



Hydrogen in Gas Grids

A systematic validation approach at various admixture levels into high-pressure grids

D6.3

Pathway and proposals summary to enable wider injection of H2 in EU gas networks

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Table of Contents

Document history	2
Executive Summary	9
1 Objective	11
2 Introduction.....	12
3 Technical feasibility of blending hydrogen into the gas transport network up to 100%	13
3.1 Summary of practical results from the HIGGS project and comparison with literature findings	13
3.2 Optimal H ₂ injection design	18
3.2.1 Introduction	18
3.2.2 Regulatory background	18
3.2.3 Main considerations in the design of the injection facility.....	21
3.2.3.1 Location in the grid.....	22
3.2.3.2 Reception terminal	22
3.2.3.3 Injection setup.....	23
3.2.3.4 Control loop	24
3.2.3.5 Odourisation	25
3.2.3.6 Emergency measures	25
3.2.3.7 Operation mode	25
3.2.3.8 Explosion protection.....	26
3.2.3.9 Overall design of a hydrogen injection facility.....	26

4	Framework and boundary conditions for blending hydrogen into the natural gas transport network at European level	29
4.1	Regulatory framework and boundary conditions at European level	29
4.2	Harmonisation of gas market and operation	29
4.2.1	Aspects for the operation of natural gas transmission grids.....	31
4.2.1.1	Odourisation	31
4.2.1.2	Gas measurement	32
4.2.1.3	Gas quality analysis	33
4.2.1.4	Minimum guaranteed pressures	33
4.2.1.5	Procedure to avoid reaching the minimum pressures.....	35
4.2.1.6	Control centres.....	35
4.2.1.7	Information on the normal operation of the system and detection of parameters out of range	35
4.2.1.8	Grid capacity supervision	36
4.2.1.9	Network emissions.....	36
4.2.1.10	Shrinkage in transmission grids	36
4.2.1.11	Shrinkage in regasification plants.....	37
4.2.1.12	Self-consumption in the transmission grid	37
4.2.1.13	Gas pipeline filling level.....	37
4.2.1.14	Minimum operating level in regasification plants (cushion gas volume)	37
4.2.1.15	Minimum operating level in underground storage facilities	38
4.2.1.16	Operational regulations for methane tanker unloading activities.....	38
4.2.1.17	Procedure for the determination of energy unloaded from methane tankers	38

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

4.2.1.18	Assignment of unloading dates to tankers at regasification plants.....	39
4.2.1.19	International connection management	39
4.2.1.20	Communication procedures	39
4.2.1.21	Actions protocols in case of incidents.....	39
4.2.1.22	Unavailability at transmission facilities	40
4.2.1.23	Unavailability in LNG regasification plants.....	40
4.2.1.24	Unavailability in underground storage facilities.....	41
4.2.1.25	System emergency	41
4.2.1.26	Analysis of new connections and facilities and its integration into the system	41
4.2.1.27	Compression.....	42
4.2.1.28	Programming	42
4.2.1.29	Grid stock and grid balancing.....	42
4.2.1.30	Individual user balancing.....	42
4.2.1.31	Degree of saturation of pressure regulation and metering stations.....	43
4.2.1.32	Communication with the technical manager of the gas system	43
4.2.1.33	Coordination and communication with the electrical technical manager	44
4.2.1.34	Interlocution with other gas system members.....	44
4.2.1.35	Public information about the normal operation of the system	44
4.2.1.36	Operations plan.....	44
4.2.1.37	Winter action plan	45
4.2.1.38	Operation in exceptional situations.....	45
4.2.2	Aspects for the maintenance of natural gas transmission grid.....	46
4.2.2.1	Network surveillance	46

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

4.2.2.2	Coating and corrosion controls.....	46
4.2.2.3	Maneuverability and valve lubrication.....	46
4.2.2.4	Leak checks.....	47
4.2.2.5	Verification and control of regulation and metering equipment	47
4.2.2.6	Regulatory safety controls.....	47
4.2.2.7	Maintenance plan.....	48
4.2.3	Aspects for the gas market.....	48
4.2.3.1	Forecast.....	48
4.2.3.2	Predictive demand analysis.....	48
4.2.3.3	Gas supply and demand forecast.....	49
4.2.3.4	Physical balancing of facilities.....	49
4.2.3.5	Individual imbalances.....	49
4.2.3.6	Capacity Procurement.....	50
4.3	TSO perspectives and customer views	50
4.4	Techno-economic considerations.....	51
5	Blending in the context of an emerging European hydrogen backbone	54
5.1	Initial situation and assumptions.....	54
5.2	Balanced capacity calculations to evaluate the fulfilment of demand by the EHB and the H2 corridors	55
6	Regulations, codes and standards.....	64
6.1	EC policies and legislation	64
6.2	National Hydrogen Strategies	66
6.3	European technical framework by standardisation	67

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

6.3.1	EU framework for standardisation	67
6.3.2	Standards for gas transmission grids	72
6.3.3	Standardisation need identified in HIGGS WP 4	80
7	Pathway / Open points	83
7.1	Technical considerations.....	83
7.2	Considerations regarding gas quality	84
7.3	National and cross-border blending considerations at transport level.....	85
7.4	EC, national policies and RCS	86
7.5	Availability of hydrogen	88
7.6	Considerations regarding injection of hydrogen.....	89
7.7	Acceptance	89
8	Conclusions	91
9	Appendices	94
9.1	National hydrogen strategies.....	94
Bibliography and References.....		113

List of Figures

Figure 1. Calculation example regarding material compatibility according to SyWeSt H2 project (assumptions: DN: 600 mm, DP 67.5 bar, L 415, wall thickness 8 mm, defect 50 mm long and 0.8 mm deep, daily load change of 10 bar) [3]	17
Figure 2. Schematic overview of a hydrogen injection facility	22
Figure 3. Simplified scheme of a natural gas pressure regulation station	22
Figure 4. Schematic scheme of a hydrogen reception terminal	23
Figure 5. Schematic view of the injection setup.....	24
Figure 6. Schematic diagram of the complete design of a hydrogen injection facility.....	28
Figure 7. Example of one of the aspects considered for the operation and maintenance of natural gas transmission grids. 1) Area of interest in which the aspect to be studied is included. It could be operation, maintenance or market. 2 & 3) Aspect to analyse and its description and characteristics according to the documentation. 4) Description of the transmission operator responsibility that is	

established in the documentation. 5) Reference where all the parameters of the aspect are defined. 30

Figure 8. Example of the aspect’s considerations when hydrogen injection into the transmission grid takes place..... 30

Figure 9. Map of European countries according to where they odorise natural gas. 32

Figure 10. Border crossing point between two countries A and B with different hydrogen blending limits with an electrolyser (I.) and a membrane separation unit within a transport pipeline (II.) 52

Figure 11: Hydrogen balances at national level with the assumptions of Scenario I in the Average Case. A green colouring of the Member State means that the hydrogen demand is covered; the redder the colouring, the greater the shortfall. 57

Figure 12: Hydrogen balances at national level with the assumptions of Scenario II in the Average Case. A green colouring of the Member State means that the hydrogen demand is covered; the redder the colouring, the greater the shortfall. 58

Figure 13: Extract from the EHB map for the year 2030, focusing on Belgium (A) and South-East Europe (B) [23]. 58

Figure 14: Hydrogen balances at national level with the assumptions of Scenario I in the Maximum Gap Case. A green colouring of the Member State means that the hydrogen demand is covered; the redder the colouring, the greater the shortfall. 59

Figure 15: Extract from the EHB map for the year 2030, focusing on the Netherlands, Norway, Denmark and Germany [23]. 60

Figure 16: Hydrogen balances at national level with the assumptions of Scenario II in the Maximum Gap Case. A green colouring of the Member State means that the hydrogen demand is covered; the redder the colouring, the greater the shortfall. 60

Figure 17. Overall objectives of REPowerEU goals [30]. 65

Figure 18. National Strategies in European countries as of September 2023 [36] 67

List of Tables

Table 1: Overview of the steel grades tested in HIGGS and SyWeSt H2 14

Table 2. Minimum admissible pressure established for some European countries. 34

Table 3: Publicly available information on the planned H₂ corridors [16], [17], [18], [19] [20], [21] . 56

Table 4. Hydrogen standardisation with relevance to pipelines requested according to AUWP 2023 [39] and AUWP 2024 (preliminary) [40] – Actions on Energy transition and reduction..... 69

Table 5: European standards for gas transmission grids (does not claim to be exhaustive) 73

Executive Summary

This Deliverable D6.3 "Pathway and proposals summary to enable wider injection of H2 in EU gas networks" summarises the main findings of the HIGGS project, with a focus on WP4-6, and analyses the findings in order to finally produce key project statements that are relevant to target groups enabling the widespread injection of hydrogen into the gas transport networks..

Chapter 3 summarises the results of the practical tests carried out as part of the HIGGS project and places them in the context of further investigations. This chapter provides a compilation of the main results obtained in WP4, which are fully developed in deliverables D4.2, D4.3 and D4.4, and how they complement other research projects (e.g. SyWeSt H2). This chapter also presents the design of an injection facility, where the lessons learned in the development of the WP3 test facility are extrapolated to scaled-up facilities suitable for injection projects in real transport networks. It summarises the work carried out by FHA on Task 6.3.1 "Optimal design for H2 injection and mixing systems". The results and interpretations are therefore fundamental for assessing the technical feasibility of hydrogen injection into European gas transport networks.

Chapter 4 begins with a summary of the framework conditions for the Gas Package, which have been derived in detail in particular in Deliverable 6.2 and which are particularly relevant to the objectives of the HIGGS project due to the blending limits at cross-border interconnection points that are regulated there. The currently discussed limits are in the range of 2 to 5 percent by volume. The work of Redexis on Task 6.3.2 "Gas market and operational considerations", which is essentially based on a detailed survey of European TSOs, is then summarised. The views of the TSOs and their customers on the issue of blending hydrogen with natural gas are then explained and substantiated on the basis of the results of the survey carried out as part of D6.2 and publicly available statements. It is shown that the plans to set blending limits of 2 to 5% by volume at cross-border interconnection points as part of the Gas Package are in line with the available opinions of European TSOs. The chapter concludes with techno-economic considerations based on the work carried out in WP 5. This chapter is therefore important as it analyses and evaluates the regulatory and economic framework conditions for the use of hydrogen in the European gas transport networks and includes the opinions of the European TSOs. This deliverable D6.3 "Pathway and proposals summary to enable wider injection of H2 in EU gas networks" summarises the key results of the HIGGS project, with a focus on WP4-6, and analyses the lessons learned in order to ultimately make key statements of the project that are relevant to the target groups of this project.

The following chapter 5 presents the plans of the European TSOs to create a European hydrogen backbone and determines to what extent the planned capacities can meet the requirements calculated in D6.1 and D6.2 on the basis of national balances. It also explains why blending will play a role in the European gas network, even though the strategic transport of large quantities of hydrogen is likely to be via pure hydrogen pipelines. The analyses carried out show that the issue of hydrogen blending in the European gas transport networks has to be considered in a differentiated way, as a distinction has to be made between gas transport networks and gas distribution networks on the one hand, and between regions with different local conditions and strategies on the other hand.

Chapter 6 gives an update of the EU policies, national hydrogen strategies and standardisation from WP2. In implementation of the EU policies and the planning of the countries for their decarbonisation of the energy system, the transport (mobility), industry and – in general - society, 18 of the 27 EU Member countries have a national hydrogen strategy; 3 of the EU27 are in the draft stage; 7 have no strategy yet. Even if different in the level of details, they all express the national vision and ambitions for the development, research, production, infrastructure and application of hydrogen technology. Regarding blending the EU and legal frameworks are not (yet) very specific. Whether blending of hydrogen with natural gas or biomethane will play a role in the countries and which role is not

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

evident from all strategies. It is hinted to the significance of strategic decisions and the need of clear transition plans regarding the utilisation of pipelines to meet the energy demand at mid- and long term and on the other hand the orientation towards the future green hydrogen system.

Chapter 7 presents a list of important issues that need to be clarified for the rapid and broad ramp-up of the hydrogen economy at European level. Where possible, solutions and projects that deal with the clarification are described.

The findings from the chapters described lead to six key messages:

- #1 Blending hydrogen into the existing pipelines of the European gas transport network is technically feasible and safe up to 100% hydrogen.**
- #2 Hydrogen will play a crucial role in making Europe a climate neutral continent by 2045 and cross-border transport of hydrogen is necessary to enable Member States' national hydrogen strategies.**
- #3 Based on the current discussions on the Gas Package and also on the prevailing opinion of the European TSOs with simultaneous planning of a hydrogen backbone, it is unlikely that blending above 2 - 5% by volume will play a major role in the cross-border transport of hydrogen.**
- #4 The addition of hydrogen to the gas network will be a decisive factor both in the transport network and especially in the distribution network.**
- #5 H₂ concentration limits in European standardisation will allow blending in the grid at different levels.**
- #6 National legal framework and national and European technical standards are (still) in development**

1 Objective

The aim of this deliverable D6.3 is to summarise the main results of Task 6.3 ("Preparing a pathway and set recommendations towards a higher acceptance of H2 in the EU gas grid").

