryers is not effected by the hydrogen concentration. Deciding point is the moisture: up to 40 mg/Nm^3 hydrogen, TEG (i.d. absorption drying) is suitable, beyond that only adsorption can be used [12].
Desulphurization	Material suitability must be granted; in terms of functionality, the amount of H_2S is deciding. Operating principle is the same as absorption drying.

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[8] It can be 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. DBI own assessment, for reference see our practical training program for underground hydrogen storage.

[9] It can be 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. DBI own assessment, for reference see the DBI practical training program for underground hydrogen storage.

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 costumers to contact them before using existing gas meters for applications with H_2 blends higher than 10 vol.-%. Anyway, some new gas meters have already obtained their metrological certification for applications up to 30 vol.-% H_2 [7].
Piping (SF and Field Pipelines) and Fittings	Here, distinction into H_2-suitable and not H_2-suitable is made. For not suitable material, a tolerance of 5 vol.-% hydrogen blending is made in analogy to the gas grids. Examples for 100 % hydrogen suitable materials are: P460 NL, P460 QH, L360 NB, L415 (ISO 3183) / X60 (API 5L) [12]. Besides the material itself, pressure levels and flow velocities must be considered. Both are adjustable via flow rate regulation.
Glykol vessels	Generally suitable as long as the material is suitable. In analogy to pipeline materials, a share of up to 5 vol.-% hydrogen is considered not critical, beyond that material suitability needs to be examined in detail, and adoptions 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. Further, the fuel gas consumption for burners is increased according to calorific value.
Tubings, Packers, SSVs	Here, distinction into H_2-suitable and not H_2-suitable is. For not suitable material, a tolerance of 5 vol.-% hydrogen blending is made in analogy to the gas grids. A detailed examination might result in the proof of suitability for regular API grades and standard equipment, however currently no supplier grants such. Field experiences show however, that at least up to 20 vol.-% hydrogen blends, standard API materials (e.g. J55, K55) are suitable.
Wellhead	Here, distinction into H_2-suitable and not H_2-suitable is made. In case of wellheads the justifications for this distinction is that there are suppliers available at the market declaring their equipment H_2-suitable [29], however, 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.

Table 17: Summary of adjustment measures for UGS components.

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