Task 6.3 consists of the following subtasks and objectives:

In **Task 6.3.1** ("Optimal design for H2 injection and mixing systems"), the aim is to prepare a working document containing the main aspects of the optimal design for hydrogen injection and blending systems, taking into account the results of Task 3.4 and the evaluation of the platform itself.

The objective of **Task 6.3.2** ("Gas market and operation considerations") is to compare the gas market and operational conditions for transmission networks with the main findings of HIGGS in this respect.

Task 6.3.3 ("Project findings with relevance for standardization of H2 in gas transmission grids") aims at collecting the relevant findings/proposals from Work Package 4 with the conclusions of the test campaigns and Work Package 5 with the corresponding techno-economic analyses. It also aims to provide an update on WP2 in relation to regulations, codes and standards as well as national hydrogen strategies.

Deliverable D6.3 is therefore intended to be the overall summary of the results and proposals of Work Package 6. It aims to take an overview of the framework conditions and address open issues that need to be considered by the target groups TSOs, DSOs, policy makers, standardisation bodies and gas associations for a rapid and widespread deployment of the hydrogen economy.

2 Introduction

The European Union has clearly identified hydrogen as an important element of the new EU-wide energy and resources strategy and has set a decisive course for the production of hydrogen in Europe, its import into Europe and the development and use of a suitable hydrogen infrastructure. The fact that large parts of the existing gas infrastructure can be retrofitted is a major advantage of this strategy. Due to specific geographical conditions, in particular for hydrogen production and import, and structural differences in demand, cross-border transport of hydrogen will be necessary in the future to meet demand and fully exploit the economic and environmental potential within the European Union.

Although the goal of widespread use of climate-neutral hydrogen in the European Union is clear, there are still a number of unanswered questions along the way. The HIGGS project provides answers to crucial questions regarding material compatibility, techno-economic assessments, injection potentials, regulations, codes and standards, and general framework conditions.

The HIGGS project addresses in a structured way relevant issues related to the use of hydrogen in gas transmission pipelines. WP2 addressed the legal, regulatory and technical aspects, e.g. by surveying the European TSOs on the characteristics of the existing gas transmission networks and by summarising the hydrogen strategies of the Member States of the European Union and the existing legal and technical framework. WP3 designed and commissioned the test facilities, which were then used in WP4 to test the compatibility of materials and components with different hydrogen blends up to 100%. WP5 developed techno-economic models and recommendations for the design of the future gas network. WP6 carried out analyses of the hydrogen injection potential and examined the current framework conditions at European level.

This Deliverable D6.3 summarises the main results and proposals of the project and analyses and evaluates them against the background of presenting the current status and describing a way forward to enable the widespread injection of hydrogen into the gas transport networks.

3 Technical feasibility of blending hydrogen into the gas transport network up to 100%

3.1 Summary of practical results from the HIGGS project and comparison with literature findings

The HIGGS project has developed and built an R&D test platform that mimics a small-scale transmission network. This platform has been used to carry out a range of tests on materials and components to answer open questions about their hydrogen compatibility. These include the following investigations:

- A. Gas tightness tests of representative valves of the natural gas grid with screwed and flanged couplings to identify potential leakages when operated with hydrogen.
- B. Constant displacement tests with API 5L steel specimen grades X42, X52, X60 and X70 for hydrogen embrittlement evaluation of representative carbon steels pipes in the natural gas grid.
- C. Inspection of welded sections of API 5L steel pipes with the magnetic particle testing method to detect surface-breaking discontinuities such as cracks and pits in the pipes after service with hydrogen.
- D. Inspection of equipment (pilot-operated pressure regulator, cartridge filter and turbine flow meter) components from the dynamic section for hydrogen damage evaluation.
- E. Inspection of components of the valves used in the gas tightness tests for hydrogen damage evaluation.
- F. H₂/CH₄ gas separation tests with a Pd-based membrane prototype.

Admixtures of 20 mol%, 20 mol% with H₂S and CO₂ and 30 mol% with H₂S and CO₂, as well as 100 mol% hydrogen were used for the investigations.

In combination with the constant displacement tests carried out in the R&D test platform, SSRT have been carried out in Tecnalía's laboratory. The SSRT tensile method has been used as a valuable primary screening method of materials.

The results of the HIGGS project should be evaluated in the context of other projects with similar or complementary approaches. In the DVGW project SyWeSt H₂, which was carried out by Open Grid Europe and MPA Stuttgart, fracture mechanics tests were carried out on a representative selection of pipeline and pipe steels used in Germany and Europe. The primary objective of the SyWeSt H₂ project was to

“investigate the applicability and transferability of the fracture-mechanical parameters specifically indicated in ASME B 31.12 for hydrogen as a transmission medium to the pipe materials featured in the German high-pressure gas pipeline grid” [1].

In addition to different steel materials, this project also analysed various pipe sections, different ages and material strengths in a total of over 200 tests. A servo-hydraulic testing system with an integrated H₂ autoclave was used in these tests. The standard settings for the tests were an H₂ pressure of 100 bar and a stress ratio R of 0.5. These two parameters were varied in individual tests. The main

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

test parameters were the minimum fracture toughness KIC and the crack propagation da/dN. An overview of the methodology used in the SyWeSt H2 project can be found in the project's final report [1].

Table 1 shows the results of the material survey in the HIGGS project, in comparison with the materials tested in the HIGGS project, on the one hand, and in the SyWeSt H2 project, on the other.

Table 1: Overview of the steel grades tested in HIGGS and SyWeSt H2

Pipeline materials according to results from survey in HIGGS	Tested steel materials in HIGGS	Tested steel materials in SyWeSt H2
A	No	Yes
B	No	Yes (St 35*)
X42	Yes	Yes
X46	No	Yes (StE320.7)
X52	Yes	Yes (L360NE/NB/360.7/NB)
X56	No	Yes (X56.7)
X60	Yes	Yes (L415)
X65	No	
X70	Yes	yes
X80	No	Yes (GRS550)
		Further materials tested
		L290 NE
		15k (St35)
		RR St43.7
		P355 NH/NL2
		StE480.7 TM
		14 HGS
		WSTE 420
		St53.7
		St60.7
		P460 NH
		L485 (ME/Schmelze 2)
		P355 NL1
		GJS400
		P460 QL1
		C22.3
		GS C25 N
		TStE 355N

This table shows that the steel grades, identified in the HIGGS project survey as significant in terms of quantity, were also tested in the SyWeSt H2 project, making it useful to compare the results.

D6.3 Pathway and proposals summary to enable wider injection of H₂ in EU gas networks

The HIGGS project has focused on developing an experimental test platform that replicates components and materials in a typical natural gas high-pressure network, on a smaller scale, but maintaining relevant operating pressures. The project is not just focused on the impact on materials of pipelines, but also on those of components and equipment of different nature.

Throughout the testing campaign, it was observed that basically all testing valves remained tight, exhibiting minimal hydrogen losses, despite variations in hydrogen content in the pipe. In the second experimental campaign with 20 mol% H₂, and trace impurities of H₂S, and CO₂, significant leakages, in the line containing flanged valves, were attributed to incorrect reassembly after the first experimental campaign. It was concluded therefore that valve reassembly should be entrusted to the manufacturer's expertise. Under 100 mol% H₂ service, the pressure oscillations, in the line, were higher compared to previous tests with hydrogen blends. However, it remained low enough to rule out potential leaks. The internal tightness of flanged valves was also assessed for 100 mol% hydrogen service, while plug valves' suitability requires further evaluation through complementary tests.

Inspection results post-exposure to various hydrogen mixtures showed no apparent damage in valves, pressure regulator, cartridge filter, and turbine gas meter components, except for significant blistering in the valve seat of the pressure regulator during the 30 mol% H₂ campaign, possibly due to a manufacturing defect because this issue was not found at higher concentration levels.

Regarding the gas separation tests, the Pd-based double-skinned membrane prototype exhibited excellent gas separation performance. Long-term stability experiments demonstrated stable permeate flow with hydrogen purity over 96 mol%. The membrane technology showed promise for hydrogen recovery and purification of low-concentration gas streams, but further development and validation, at larger scales and longer durations with real gas mixtures, were recommended.

Magnetic particle inspection of welded pipe sections and constant displacement tests on various steel specimens exposed to hydrogen blends showed no discontinuities, cracks, or pits, indicating no signs of embrittlement, after approximately 11,000 hours of exposure to hydrogen at different concentration levels.

Constant displacement test to study hydrogen embrittlement susceptibility of steels were performed with C-ring, 4-point-bend and CT-WOL specimens in HIGGS. No cracking was identified in any of the specimens, including type C-ring and 4pb, in the base material, the Heat Affected Zone (HAZ), or the welded material. These specimens were stressed at 100% of the material's yield strength, exposed to various hydrogen blends at 80 bar pressure, and tested for durations up to 3000 hours. Additionally, there was no observed crack propagation in CT-WOL specimens. As a result, it can be concluded that, in the tests evaluating the compatibility of steels using constant deformation specimens, there were no signs of embrittlement detected after the completion of the four experimental campaigns.

The previous tests were complemented with Slow Strain Rate (SSR) tests for a better assessment of embrittlement phenomena on carbon steels. The results of the SSR tests conducted in both air as a reference medium and in 100 mol% H₂ at 80 bar pressure yielded NTS (notched tensile strength) ratios ranging between 0.90 and 0.96. These ratios fall into the category of low sensitivity to hydrogen embrittlement. However, a considerable loss of ductility was observed in notch specimens, reflected in reduced RA values and changes in the morphology of the fracture surface. While specimens tested in air displayed a fully ductile fracture surface with dimple formations, areas of transgranular cleavage were detected on the periphery of specimens tested in hydrogen.

The degree of embrittlement varied depending on loading conditions (static or rising load) and the presence or absence of notches in the material. Generally, rising load tests produced higher embrittlement indexes. It is recommended to combine constant displacement tests, which allow for significantly longer exposure times, with rising load tests such as SSRT, fracture toughness, and fatigue

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

tests. This combination is particularly crucial for steel qualification or component design considerations.

In conclusion, according to the testing conditions selected in HIGGS, the high-pressure natural gas grid appears ready for transporting hydrogen at blending levels up to 100 mol%, but further research, especially in fracture toughness tests, is necessary for proper material certification (s. SyWeSt H2). The results of the experimental campaign performed in HIGGS are fully developed among the deliverables D4.2, D4.3 and D4.4, which can be found in the project website and in the Zenodo repository [2].

SyWeSt H2 project is just focused on the impact of hydrogen on the steel present in German transmission grid and it provides complementary tests to those performed in HIGGS to study hydrogen embrittlement phenomena. While hydrogen embrittlement in steels is studied through constant displacement tests (i.e. using C-ring, 4pb and CT-WOL specimens) and SSR tests, SyWeSt H2 relies on fracture mechanical tests, specifically static and dynamic fatigue crack growth tests with CT specimens.

Fracture-mechanical crack growth investigations within the SyWeSt H2 project came to the conclusion that “all pipeline steel grades investigated are fundamentally suitable for hydrogen transmission”. Additionally, fracture toughness was investigated showing that all investigated pipeline steel grades exceeded the minimum value as specified in ASME B 31.12, in the majority of the cases considered [1].

The significance of the results for the hydrogen suitability of steel pipelines in the transport network is impressively demonstrated by a calculation example which shows after how many years an existing crack in a steel pipeline will lead to failure of the component under the influence of hydrogen and under certain assumptions (Figure 1) [3].

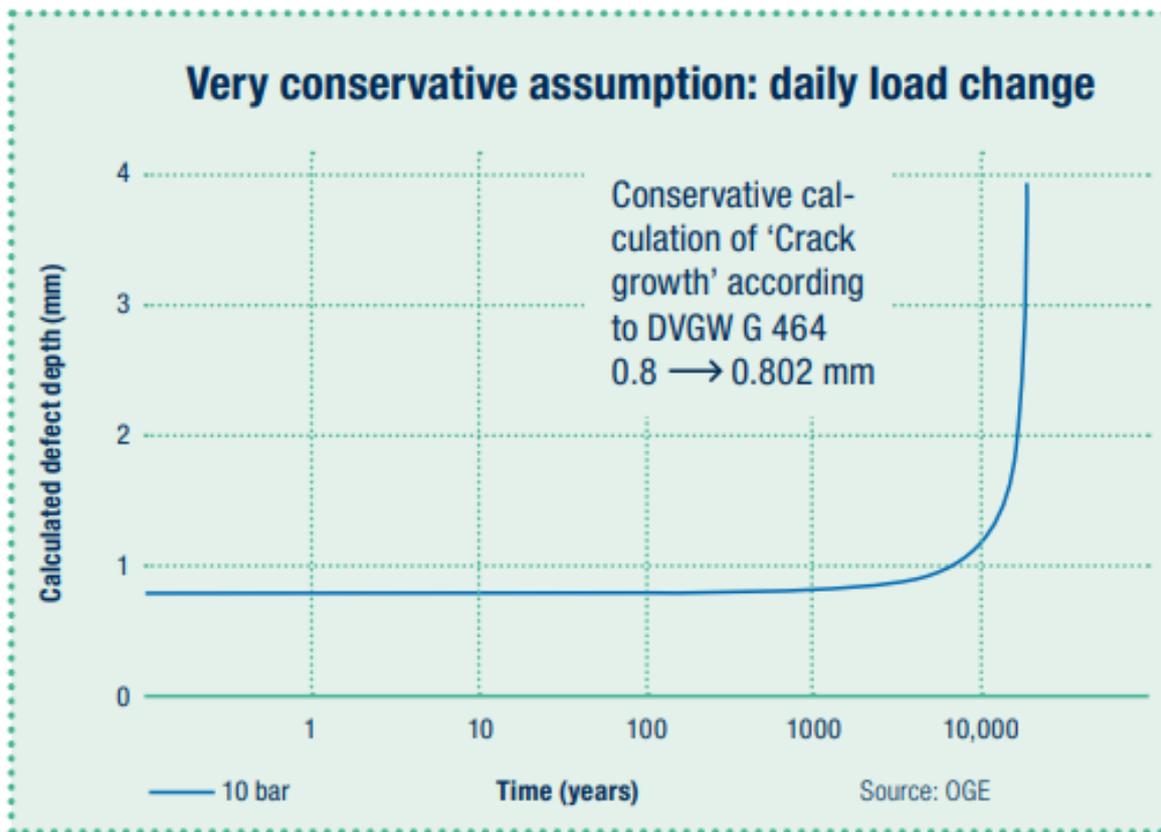


Figure 1. Calculation example regarding material compatibility according to SyWeSt H2 project (assumptions: DN: 600 mm, DP 67.5 bar, L 415, wall thickness 8 mm, defect 50 mm long and 0.8 mm deep, daily load change of 10 bar) [3]

On the one hand, the results show that even under conservative assumptions, the transport of hydrogen in steel pipelines does not harbour any safety-relevant risks under normal operating conditions of a transport network. On the other hand, they also show the importance of a sensible application of the specific values, such as in the DVGW regulations in G 464 [4]. The presented calculation example applies to the transport of 100 mol% H₂. Results for hydrogen blending can be derived from the findings regarding the variation of the hydrogen partial pressure.

The mechanical tests performed in SyWeSt H2 complement those conducted in HIGGS with pipe materials, covering a wide experimental range regarding hydrogen embrittlement on steels. Combining the results of both projects reinforces the conclusion that the European high-pressure gas grid are already suitable for operation with 100 mol % H₂, regarding material compatibility. Although technically feasible, European rules and criteria are still needed to establish a proper material certification. Specific future projects such as PilgrHYm (Clean Hydrogen Partnership, Horizon Europe, Project ID 101137592) can verify and elaborate the available technical findings from HIGGS and SyWeSt H2.

3.2 Optimal H₂ injection design

3.2.1 Introduction

Hydrogen injection facilities and mixing systems are those positions to be built in a natural gas grid to allow the entrance of hydrogen in the gas system. From the technical point of view, they are entry points, with the peculiarity that it is hydrogen and not natural gas what is being added to the grid. The design can follow the procedures of gas mixture systems, a fully developed technology, but adapted to the flow rates and particular characteristics of the gases to be mixed, hydrogen and natural gas, and to the particular regulatory and normative requirements that the corresponding gas system requires in each case for this type of installations.

HIGGS project has developed an experimental setup in WP3, in which blends of hydrogen in methane, as well as 100% hydrogen, are injected at high pressure (i.e. 80 bar) in a testing facility. Actual materials, components and equipment of the grid are exposed to hydrogen/hydrogen blends at high pressure in it. This experimental setup considers therefore an injection facility (called admixture system in previous WP3-WP4 reports) that can set the basis for the design of analogue setups in actual transmission positions. There are, however, several aspects that limit the direct extrapolation of the design to a “real installation” that need to be considered:

- HIGGS experimental platform is not connected to costumers. It has been built as an isolated grid for the tests.
- The experimental setup does not operate in a continues injection mode. The platform is filled with gas until the operating pressure is reached, and the injection is stopped afterwards.
- HIGGS operates at relevant transport pressure (i.e. 80 bar), but the gas flow is much smaller than in actual gas pipelines.

The goal in deliverable D6.3 is to develop the design of a hydrogen injection facility, overcoming the limitations and lessons learned in WP3-WP4, to provide useful guidelines to apply in an actual transport natural gas grid.

3.2.2 Regulatory background

There is currently no publicly available European specification for hydrogen injection into gas grids, neither as a blend with natural gas, nor as 100 % hydrogen. However, CEN/TC 234 has prepared a draft standard at stage for final approval in spring 2024 that can provide useful information for the task. The document prEN 17928-1 “*Gas infrastructure - Injection stations - Part 1 - General requirements*” contains normative requirements on the generic specifications for the injection of renewable gases into gas transmission and distribution systems operated with fuel gases (natural gas, bio-methane, SNG, hydrogen fuel gas, fuel gas mixtures), in accordance with European technical rules that ensure the interoperability of systems. It also applies to refueling stations that feed such gases back into upstream gas supply networks. Besides, the document prEN 17928-3 “*Gas infrastructure - Injection stations - Part 3: Specific requirements regarding the injection of hydrogen fuel gas*” specifies the technical safety requirements to be observed with respect to the chemical and physical properties of hydrogen fuel gas.

In the context of the interoperability and safety of systems the draft standards give reference to the following standards:

- EN 437, Test gases — Test pressures — Appliance categories.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

- EN 764-7, Pressure equipment - Part 7: Safety systems for unfired pressure equipment.
- EN 1081, Resilient floor coverings — Determination of the electrical resistance.
- EN 1127-1, Explosive atmospheres — Explosion prevention and protection — Part 1: Basic concepts and methodology.
- EN 1555-5, Plastics piping systems for the supply of gaseous fuels — Polyethylene (PE) — Part 5: Fitness for purpose of the system.
- EN 1594, Gas infrastructure — Pipelines for maximum operating pressure over 16 bar-Functional requirements.
- EN 1776, Gas infrastructure — Gas measuring systems — Functional requirements.
- EN 1998, National Annex - Nationally determined parameters - Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings.
- EN 10204, Metallic products — Types of inspection documents.
- EN 12007-1, Gas infrastructure — Pipelines for maximum operating pressure up to and including 16 bar — Part 1: General functional requirements.
- EN 12007-3, Gas infrastructure — Pipelines for maximum operating pressure up to and including 16 bar — Part 3: Specific functional requirements for steel.
- EN 12186, Gas infrastructure- Gas pressure regulating stations for transmission and distribution —Functional requirements.
- EN 12405, Gas meters — Conversion devices — Part 1: Volume conversion.
- EN 12327, Gas infrastructure — Pressure testing, commissioning and decommissioning procedures — Functional requirements.
- EN 12732, Gas infrastructure — Welding steel pipework — Functional requirements.
- EN 13306, Maintenance – Maintenance terminology.
- EN 13774, Valves for gas distribution systems with maximum operating pressure less than or equal to 16 bar - Performance requirement.
- EN 14141, Valves for natural gas transportation in pipelines — Performance requirements and tests.
- EN 14382, Safety devices for gas pressure regulating stations and installations — Gas safety shut-off devices for inlet pressures up to 100 bar.
- EN 15001-1, Gas Infrastructure – Gas installation pipework with an operating pressure greater than 0,5 bar for industrial installations and greater than 5 bar for industrial and non-industrial installations – Part 1: Detailed functional requirements for design, materials, construction, inspection and testing.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

- EN 15446, Fugitive and diffuse emissions of common concern to industry sectors - Measurement of fugitive emission of vapours generating from equipment and piping leaks.
- EN 16723-1, Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network — Part 1: Specifications for biomethane for injection in the natural gas network.
- EN 16726, Gas infrastructure — Quality of gas — Group H.
- EN 17649, Gas infrastructure - Safety Management System (SMS) and Pipeline Integrity Management System (PIMS) - Functional requirements - Functional requirements.
- EN 17659, Welding - Multilingual terms for welded joints with illustrations (ISO 17659:2002).
- EN 50495, Safety devices required for the safe functioning of equipment with respect to explosion risks.
- EN 60034-1, Rotating electrical machines — Part 1: Rating and performance.
- EN 60079-10-1, Explosive atmospheres — Part 10: Classification of areas-Explosive gas atmospheres.
- EN 60079-14, Explosive atmospheres — Part 14: Electrical installations design, selection and erection.
- EN 60947-5-1, Low-voltage switchgear and control gear — Part 5-1: Electromechanical control circuit devices.
- EN 61508-1, Functional safety of electrical/electronic/programmable electronic safety-related systems -Part 1: General requirements (IEC 61508-1:2010).
- EN 61508-4, Functional safety of electrical/electronic/programmable electronic safety-related systems — Part 4: Definitions and abbreviations (IEC 61508-4:2010).
- EN 61511 (all parts), Functional safety — Safety-instrumented systems for the process industry sector.
- EN 62305 (all parts), Protection against lightning.
- CEN/TS 17977, Gas infrastructure - Quality of gas - Hydrogen used in rededicated gas systems.
- EN ISO 6974, Natural gas — Determination of composition and associated uncertainty by gas chromatography.
- EN ISO 9001, Quality management systems - Requirements (ISO 9001:2015).
- EN ISO 10675, Non-destructive testing of welds — Acceptance levels for radiographic testing — Part 1: Steel, nickel, titanium and their alloys.
- EN ISO 10715, Natural gas - Sampling guidelines.
- EN ISO 12213, Natural gas — Calculation of compression factor.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

- EN ISO 12944, Paints and varnishes — Corrosion protection of steel structures by protective paint systems.
- EN ISO 13849-1, Safety of machinery - Safety-related parts of control systems - Part 1: General principles for design (ISO 13849-1).
- EN ISO 14001, Environmental management systems - Requirements with guidance for use (ISO 14001:2015).
- EN ISO 14090, Adaptation to climate change - Principles, requirements and guidelines.
- EN ISO 50001, Energy management systems - Requirements with guidance for use (ISO 50001:2018).
- IEC 60364 (all parts), Low-voltage electrical installations.
- ISO 1217, Displacement compressors - Acceptance tests.
- ISO 14687, Hydrogen fuel quality - Product specification.
- ISO Guide 51, Safety aspects — Guidelines for their inclusion in standards equipment, information for use and installation, and training.
- ISO/TR 15916, Basic considerations for the safety of hydrogen systems.
- ASME B 31.12, Hydrogen Piping and Pipelines.

Besides, relevant other relevant standards and codes that can be helpful for such an installation due to be handling with gaseous hydrogen are the following:

- NFPA2. Hydrogen technologies code.
- UNE 181001:2010. Hydrogen technologies. Terminology.
- CGA G-5.5. Hydrogen Vent Systems.
- EN 17127:2020. Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols.

3.2.3 Main considerations in the design of the injection facility

An injection facility should be coupled to an existing transport facility, and it must include a hydrogen reception facility to manage the hydrogen provided by a producer via pipeline. Besides, a gas injection and gas analysis module must be considered for the successful integration of hydrogen in the grid. The injection process must be governed by a control loop supervising all units as a whole. A schematic overview of an injection facility is depicted in Figure 2. The different considerations to be considered in the design of an injection facility are developed in the following subsections.

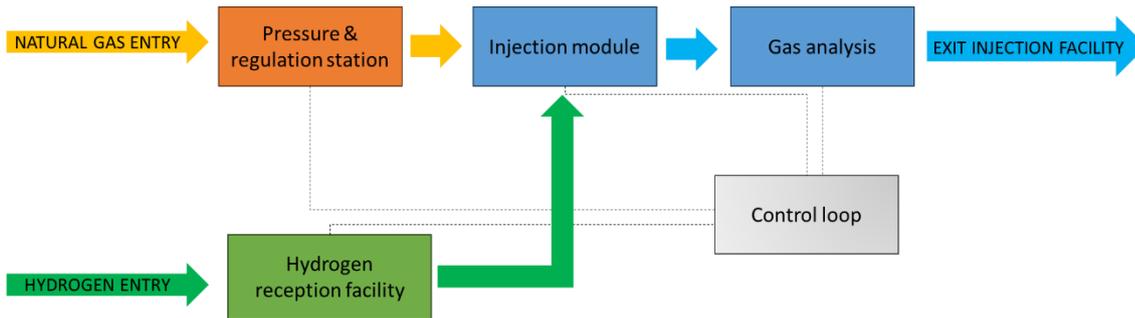


Figure 2. Schematic overview of a hydrogen injection facility

3.2.3.1 Location in the grid

Injecting hydrogen into the gas grid needs an accurate control of flow, temperature and pressure conditions. Owing to this reasons, pressure regulation and metering stations are the best location to build an injection site. The flow conditions at the exit of the station are clearly identified and the signals can be used for the control loop of the injection facility. The basic scheme of a pressure regulation station can be seen in Figure 3. [5] The injection facility is advised as an add-on of this transport facility.

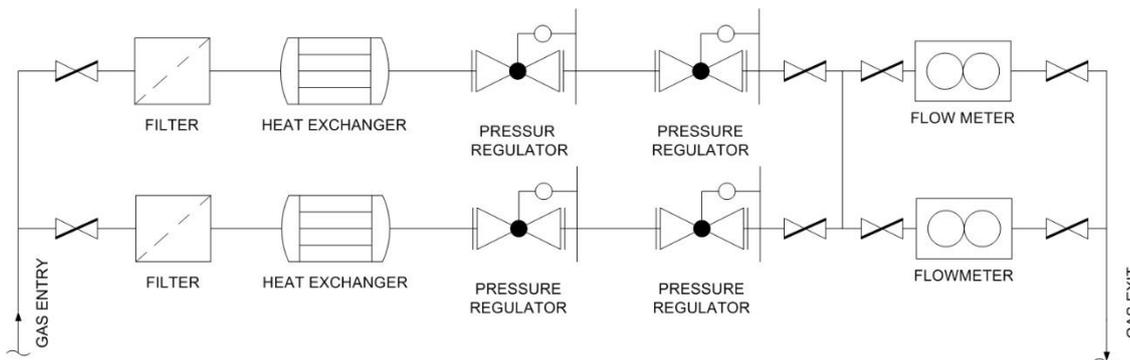


Figure 3. Simplified scheme of a natural gas pressure regulation station

3.2.3.2 Reception terminal

The nature of the reception facility will highly depend on the way hydrogen is delivered to the injection point. If hydrogen is supplied via pipeline at low pressure from the production site (e.g. at 30 bar as most state-of-art electrolysers currently operate), it will be necessary to install hydrogen compression systems as well as pressurised hydrogen storage systems at this facility. If on the contrary hydrogen is supplied at high pressure (higher than the pressure of the gas pipeline into which it is injected), the reception facility may not need such hydrogen compression units and the own hydrogen pipeline will aim as buffer itself. The necessary compression power depends on the dimensions of the hydrogen pipeline (i.e diameter) and the suction pressure, and it must consider the electrical power available on site for a right design. In the case that compressing hydrogen is found necessary owing to the operational parameter of the injection station, it is advisable to do it at the production point instead of at the reception terminal. This way smaller diameters can be used in the main part of the hydrogen pipeline, which will be in such case that operating at high pressure.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Although building a compression unit may not be compulsory if hydrogen is supplied at high pressure, it is advisable for a continuous operation of the injection station. The compression system allows to achieve a hydrogen pressure higher than the operating pressure of the natural gas pipeline. If such station is not considered, the injection of hydrogen will have to be stopped when the hydrogen supply pressure drops below the operating pressure of the gas pipeline. A scheme of a hydrogen reception terminal is depicted in Figure 4.

The requirements of hydrogen in terms of flow and gas quality must comply with sectoral legal and regulatory requirements. As stated above, it is advisable to supply hydrogen at higher pressures than the operating pressure of the gas pipeline. In cases where the hydrogen supply pressure is lower, high compression stress will be required to allow the injection. The lower the pressure of supply of hydrogen, the greater the compression stress will be required. Optionally, the TSO can install an analysis unit to verify that the quality of the hydrogen provided meets the specifications. The metering equipment must meet the national legal metrology requirements.

The compression unit should work at suction pressures between the minimum required pressure and the MOP of the hydrogen supply grid (eg. 30 bar) and pump the gas into a high-pressure buffer operating over the MOP of the gas pipeline. The design pressure and volume of this buffer may differ depending on the quantity of hydrogen to inject, the way of injection (constant concentration vs. constant flow, see section 3.2.3.7) and the flow and pressure of the natural gas that circulates through the gas pipeline. In order to simplify the engineering project, it is advised to design this buffer with the lowest volume possible.

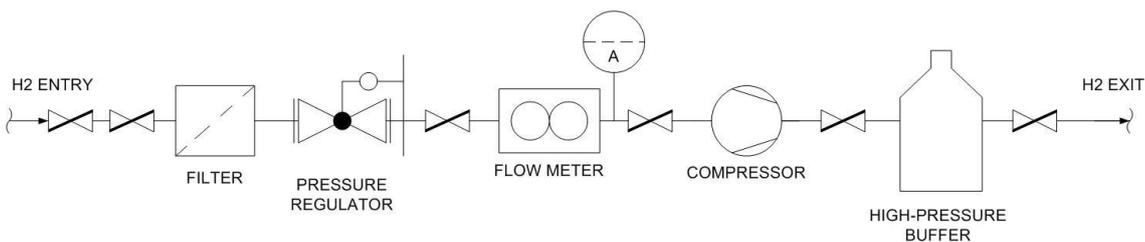


Figure 4. Schematic scheme of a hydrogen reception terminal

3.2.3.3 Injection setup

The injection setup is the part of the injection facility in which hydrogen physically enters the natural gas pipeline. It is the part connecting the reception terminal with the gas pipeline (see scheme in Figure 5). The exit flow of the injection facility must comply with the requirements of the grid downstream regarding composition, pressure, and temperature. Requirements for odorization must be considered. [6, 7] At the exit of the high-pressure buffer, the pressure and flow of hydrogen are regulated to the desired parameters and hydrogen is fed to mixing tee installed in the gas pipeline. For safety reasons it is advisable to build a derivation in the gas pipeline for the injection. This way, the original gas pipeline can work as security by-pass in case the injection may be interrupted.

The mixing tee can be as static mixer if the H₂/NG blend is difficult to achieve. The blend must be homogeneous before the analysis point at the very end of the installation. For whole repurposed gas pipelines (i.e. 100 % hydrogen transport) static mixers are not necessary. The pressure of hydrogen prior injection must be at least that of natural gas to avoid backflow in the hydrogen line.

Analysing the gas composition at the very end of the facility is necessary to ensure that the right gas quality will be accomplished downstream. This gas analysis should consider the following aspects: [6, 7]

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

- It has to measure the composition parameters (i.e. gas composition) as required by national regulations, taking into account admissible limit values.
- It has to calculate the calorific value following national regulations, as well as other relevant physical parameters (e.g. density).
- The sampling procedure should follow the EN ISO 10715 standard, considering the sample conditioning, analysis and purging.
- It should be able to handle a database with the measurements.

Gas chromatography has a slow response due to the long analysis times (minutes) and discontinuity in the measurements. It is more advisable to use alternative technologies for continuous online analysis, such as the measuring changes in the gas density, which is directly related to the content of hydrogen in the blend.

If the gas composition goes beyond or below the admissible range, the analyser must send an alarm to the PLC to shut-off the injection and vent the gas.

The compressibility factor should be also calculated following the EN ISO 12213 and EN 12405 standards. Volume converters calculate the volumetric flow rate of gas under standard conditions using a set of state equations. [6, 7] The SGERG-88 and AGA8 equations ensure calculation accuracy for hydrogen concentrations below 10 mol%. The GERG2004/08 can be used for concentrations below 40% mol. Both AGA8 and GERG2004/08 require the molar composition of the gas to perform the calculation [8].

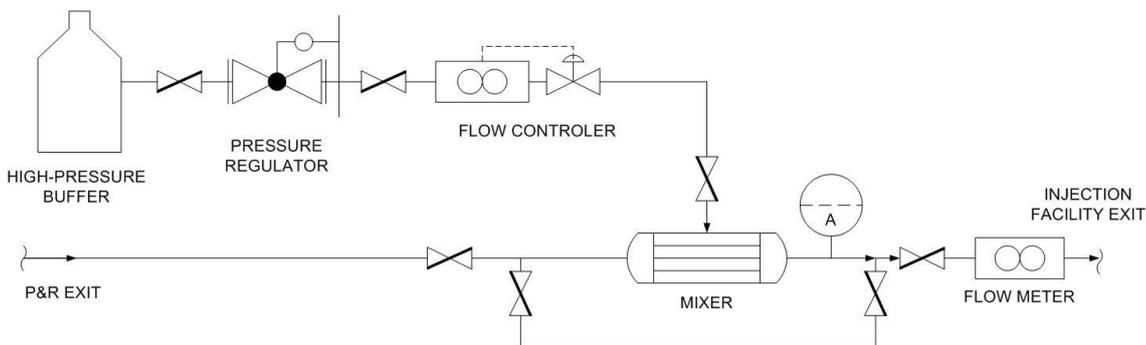


Figure 5. Schematic view of the injection setup

3.2.3.4 Control loop

The injection facility needs a control loop to:

- Manage the flow of hydrogen to inject, controlling the relevant parameters (flow, pressure and temperature).
- Calculate the composition of gas at the exit of the station and proceed depending on the deviations.
- Trigger safe modes when relevant parameters reach dangerous levels (e.g. venting the gas in case of overpressure or activating the natural gas by-pass).

The control loop should be linked to that of the pressure regulation station so that the facility can be operated as a whole. The control loop can perform a direct or indirect operation. It is desirable to

choose the direct operation so that the quality of the blend can be controlled. The PLC must regulate the opening degree of the valve supplying hydrogen to the mixer.

3.2.3.5 Odorisation

No odorization system should be needed in injection setups. In some countries, such as Germany, natural gas is not odorized at transmission level, but in distribution grids. For the countries odorising in high-pressure grids (e.g. Spain), the natural gas already contains the odorant. It is, however, necessary to verify that after blending natural gas with hydrogen the concentration of odorant in the resulting mixture does not drop below the minimum legal limits. For the case of 100 mol% hydrogen transport, the need for odorization is still not clear enough with the current regulation.

3.2.3.6 Emergency measures

The *Working Draft of prEN xxx-1 (WI 00234087) Gas infrastructure - Injection stations - Part 1 - General requirements* states that injection facilities shall be equipped with an emergency shut-off system. The emergency system must close the lines upstream and downstream the station in case of an emergency shut-off or energy failure. A remote-control acknowledgement and deactivation of the emergency shut-off system is not advised.

In case of overpressure, the compressor or other source of overpressure shall be switched off if the set limit value is surpassed. The compressor should be switched off before the safety-relief valve are shot. The pressure protection of pipelines should be defined according to the EN 12007-1 and EN 1594 standards.

Likewise, if the working pressure drops below the minimum allowed pressure shut-off valves must be actuated. If the inlet pressure of compressor is too low, the compressor shall be disconnected by safety devices.

The temperature in the line must be also monitored with temperature transmitters and safety devices must act if the temperature range goes beyond the operational limits.

The injection setup must be equipped with gas detectors that can check the presence of fuel gases in air. These devices should comply with the European Directive 2014/34/EU.

Finally, if the gas composition analysis at the end of the injection facility does not match the specifications of the TSO, the gas must be vented so that it does not enter the main gas grid. The venting pipes should be connected to a manifold. The diameter of this manifold must be designed to avoid reaching the erosion velocity, and above all, the self-ignition velocity of hydrogen. It will be in all events bigger than the individual pipes connected to it.

3.2.3.7 Operation mode

There are two ways to operate an injection facility according to the final concentration of hydrogen after the mixing point: constant concentration and constant flow.

In the constant concentration mode, the level of hydrogen in the blend must remain constant. Since the flow of natural gas in a transport facility is not even, but varies depending on the consumption downstream, the control loop of the injection facility must adapt the flow of hydrogen and its pressure to the readings that the pressure regulation station provides. The control loop becomes more complicated because it is necessary a fast and constant data acquisition so that the level of hydrogen becomes accurate.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Pros:

- A constant hydrogen concentration will facilitate billing issues.
- A higher acceptance rate at customer level (at least for some customers).

Cons:

- Control loop is more difficult.
- A varying hydrogen flow means the need for more storage capacity prior injection to manage flow peaks.
- Low feed-in in times of lower offtake (seasonality).

In the constant flow mode, the injection facility feeds the same amount of hydrogen in the gas pipe. Due to the hourly variation of natural gas flow mentioned above, the concentration of hydrogen in the blend will vary depending on the moment of the day and the day of the year. The control loop of the injection facility is easier, but it is necessary to define the hourly flow profile of natural gas as good as possible so that the concentration of hydrogen in the blend gets between the maximum and minimum tolerated intervals.

Pros:

- Easier control loop.
- The amount of hydrogen to manage is constant. Smaller storage and easier supply.

Cons:

- Hydrogen concentration in the grid is an interval. Wobbe index, as well as other properties will vary making billing more difficult.
- Need for an accurate profile of natural gas flows.

Both approaches are technically feasible, but the constant flow methodology is more realistic because it adapts better to the dynamic nature of transport grids.

3.2.3.8 Explosion protection

The ATEX analysis of the equipment installed must be performed according to EN 1127-1 or to national standards/ or regulations. Likewise, a risk analysis owing to explosive atmospheres must be performed, classifying hazardous areas in zones following the EN 60079-10-1 standard. [6, 7]

3.2.3.9 Overall design of a hydrogen injection facility

This section shows the design of an exemplary hydrogen injection facility based on the considerations described in the previous sections. Its P&ID diagram is depicted in Figure 6.

The control loop is responsible for data acquisition in the original natural gas line to monitor the pressure and meter the flow, transforming it to normal cubic meter units using volume converters. The control loop is also responsible for monitoring the pressure and flow of hydrogen supply, analysing its composition to verify that it meets the required standards. The hydrogen compression unit

D6.3 Pathway and proposals summary to enable wider injection of H₂ in EU gas networks

should be linked to the general control loop to manage the amount of hydrogen stored and its conditions.

Another important role of the control loop is managing the injection. It has to operate the flow controller to inject the desired amount of hydrogen in the grid depending on the operational mode (constant flow or constant composition) and monitor the gas composition before the gas exits the facility. The control loop can actuate on the four solenoid valves to allow or interrupt the injection.

The design does not consider metering the flow downstream the mixer because the flow of natural gas and hydrogen are known parameters, being sufficient to close the mass balance. In any event, a new device can be added if the TSO finds it useful to replicate the data and gain confidence in the facility.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

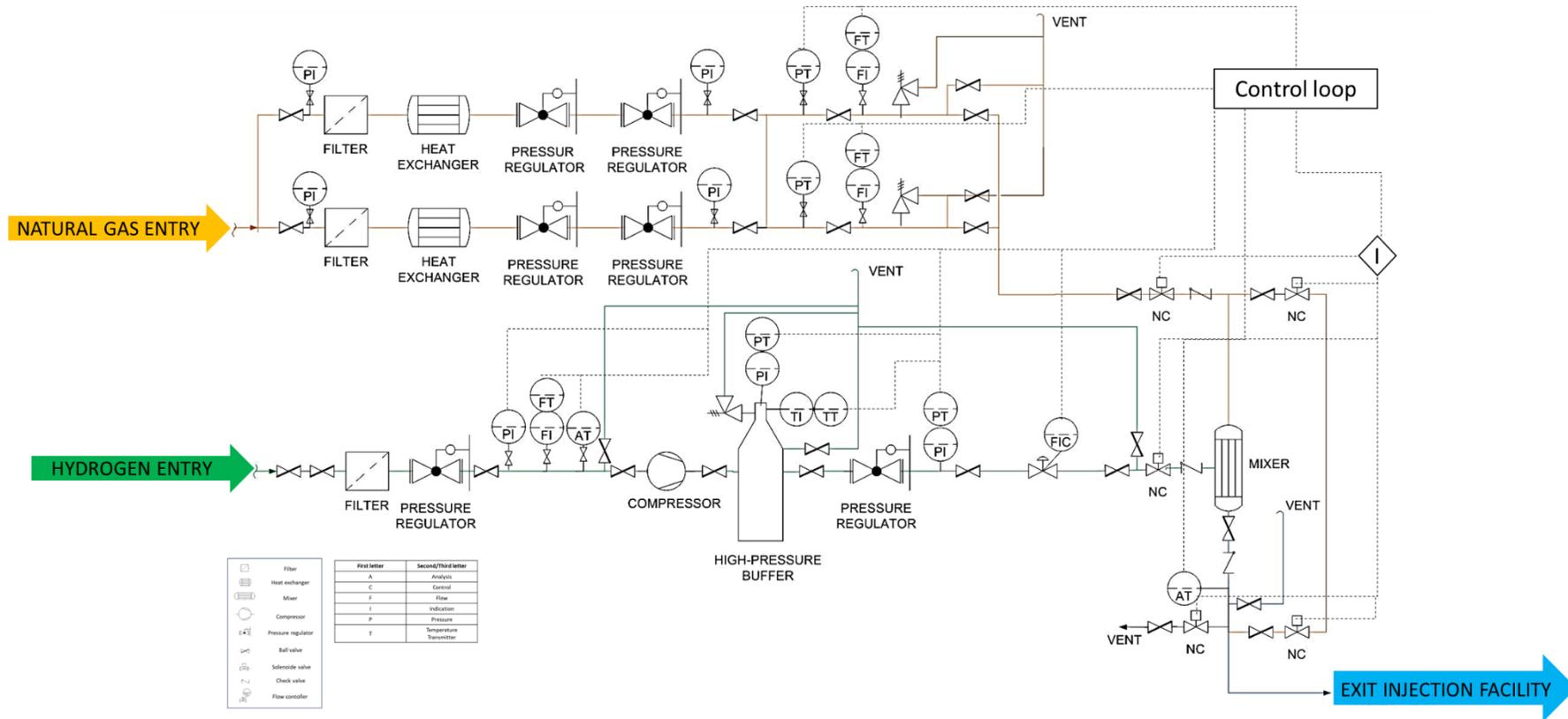


Figure 6. Schematic diagram of the complete design of a hydrogen injection facility

4 Framework and boundary conditions for blending hydrogen into the natural gas transport network at European level

4.1 Regulatory framework and boundary conditions at European level

At the time of writing, the **Gas Package** is in the trilogue and thus, in final negotiations between the institutions of the European Union. With regard to blending at border crossings, an upper limit of between two and five per cent by volume is emerging. It can be assumed that there will be a) the possibility to agree on higher blending rates through corresponding agreements between neighboring transmission networks and b) the possibility to allow higher blending rates in national networks.

This presumed orientation of the Gas Package towards blending means that a strategic transport of large quantities of hydrogen from countries with a high hydrogen production potential to countries with a high hydrogen demand is difficult or unlikely. This also directly strengthens the case for pipeline transport of pure hydrogen within the European Union.

It is conceivable that, in some places, bilateral or multilateral agreements will be concluded to agree on higher blending rates, for example where high production meets low transport capacities for pure hydrogen and limited uptake by the distribution network. This may be the case, for example, with single-line pipeline connections. The same applies to transport on national networks. In both cases, however, appropriate concepts must be developed to ensure that there is no "spill-over" of unacceptable hydrogen concentrations into neighboring areas of the transport network. At the same time, it is crucial for the transport network operators to deliver gas of compatible quality to the customers.

It is important to emphasise that the blending of higher concentrations at distribution network level is planned at various points and is possible according to national specifications and regulations (see National Hydrogen Strategies, 6.2). In this way, the various customers of the distribution grid can gradually experience increasing decarbonisation. Furthermore, blending at distribution grid level significantly increases the flexibility of hydrogen uptake and the necessary link between renewable energy production and the gas grid. Blending with natural gas in the distribution grid will only be a transitional solution on the way to the pure use of climate-friendly gases and climate neutrality in the European Union. It is more likely that distribution networks will start by blending hydrogen with natural gas and then gradually move to 100% hydrogen or 100% climate-friendly gases. In the latter case, blending with climate-friendly methane (e.g. biomethane) is also likely. However, the exact solution will ultimately depend on local conditions.

4.2 Harmonisation of gas market and operation

In order to compile the different considerations regarding the gas market, and the operation and maintenance of natural gas transmission grids, the methodology follows as described below.

Redaxis, as TSO, has prepared a list that considers different aspects that affect day-to-day gas operation in the above-mentioned areas, focusing on the operation of natural gas transmission pipelines in Spain. This list is divided in two parts, one focused on referring to the normal operating conditions with natural gas and the other, on how these aspects could be affected once hydrogen is injected into the grid.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

The two parts mentioned, one for natural gas and one for hydrogen, are presented in Excel format (Figure 7 and Figure 8), and DVGW disseminated them as a questionnaire to several TSOs and national and European gas associations, to collect their perspective at national and European level. The dissemination of these aspects has the aim of:

- Finding out which aspects of those presented apply to other countries.
- Allowing the surveyed TSOs to add those aspects that haven't been considered.
- Finding out the particularities of each aspect according to the country, the entity which is responsible for it and in which documents (standards/regulations/codes) it is reflected.

Fundamental aspects for the operation and maintenance of natural gas transmission grids					
ID	Application area	Aspect	SPAIN		Reference documentation /standards/ regulations/codes
			3 Description / Definition	4 Transmission operator responsibility	
1	1 Operation	2 Odourisation	3 Gas must be odourised so that any leak is easily detectable to the normal human nose in a mix with a concentration of one fifth of the lowest limit for inflammability. The odorant used must meet the conditions that are described in the PD-01 section 9.2.	4 The transmission companies for the primary network will deliver odourised natural gas at the entry points to the gas transmission system, at entry point to the distribution network and to consumers directly connected to their networks. The odourised gas that they will deliver have to follow the criteria that are describes in the PD-01 section 9.3.	5 NGTS PD-01 section 9

Figure 7. Example of one of the aspects considered for the operation and maintenance of natural gas transmission grids. 1) Area of interest in which the aspect to be studied is included. It could be operation, maintenance or market. 2 & 3) Aspect to analyse and its description and characteristics according to the documentation. 4) Description of the transmission operator responsibility that is established in the documentation. 5) Reference where all the parameters of the aspect are defined.

Considering Hydrogen injection			
Aspect	Priority level	Considerations about the use of hydrogen in NG grids	Suggestions about new codes, standars and specifications
Odourisation	1	Importance of studying the combined effect of odorants (usually with Sulfur) and H2 on gas grids. Identification of suitable odorants.	H2 odorization regulations.

Figure 8. Example of the aspect's considerations when hydrogen injection into the transmission grid takes place.

In total, 51 aspects have been analysed, which have been organised into three categories: operation, maintenance and market, as follow:

- 38 aspects related to the operation of natural gas grids.
- 7 aspects related to the maintenance of natural gas grids.
- 6 aspects related to the gas market.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

The classification into three categories has been made to discretise and simplify the analysis, although there are aspects that could be included in two or even three of the categories. For example, "Gas measurement" is included as an operation aspect, although this equipment requires specific maintenance guidelines, and gas measurement is also essential for the market.

Once Redexis finished the analysis of all these aspects, the table obtained was disseminated among the stakeholders. The questionnaires that have been received are from countries in the following regions: South Europe, Middle Europe and Northern Europe.

Finally, to be able to establish the particularities of each aspect, the entity which is responsible of them, the effect on this considerations once hydrogen is injected in natural gas transmission networks, and to be able to elaborate suggestions for their inclusion in new codes, specifications and standards, or in the revision of existing ones, during the analysis of the above-mentioned aspects, not only the answers received to the questionnaire were taken into account, but also publicly available information, as the seventh report prepared by the Council of European Energy Regulators (CEER) and the Energy Community Regulators (ECR), regarding the Benchmarking Report on the Quality of Electricity and Gas Supply [9], or the report "Odorisation of Natural Gas and Hydrogen Mixtures" prepared by MARCOGAZ [10].

4.2.1 Aspects for the operation of natural gas transmission grids

4.2.1.1 Odorisation

In some countries natural gas must be odorized, which means that a substance known as odorant must be injected into the natural gas to give it a characteristic smell, so that any leak is easily detectable to the human nose.

In some countries, such as Spain, the TSOs are responsible for delivering odorized natural gas at the entry points to the gas transmission system, at the entry points to the distribution grid and to consumers directly connected to their network, which means that they not only have to odorize the natural gas, they must ensure that the odorant concentration in the natural gas is always above the minimum established in regulations. This value varies depending on the country and the entry point considered.

In Germany for example, the TSOs have the same responsibility, but they only odorize the distribution grid, not the transmission grid. Other differences are in the odorant used and in their concentration. In Poland and Czech Republic happens the same as in Germany, only the distribution network is odorised, the difference between these countries is that in these two, the DSOs (Distribution System Operators) are responsible for odorising the natural gas. In Malta, the situation is the opposite, as natural gas is only used for power generation, so odorization is not mandatory.

In Figure 9, it can be seen in which countries it is mandatory to odorise the transmission grid, the distribution grid or both.

Regarding the odorisation, once hydrogen is injected into the natural gas transmission grid, it is important to study the combined effect of odorants and hydrogen on the gas grids and if large shares of hydrogen can mask the odorant. It is also needed to identify the best suitable odorants.

If countries odorised at transmission or distribution level, it is expected that they will continue doing it once hydrogen is injected into the grid. But in the questionnaires received, some TSOs mention the possibility of no odorisation the gas when it is 100% hydrogen.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

MARCOGAZ’s Odourisation Working Group prepared the report “Odourisation of Natural Gas and Hydrogen Mixtures” [10], in which they analyse the impact of odorizing the transmission grid when blending natural gas with hydrogen. The report shows that sulphur based odorants like THT (Tetra-HydroThiophene) or mercaptans seem likely to no react with hydrogen at gas distribution operating conditions. They also highlight the importance of choosing the odorant to inject, as it cannot affect the gas density and the vapour pressure.

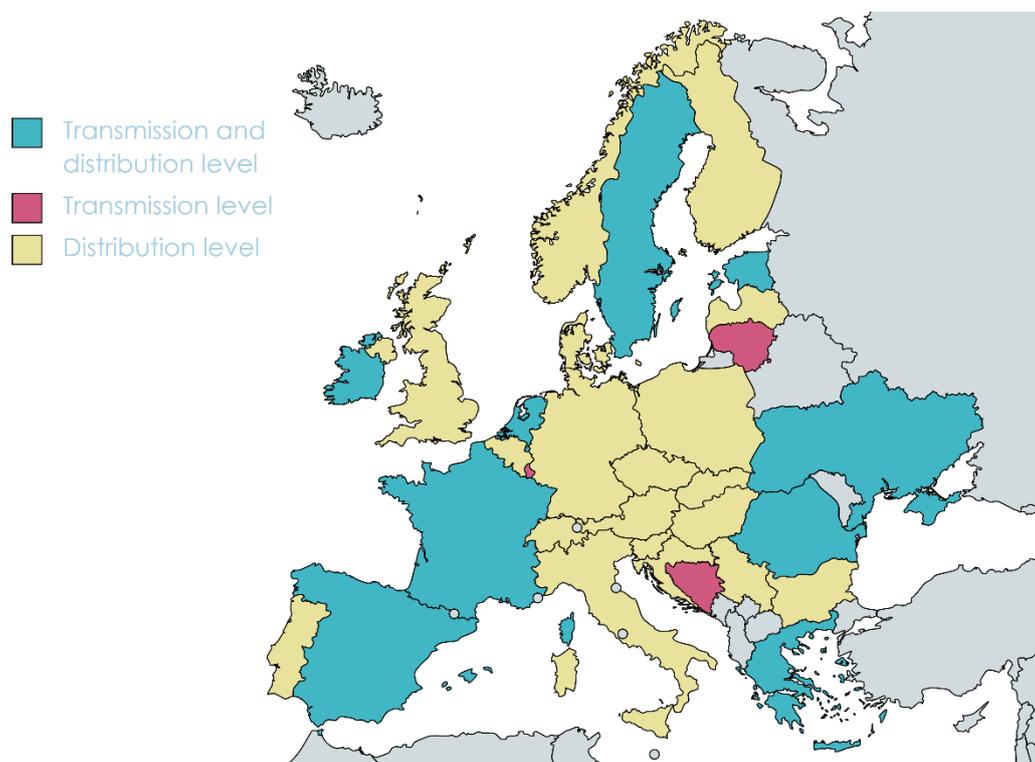


Figure 9. Map of European countries according to where they odorise natural gas.

4.2.1.2 Gas measurement

Process of determining the amount of gas that passes through a specific point in the system, where a measuring equipment has been installed. Gas measurements are made at entry, exit or connections points of the natural gas transmission system and the results can usually be controlled using dispatch software.

The TSOs are responsible for measuring gas in their facilities, including the installation tasks of the necessary measurement equipment and auxiliary systems, their operation and maintenance, in accordance with specific regulations. They are also responsible for transmitting the measures to the technical managers of the gas system or other bodies, in those countries where these figures exist.

When injecting hydrogen into natural gas networks, it has to be considered that the gas measurement must be carried out with certified equipment, valid for the different percentages of hydrogen allowed in the mixture with natural gas, and through appropriate measurement protocols to the gas mixture. For low blending percentages, most of the current equipment may be valid; for higher percentages, special measuring equipment will be necessary.

D6.3 Pathway and proposals summary to enable wider injection of H₂ in EU gas networks

This measuring equipment may require different maintenance and calibration than those for natural gas, so existing procedures have to be adapted to this new equipment and the new operating conditions.

Therefore, changes to the codes and measurement specifications should be necessary to make them valid for natural gas and hydrogen blends, and 100% hydrogen.

4.2.1.3 Gas quality analysis

Process of determining the quality of the gas that passes through a specific point in the system, where an analysis equipment has been installed. All gas that is injected into the gas system of most of the countries must meet certain gas quality requirements defined in the corresponding regulations, to ensure that the gas delivered to the consumer conforms to established physical and chemical parameters, and that it does not contain dust particles or any other impurity, in quantities that may be harmful to the health of consumers or damage their facilities. These gas quality values are also essential for billing processes.

In general, it is the technical manager of the national gas system who establishes at which specific points the gas quality needs to be measured. In some countries, these points are determined by the TSOs themselves. The owners of these points, producers, owners of regasification plants and international connections, and TSOs, are obliged to install the gas quality control equipment, and to carry out its periodic control to ensure that it is functioning properly. They are also responsible for reporting gas quality values to the technical manager and other bodies.

Gas quality analysis equipment must be suitable and certified to measure hydrogen percentages according to the levels injected into blending with natural gas, or specific for hydrogen in the use of dedicated hydrogen transport network. For low mixing percentages it will be necessary to adapt existing chromatographs and other equipment. For higher percentages, new equipment will be necessary. This equipment may have specific maintenance and calibration guidelines.

4.2.1.4 Minimum guaranteed pressures

The gas transmission grid must be designed and sized to guarantee a minimum pressure at all connection points with other grids and with directly connected consumers, for the correct and safe operation of the system. The grid operation pressure must be operated at a pressure equal to or greater than the specified minimum pressure.

The value of the minimum guaranteed pressure will depend on the type of transmission gas pipeline and the facilities connected downstream. Depending on the country, these values are established in national regulations or in agreements for connection to the transmission network. In Spain, the natural gas transmission grid shall be designed so that it is able of maintaining a minimum pressure that will be 16, 30 or 40 bar, depending on the type of the grid and the existing connection points, being one of these values the minimum pressure allowed in that part of the grid. In Germany, this value is 16 bar for the whole grid. In Table 2 the information collected for some countries, regarding this aspect is presented:

Table 2. Minimum admissible pressure established for some European countries.

Country	Minimum admissible pressure
Belgium	Not established at regulatory level.
Croatia	45, 70 bar depending on the operating pressure.
Czech Republic	40 bar at border exit points, according to contractual pressures.
Finland	It is defined in terms of use between the end user and the network operator.
France	40 bar for high-pressure pipes.
Germany	16 bar
Hungary	25 bar for high-pressure pipes.
Ireland	50 bar
Latvia	25 bar
Lithuania	16 bar
Poland	It is defined according to the agreements reached.
Slovakia	Depending on the pressure requirements of the costumers.
Slovenia	30 bar
Spain	Depending on the type of the grid and the existing connection points, 40 bar, 30 bar or 16 bar.
Sweden	Not established at regulatory level.
Switzerland	20 bar
The Netherlands	40 bar
Ukraine	12 bar

TSOs must maintain the grid they operate at a pressure equal to or greater than the specified minimum for the correct and safe operation of the system. In countries, where this value depends on an agreement, the TSO is a party of it and has to comply with its conditions.

After analysing the responses received from European TSOs and gas associations, there is no single opinion regarding the effects of hydrogen injection on the guaranteed pressure. Some TSOs consider that the fact of transporting less energy when injecting hydrogen into the grids, may require an increase in the guaranteed pressure, to assure the same energy supply.

Others believe that in mixtures of natural gas and hydrogen, the guaranteed pressure is expected to be as for natural gas, although when used with 100% hydrogen for repurposed systems, it is expected to be lower than for natural gas.

In any case, the pressure level and the range of pressure variation can determine the hydrogen impact's degree on transmission infrastructure components.

4.2.1.5 Procedure to avoid reaching the minimum pressures

Procedure that establishes the way of acting when in any area of the basic network the minimum pressures are reached or are expected to be reached, due to an increase in the transported flows.

In such situations, the TSOs must inform those responsible for managing the gas system so that they can analyse the situation, identify the affected gas pipelines and propose the necessary corrective measures to return the system to normal operating conditions, such as activating the gas compression stations, restricting new supply contracts or increasing the existing ones.

Once the Technical Manager of the gas system or the competent body of each country receives the information from the TSO, it must analyse the situation and, where appropriate, declare the affected pipelines saturated, subsequently proposing the necessary corrective measures, including compulsory planning proposals. If this situation persists, restrictive measures may be applied to new contracts or increases in existing ones. Additionally, the requirement to comply with the minimum guaranteed pressures under normal operating conditions could be suspended until the proposed corrective measures are implemented.

It is considered that the hydrogen injection should not affect the described procedure.

4.2.1.6 Control centres

Places where all the essential signals are received to control the operation of an entire installation and which allows to act accordingly, depending on the value of these signals, to establish emergency situations or to share technical and commercial information with other operators. In general, all stations in the transmission grid are operated remotely.

In general, TSOs are required to have a control centre for the operation of their network, monitoring them 24/7. This facility must comply with the requirements established in its national regulations and must report to a central control centre of the national gas system, owned by the technical manager of the system or the competent body of each country.

As a central control centre, it exchanges information from all system agents, shippers, producers, operators, etc., as well as authorities and agencies. At the same time, it can function to obtain initial information in case of interruptions and damages in the gas pipeline network, in gas-specific processes, etc.

The hydrogen injection will make it necessary to establish new normal operating values for the different signals received in the control centres, adapted to the new gas conditions (natural gas and hydrogen, or 100% hydrogen), for those infrastructures that will work with these new gases.

It will also be necessary to determine if these new gases require different communication protocols from those used for natural gas, between TSO and central control centers.

4.2.1.7 Information on the normal operation of the system and detection of parameters out of range

The gas system is in a normal operating situation when the basic variables are within the normal operating ranges of the system.

The Technical Manager of the gas system, or the equivalent national body defines and publishes the basic system variables and proposes the operating procedure for the calculation of their admissible ranges, in order to define the normal situation of the system.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

The TSOs, through their control centres, must continuously supervise the operation of their network, analysing the basic control variables, and detecting parameters outside normal values, so that they can implement certain actions to guarantee the supply and security of the facilities.

In addition to what is established in the previous section for control centres, hydrogen injection will also require the establishment of new alarm values for the signals received in the control centre, appropriate to the new gas conditions in the facilities working with these new gases.

Therefore, existing regulations that established the basic control variables and normal operating ranges, as well as communication and alarm procedures, may need to be revised.

4.2.1.8 Grid capacity supervision

Based on the main design parameters, the capacity of the gas grid is determined, as well as their operating and safety margins. It is monitored that the grid capacity always adapts to demand.

Operators shall publish for each of their facilities the maximum, nominal and useful capacity of their facilities, as well as details of their contracting, the capacity contracted for the market, for international transit and the capacity available for contracting. Facility capacities shall be updated periodically.

By injecting hydrogen into the network, which has a calorific value much lower than natural gas (around 1/3), the capacity of the network is reduced, and therefore, the capacity to adapt to demand.

It may be necessary to review the regulations that establish the main design parameters and capacity calculation formulas for their application to infrastructures that operate with new gases.

4.2.1.9 Network emissions

The emission of a network is the total amount of gas that will be distributed through the connection points of that network therefore, it is the result of considering the gas inputs and outputs of that network.

The TSO of a network must provide the necessary information on network emissions in time for daily balancing. This will be of special interest when biomethane and hydrogen injection points become widespread in transmission networks.

At the connection points, the presence of new gases and their variability (variation of the average hydrogen in blending depending on the amount of hydrogen injected into the grid at each time, which will depend on the availability of hydrogen for injection and the injection margins allowed by the blending equipment at each point of the network) must be taken into account.

4.2.1.10 Shrinkage in transmission grids

The shrinkage of a transmission grid is the amount of gas retained as losses and measurement differences caused by gas transmission in that transmission grid.

Owners of entry points to the overall transmission network retain gas from users more than their allocated entry quantity for shrinkage losses and measurement differences.

Operation with new gases and the existence of new injection points in the gas system may make it necessary to redefine the shrinkage calculations.

4.2.1.11 Shrinkage in regasification plants

The shrinkage of a regasification plant is the amount of gas retained as losses and measurement differences caused by the plant operation.

Hydrogen injection into the gas system will be carried out downstream of the regasification plants, so this condition should not be affected.

4.2.1.12 Self-consumption in the transmission grid

Amount of gas used in a gas grid facility through which gas flows for its correct operation, for example in the gas heating systems (boilers) of pressure regulation stations (PRS).

The self-consumption produced in the facilities will be acquired by the operator or by the technical manager of the system, in accordance with the provisions of the legislation in force.

TSOs must measure and report the self-consumption in their grids to the technical manager of the gas system or to other bodies.

It should be analysed how the presence of new gases (natural gas and hydrogen mixtures, and 100% H₂) affects self-consumption. For networks operating with 100% hydrogen, heating of the gas in PRS will not be necessary, as the Joule-Thompson effect is the reverse of that for natural gas. Therefore, in PRSs operating with mixtures of natural gas and hydrogen, it can be assumed that self-consumption is lower than for natural gas, however, the injection of hydrogen reduces the calorific value of the mixture, potentially increasing self-consumption.

4.2.1.13 Gas pipeline filling level

Minimum volume of gas belonging to the transmission grids owners (TSOs) that is needed inside the pipelines for its correct operation and commissioning.

TSOs or infrastructures owners must purchase and supply a quantity of gas in order to meet the pipeline filling level or the reference value of the transmission networks reserves, and they must also ensure that there is always a quantity of gas in them that allows its safe operation. This amount contributed cannot be used by TSOs or owners.

By injecting hydrogen into a gas network, the amount of energy stored in that network is reduced. This may affect the gas volume to be kept inside the networks to allow their safe operation. The effect of hydrogen injection and the percentage of hydrogen injected on the pipeline filling level or the reference value of the reserves should be analysed.

4.2.1.14 Minimum operating level in regasification plants (cushion gas volume)

Volume of gas contained in the minimum operating capacity of the regasification plant tanks. Its value depends on the way each tank is constructed.

Regasification plants operators contribute a quantity of liquid natural gas (LNG) to constitute the minimum operating level of the LNG tanks of the regasification plant. The quantity contributed to the minimum filling level will remain immobilised within the plants, without the operators being able to make use of it.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Hydrogen injection into the gas system will be carried out downstream of the regasification plants, so this condition should not be affected.

4.2.1.15 Minimum operating level in underground storage facilities

Minimum volume of gas contained in an underground storage for reservoir management purpose and to maintain an adequate minimum storage pressure needed to enable the extraction of gas at the pipeline design pressure.

Infrastructure operators provide a quantity of gas to constitute the minimum operational level of storage. The amount contributed to the filling level will remain locked inside the storage facilities; the owners will not be able to make use of it.

By injecting hydrogen, the energy per unit volume of the resulting gas is reduced, therefore the energy stored in each underground storage would also be reduced. The different compressibility factor of hydrogen is also affected. These circumstances can affect the volume of gas that must be kept inside the storage.

Likewise, it should be analysed whether current underground storage facilities are technically valid for storing hydrogen or mixtures of natural gas and hydrogen.

4.2.1.16 Operational regulations for methane tanker unloading activities

Procedure that defines the coordination of logistical and technical activities for the management of LNG discharges at regasification plants.

Hydrogen injection into the gas system will be carried out downstream of the regasification plants, so this condition should not be affected.

In any case, in the future, hydrogen on board ships will have to be considered, for which new infrastructure will have to be built, or adapt the existing ones, and modify codes and regulations accordingly.

4.2.1.17 Procedure for the determination of energy unloaded from methane tankers

Procedure that establishes the conditions for the correct unloading of LNG tankers at regasification plant ports, as well as the calculation of the unloaded LNG.

Hydrogen injection into the gas system will be carried out downstream of the regasification plants, so this condition should not be affected.

As mentioned in the previous section, given the possibility of hydrogen arriving on ships in the future, it will be necessary to generate new codes appropriate to these circumstances.

4.2.1.18 Assignment of unloading dates to tankers at regasification plants

Detail Protocol for outlining the process of assigning unloading dates to ships programmed by users at system's regasification plants.

Hydrogen injection into the gas system will take place downstream of the regasification plants, so this condition should not be affected.

In anticipation of future ship-based hydrogen supply, it will be necessary to develop all the corresponding regulations and codes.

4.2.1.19 International connection management

Gas exchanges at international connections must comply with legislation in force on both sides of the connection. Interconnected operators must establish operating agreements that respect the procedures established to manage this type of connections.

TSOs operating these connections must control the parameters of the natural gas exchanged, informing the technical manager of the national gas system or other bodies of the operations carried out at the international connection points.

At international connections, criteria will have to be unified between the different interconnected countries, or between the overall European system, on the gas quality, the percentages of hydrogen admitted and odorization, among other aspects. The procedures to be applied to natural gas and hydrogen blends, or to 100% hydrogen, at these connections, are expected to be similar to those applied to natural gas, with the relevant modifications to take into account the different characteristics of the gases that may circulate.

4.2.1.20 Communication procedures

Rules established for the transfer of grid information between different TSOs and the technical manager of the system or the equivalent body, and other organizations.

The TSO has the obligation to follow and comply with the minimum communication procedures set out in the sectoral regulations applicable in its country, providing information related to gas flow, actions on the network, stocks, etc.

Data communication should be in the nationally standardized format, using the information exchange systems established for this purpose.

The established communication procedures should not be substantially modified; in any case, they should be reviewed to include special requirements due to the presence of hydrogen in the gas.

4.2.1.21 Actions protocols in case of incidents

Procedures and actions to be taken in case of incidents to minimise their consequences.

These procedures may be based on a systematic risk assessment, identification and evaluation of the hazards to which workers and others in the danger zone are exposed. This includes establishing the necessary and appropriate measures required for the protection of safety and health at the workplace.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

The TSO must establish a permanently attended control centre, to receive notifications, both from its own and external personnel, related to anomalies, leaks or incidents in the grid. In addition, there must be a written emergency plan that describes the organisation and performance of human and material resources in normally foreseeable emergency situations.

The consequences of incidents will be conditioned by the gases that are transported in each infrastructure of the gas system, so it is necessary to adapt these Action Protocols to contemplate the possible presence of new gases (natural gas and hydrogen blends, and 100% hydrogen).

Therefore, a review of incident action protocols should be carried out for those infrastructures that work with new gases.

4.2.1.22 Unavailability at transmission facilities

Any situation of total or partial limitation on the operation of a transmission facility, whether due to maintenance, infrastructure commissioning, an emergency, force majeure, unforeseen events or any other circumstance.

In the event of unavailability at a transmission facility, the TSO that owns that facility is expected to provide informed and appropriate responses to events, process deviations or technical disturbances. This event should be limited in terms of time and location.

In these situations, the TSO must communicate to the users with contracted capacities on it, to other TSOs connected and to the technical manager of the gas system, what its available capacity is during the situation of unavailability.

If, as a result of such unavailability, the supply capacity to end users is reduced, the remaining capacity shall be distributed among the affected users, in coordination and under the supervision of the technical manager or the competent body.

The circulation of new gases (natural gas and hydrogen mixtures, and 100% hydrogen) through the system should not imply a priori unavailability, except in the processes of adaptation of specific installations for the operation with these new gases.

4.2.1.23 Unavailability in LNG regasification plants

Any situation of total or partial limitation on the operation of a LNG regasification plant, whether due to maintenance, infrastructure commissioning, an emergency, force majeure, unforeseen events or any other circumstance.

Regasification plants operators must inform the technical manager of the gas system and the parties with current access contracts of any ongoing or planned amendment or change that affects, or may affect, the characteristics or the operation of these facilities.

Hydrogen injection into the gas system will be carried out downstream of the regasification plants, so this condition should not be affected.

In the future, similar situations of unavailability may occur in hydrogen reception plants. The procedures may be similar to those for LNG regasification plants, adapted to the characteristics of hydrogen and the way it is stored (compressed hydrogen, liquid hydrogen, or in hydrogen carriers).

4.2.1.24 Unavailability in underground storage facilities

Any situation of total or partial limitation on the operation of an underground storage facility, whether due to maintenance, infrastructure commissioning, an emergency, force majeure, unforeseen events or any other circumstance.

Underground storage operators must inform the technical manager of the gas system and the parties with current access contracts of any ongoing or planned amendment or change that affects, or may affect, the characteristics or the operation of these facilities.

Hydrogen injection should not imply unavailability, except in the processes of adaptation of specific installations for operation with new gases (natural gas and hydrogen mixtures, and 100% hydrogen).

4.2.1.25 System emergency

The gas system is in an emergency when gas supply shortage may make it necessary to use strategic reserves, or the safety of people, devices or facilities or the integrity of the grid may be threatened. Emergency situations must be resolved urgently, and require immediate actions, often involving government authorities.

In the event of an emergency, the competent body of the national administration will be the one who will establish the conditions under which the strategic natural gas reserves may be used.

TSOs and other infrastructures' owners will comply with the orders of the competent body and will be coordinated by the technical manager of the gas system or the corresponding organization at the national level.

The effect of hydrogen injection on the facilities of a particular gas system, and the extent to which it may affect their integrity, should be analysed. Furthermore, the presence of new gases should be considered in the actions resulting from the emergency.

4.2.1.26 Analysis of new connections and facilities and its integration into the system

New facilities to be integrated into the gas system, for example, biogas production plants or industries using gas as a utility or raw material, will require a new connection to the natural gas grid, so it is necessary to create a new entry or exit point to the system.

These new installations must comply with technical regulations in force and be technically and operationally compatible with the installations to which they are connected, among other requirements.

In general, the TSO, owner of the grid to which the new facility is connected, will be in charge of analysing the viability of connecting new supplies and detecting infrastructure with possible saturation problems due to the evolution of downstream consumption, as well as verifying that the new facilities meet the requested requirements.

The hydrogen injection facilities (blending) require a new connection to the grid and thus a new entry point to the system. On the other hand, at certain delivery points in the transmission grid it will be necessary to remove hydrogen from the grid (deblending), for example, in supply grids that technically cannot accept more than a certain percentage of hydrogen in the mixture with natural gas, or that supply end consumers who also have limitations in that way.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Codes and regulations should be revised to include hydrogen entry points into the grid, and hydrogen exit points from the grid.

4.2.1.27 Compression

Compression stations are facilities present in the gas transmission grid that have equipment capable of increasing the pressure of the circulating gas to reach the minimum required pressure in the network or in a part of it, or to redirect gas flow in meshed networks.

Compression stations operators shall follow the orders of the technical manager of the gas system or the competent body, for the correct overall management of the system.

The effect of hydrogen injection can significantly condition the operation of natural gas compressors; it will be necessary to carry out studies of the existing compression stations to determine what percentage of hydrogen they are capable of managing, and what adaptations are required depending on the maximum amount of hydrogen supported by each grid.

4.2.1.28 Programming

Information to be issued by the parties that use the gas system facilities in relation to the gas they estimate that they will inject, extract, store, supply or consume in a specific period.

The programming will include information on the demand for conventional gas, the demand for electricity generation, the gas inputs and outputs of the transmission grid with regasification plants, deposits, international connections and underground storage, the gas intended for self-consumption necessary for the operation of the different infrastructures of the gas system and the minimum filling level of the new infrastructures, among others.

Once hydrogen is injected into the grid, it would be necessary to adapt performing simulation software for doing the programming to include hydrogen. In addition, the aspects to be programmed for natural gas should be reviewed in case any should be added for hydrogen.

4.2.1.29 Grid stock and grid balancing

The grid stock level is the indicator that summarises the pressure balance at the points of a transmission grid and, therefore, its operational status, establishing maximum and minimum stock limits associated with maximum and minimum pressure values in that grid.

The technical manager of the gas system or the equivalent national body must carry out grid balances to maintain the transmission network within its operational and stock limits.

Before the entry of a new gas into the system (hydrogen, either blended with NG or 100% hydrogen), the values and calculation methodology of the grid parameters should be reviewed, establishing new limits depending on the gas expected by the different parts of the grid.

4.2.1.30 Individual user balancing

Gas stock assessment process for each of the system's facilities. The physical balances will serve the operator of each infrastructure to:

- Guarantee the correct operation of each infrastructure.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

- Control, minimise and supervise the volume of supply losses associated with losses, leaks, venting and measurement differences.
- Supply gas throughout the day to users at each facility's entry and exit point.

The technical manager of the gas system, or equivalent national body, must produce individual balancing for each of the users of the gas system facilities.

Differences in balances or imbalances are settled based on the reference price of natural gas on the market. When hydrogen is injected into the network, a new reference price will need to be established.

4.2.1.31 Degree of saturation of pressure regulation and metering stations

The pressure regulation and metering stations (PRS) and metering stations (MS) are located at the points of the system where it is necessary to reduce the gas pressure and measure the gas flow, or to measure only the gas flow, which is transferred to another network or operator. In these facilities it is necessary to calculate their capacity or degree of saturation.

The regulations indicate how the calculation should be carried out and sets out the criteria to determine whether a transmission system's PRS or MS is saturated in its regulation or measurement capacity.

Each TSO will periodically prepare, according to the criteria established in the regulations, a study on the current state of saturation of its PRS and MS, indicating their degree of saturation.

Hydrogen injection affects the capacity of the PRS and MS, so it would be necessary to define the degree of saturation as a function of the percentage of hydrogen present. Some facilities could become saturated, and others underused, when new gases are injected into each network, which will require modification of the facilities and measurement equipment to adapt to the new working range.

4.2.1.32 Communication with the technical manager of the gas system

The Technical Manager of the gas system, or the equivalent body of the national gas system, will have constant access to remote measurements at all exit points on the basic transmission grid. It must receive remote measurements, daily, from consumers whose behaviour may affect the normal operation of the part of the grid to which they are connected, either directly or through the transmission or distribution system operator.

TSOs are responsible for having the appropriate equipment for the measurements and for being able to offer this information on a continuous basis.

This aspect would not be affected once hydrogen is injected into the grid, as communication will continue, only that there will be more measures, some specific for hydrogen.

4.2.1.33 Coordination and communication with the electrical technical manager

The electrical system is closely linked to the gas system due to the natural gas supply to the power plants.

The Technical Manager of the gas system or the competent body of each country is responsible for the coordination with the electrical Technical Manager for the correct connection between both infrastructures.

Once hydrogen is injected into the grid, the energy storage effect of gas grids (hydrogen production with surplus electricity from renewable sources) and the existence of new gases in the system, that could feed electricity production plants should be considered.

4.2.1.34 Interlocution with other gas system members

The gas system requires a flexible, real-time communication tool between the various parties involved in the gas system, thus supporting the management of the entire gas cycle. It should reflect requests for capacity, contracting, programming and nominations, measurements, allocation, balancing and invoicing, among others.

The Technical Manager or the competent body of each country should provide users with access to the information system. It is also responsible for keeping the system updated and operational, and the system shall be easily accessible, guaranteeing the accuracy and up-to-date nature of the information provided, as well as its security and confidentiality, and respecting the principles of transparency, objectivity and non-discrimination.

The fact of having new gases circulating through the system should not affect the communication procedures, but it should affect the information to be communicated.

4.2.1.35 Public information about the normal operation of the system

The Technical Manager of the gas system or the competent body of each country should publish, in an accessible way for the parties involved in the gas system, all the public information established on the use and operation of the system.

Some of the information that may be public is actual and forecast daily demand, forecast monthly demand, plant usage levels, winter gas demand cover plan, aggregate level of planned LNG stock or of underground storage facilities.

The hydrogen injection into the gas system would not affect this aspect, except that it would increase the public information by including on new gases, for example, data related to the percentage of hydrogen admitted and existing in each part of the grid.

4.2.1.36 Operations plan

The operations plan must include, at least, the organization of all gas going into the system, the gas movement within regasification plants and storage facilities, a breakdown of supplies and inventory levels, and the system autonomy.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

The technical manager of the gas system, or the competent body at national level, through the established programming and nominations, as well as the demand forecast provided by the parties that make use of the system, must prepare an operational plan with daily details and monthly details on the operation of all transmission facilities, grouping the information received through the programming and nominations of the gas transmission companies.

When hydrogen is injected into the grid, the plan should include the hydrogen inputs and outputs of the gas system.

4.2.1.37 Winter action plan

The winter action plan aims to secure supply in response to increased demand due to seasonality of the domestic and commercial market and sudden cold snaps. This plan may include the following measures: reservation of entry capacity on interconnections with international pipelines and setting minimum quantities of safety stocks to be held in LNG tanks and underground storage facilities.

This plan may also include special maintenance measures. Considering the special potential risk of leaks on icy and gas-impermeable surfaces, unscheduled inspection measures could be carried out depending on the local condition.

The Technical Manager of the gas system or the competent body of each country, in collaboration with the other parties involved in the gas system, shall draft a winter action plan.

Hydrogen injection should not affect this aspect, only the hydrogen inputs to the system would have to be considered.

4.2.1.38 Operation in exceptional situations

Exceptional Operating Situations are defined as those in which it is expected that any of the parameters defining of Normal Operation will not be met, but without requiring the declaration of an Emergency Situation.

These situations will normally arise due to unavailability of gas for supply in an area of the gas system, total or partial shutdown or unavailability of an LNG plant, reduction of gas supplied by an international pipeline, a significant and unforeseeable increase in consumption, unavailability of equipment in the transmission network or a disturbance in the system.

If an exceptional operating situation is foreseen, unless urgent reasons require more immediate action, the Technical Manager of the gas system or the competent body of each country shall make a preliminary assessment taking into account the following parameters: cause of the exceptional operational situation; the weather forecast; the estimated duration of the cause of the imbalance; the users whose operations will be affected; the emission capacities of LNG plants and the autonomy of stock; the natural gas connection capacities of international pipelines, emission capacities of gas production fields and underground storage facilities, as well as stock levels; transmission and distribution limitations leading to emission capacity constraints; determination of the demand that can be met during the situation; and any other relevant information.

The Technical Manager or competent body is also responsible for the correct application of the procedures to be followed for the correct system operation when it is in an exceptional situation, for which it will issue the corresponding instructions to gas transmission and distribution companies and directly supplied consumers.

D6.3 Pathway and proposals summary to enable wider injection of H₂ in EU gas networks

Exceptional situations could be divided into different levels according to the situation's severity degree, with corrective measures at each level to return the system to the normal operating conditions. The severity level would increase if these measures do not work.

Once hydrogen is injected into the grid, it would be necessary to review the operation in exceptional situations in grid, where there may be hydrogen and review the parameters to be considered.

4.2.2 Aspects for the maintenance of natural gas transmission grid

4.2.2.1 Network surveillance

Control of the grid trace to detect actions or events that may endanger or place the pipeline and/or its associated installations in unsafe conditions, such as actions by third parties (constructions, works, etc.), subsidence, damage to signaling, invasion of the trace by vegetation, etc.

TSOs must have a surveillance, review and control program to observe the surface conditions of the entire route over which their pipeline runs, to identify signs of leaks, construction activities and other factors that could affect safety and operation.

A review of surveillance programs should be done to consider the possible presence of new gases in the grids.

4.2.2.2 Coating and corrosion controls

Activity to verify the status of coating and internal and external corrosion of pipelines.

To avoid corrosion, high technical standards are applied from the design and construction phase. Active and passive cathodic protection in combination with internal in-line pipeline inspection is used to ensure pipeline integrity.

Operators should carry out controls on the pipe coating to prevent the pipe from coming into contact with the external electrolyte, which would facilitate the corrosion process of the steel pipe. They should also carry out continuous monitoring of the cathodic protection system, when possible, and periodically inspect the status of the cathodic protection of the pipelines.

Hydrogen can affect steel by embrittlement, so it may be necessary to modify the controls carried out on the pipes and increase their frequency. It should be analysed whether it is possible to adapt current inspection techniques (smart pigs, etc.) of the networks in operation to allow this type of conditions to be detected.

4.2.2.3 Maneuverability and valve lubrication

Verification of the maneuverability of pipelines valves nodes and verification of the tightness of their bodies.

It is the responsibility of the TSOs to review the good state of conservation and operation of the grid valves with the frequency established in regulations.

When injecting hydrogen, with a smaller molecule size, it is possible that a differential permeation through the valves bodies and components may occur, that make it necessary to increase the frequency of leak detections and/or use specific sealing greases.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Valve manufacturers should determine if their equipment is valid for use and tightness with hydrogen, by establishing specifications to validate the use of their valves for natural gas and hydrogen blends, or 100% hydrogen. Therefore, the TSOs will have to adapt to what they have defined for the use of greases, etc.

Maintenance procedures should be adapted for application to infrastructures carrying new gases, considering the specifications and recommendations of the equipment manufacturers.

4.2.2.4 Leak checks

Control of gas leaks both in the pipeline layout and in its auxiliary facilities.

When hydrogen is injected into the grid, leakage control should be carried out with appropriate detectors and for the allowed concentration ranges in each part of the grid.

The leakage control regulations should be reviewed to consider the possibility of the presence of new gases in the networks (natural gas and hydrogen mixtures, 100% hydrogen), including the type of detection equipment to be used and possible changes in monitoring frequencies, if appropriate.

4.2.2.5 Verification and control of regulation and metering equipment

Verification that the transmission grid regulation and measurement station equipment maintain its proper condition and operation.

TSOs must carry out the maintenance controls established in the regulations and follow the recommendations of the manufacturers of the equipment present in each of the facilities. Regarding the measuring equipment, they must also carry out metrological control.

Equipment manufacturers should indicate whether their equipment is valid for working with new gases (mixtures of natural gas and hydrogen, or 100% hydrogen) and, where appropriate, update their specifications and recommendations for use and operation under the new conditions.

Maintenance procedures should be adapted for application to infrastructures carrying new gases, considering the specifications and recommendations of the equipment manufacturers.

4.2.2.6 Regulatory safety controls

Controls common to any type of installation according to the regulations established for fire protection systems, maintenance of electrical installations, etc.

These installations are subject to supervision by the authorities and require an operating permit, at the time of commissioning, and a periodic operating permit issued by an authorized technical inspector.

It is the responsibility of the operator to comply with the established regulations.

This condition should not be affected by the injection of hydrogen into the gas grid.

4.2.2.7 Maintenance plan

Plan that includes all inspection, control, servicing and/or repair activities aimed at maintaining the gas system facilities in optimum safety and operating conditions. It will list, at least: type of servicing or maintenance, facility, consumers, and other affected parties, proposed date and estimated duration, and impacts on operation and supply.

The TSOs must prepare, before the end of the year, the programming of the activities that require or may cause operational restrictions at their facilities for the following year.

Operators should review the maintenance plans of their facilities if, due to the injection of hydrogen into the grid, the applicable regulations and equipment manufacturers establish different maintenance conditions than those existing before the injection.

4.2.3 Aspects for the gas market

4.2.3.1 Forecast

Estimation of the gas volume that will exit the system based on demand prediction data.

Usually, to ensure grid stability and transmission planning, the TSO forecasts the load situation of its network considering nominations and quantity notifications. The TSOs are responsible for carrying out daily and intraday forecasting of the outputs of the transmission gas system, telemetered and non-telemetered by marketer and connection point.

The market area's responsible entity coordinates the utilization of ancillary services to ensure the grid stability. Ancillary services are the differences resulting from comparing the physical input and off-take quantities within the market area or parts of the market area.

Estimation of the gas volume that will exit the system based on demand prediction data.

Usually, the TSOs are responsible for carrying out daily and intraday forecasting of the outputs of the transmission gas system, telemetered and non-telemetered by marketer and connection point.

The forecasts are made in terms of energy, not volume of gas transported, so the fact of working with new gases (natural gas and hydrogen mixtures and 100% hydrogen) should not affect demand predictions.

4.2.3.2 Predictive demand analysis

Demand prediction is an estimate of the gas consumption in the gas system, referring to a period that can be annual, monthly, weekly, daily or even hourly.

Each party in the gas system is responsible for preparing its own demand forecast.

As mentioned for forecasts, the predictive demand analysis is done in terms of energy, so it should not be affected by the hydrogen injection into the network.

4.2.3.3 Gas supply and demand forecast

Estimation of the amount of gas that will be available to users (supply) and the amount of gas that they will need (demand).

The technical manager of the gas system or the competent national body, through the programming, nominations, as well as the demand forecast provided by the parties that use of the system, will prepare an operational gas supply and demand forecast document for the year with monthly details, breaking down the gas flows into and out of the system, the operation of regasification plants and management of storage facilities, identifying possible surpluses or deficits of gas in the system and for each of the parties affected.

When hydrogen is injected into the system, not only the quantity of gas demanded has to be taken into account, but also the quality of that gas in the offer to users.

4.2.3.4 Physical balancing of facilities

Gas reserves evaluation process for each of the facilities. The physical balancing will be used by the operator of each infrastructure facility to:

- Ensure the correct operation of each infrastructure.
- Control, minimise and supervise the volume of losses associated with leaks, vents and measurement differences.
- Provide information on the gas delivered to other operators and users at each entry and exit point of the grid.

The TSOs must carry out the physical balance of the gas that passes through their facilities, in accordance with the formulas and frequencies established in national regulations.

To evaluate gas stocks, TSOs will have to consider the possible presence of different gases (natural gas, natural gas and hydrogen mixtures, and hydrogen) in their grids for balancing purposes. Therefore, the formulas for calculating these stocks will have to take into consideration the possible presence of different gases.

The fact of operating with gases other than natural gas may require a review of the regulations for calculating stocks and balances, for their application to those infrastructures that work with new gases.

4.2.3.5 Individual imbalances

A gas system user shall be in an individual imbalanced situation when its level of gas stock in the system is not within the tolerance margins established by regulations.

In these situations, the operator must take the necessary measures to prevent escalation and to restore normal operation, such as gas purchase and sale operations to other users or interrupting the gas supply to those users for whom they have contracts that allow this interruption.

New tolerance margins must be considered for those infrastructures working with new gases (natural gas and hydrogen mixtures, and 100% hydrogen).

Therefore, it may be necessary to review the regulations on the tolerance margins determination and action in the event of imbalances for those infrastructures working with new gases.

4.2.3.6 Capacity Procurement

The capacity of a user is the amount of gas that this grid user needs to carry out its activities. It can contract capacity in regasification plants, underground storage, transmission and distribution grids, etc.

In general, the technical manager of the gas system or equivalent body, is responsible for managing the contracting of grid capacity.

In grids that can transport new gases (mixtures of natural gas and hydrogen, and 100% hydrogen), it is expected that the user will not only specify the quantity of gas required, but also the quality of that gas. This circumstance adds a further variable that should be considered when contracting capacity.

4.3 TSO perspectives and customer views

In addition to the influence of the Gas Package on the ambitions to introduce hydrogen into the European transport networks, another focus of D6.2 is the view of the European TSOs on this issue. Although participation in the survey is limited to eight countries, the basic conclusion seems to be that European TSOs are critical of large-scale blending of hydrogen into the transport network in a concentration range above 5 percent by volume. The exact preference in the range below 5% by volume is not clear. In principle, the opinions of the TSOs seem to be in line with the likely blending limits at border crossings, which are still being negotiated in the trilogue and are likely to end up in a range between 2 and 5 percent by volume.

Issues identified by TSOs in the survey as justifying the critical attitude are:

- Operational safety, including material compatibility.
- Cost of conversion.
- Cost of separation processes (see also analysis in D5.3).
- Compatibility with network components other than pipelines (e.g. compressor stations).
- Compatibility with end-user technologies, which often prefer pure hydrogen.
- Concerns about capacity losses (flow rate and operating pressure).
- Integration of gas storage.
- Need for harmonisation, therefore no deviation from EU requirements.

In this context, the opinion of industrial gas users is also relevant, as they are ultimately the main consumers of gas volumes from the transport networks, in addition to the distribution networks. The industrial uses of hydrogen can be broadly divided into material and energy uses. In the case of material use, chemical catalytic processes in the chemical industry and in refineries are particularly important. Various associations in Europe have published statements on the issue of blending at transport network level. Exemplary:

- VCI (Verband der Chemischen Industrie) and IG BCE (Industriegewerkschaft Bergbau, Chemie, Energie) from Germany have written in a joint strategy paper that the blending of hydrogen in natural gas networks should only take place at distribution network level and only if sensitive consumers are not affected [11].

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

- CEFIC (European Chemical Industry Council) rejects the top-down approach to hydrogen blending as described in the Gas Package and cites commercial, safety, regulatory and practical reasons why TSOs should be able to reject gas at border crossings if hydrogen has been added. In this context, the different needs of gas consumers should also be taken into account. CEFIC considers that blending should rather take place at distribution system level [12].

The issue of blending is not entirely clear-cut when it comes to utilising hydrogen as an energy source. Many processes and systems can already be operated with different hydrogen concentrations today or will be able to do so after future developments, but fluctuating hydrogen concentrations are problematic. Other processes and systems, especially in the domestic environment, can already be operated with varying hydrogen concentrations.

- Domestic gas appliances: A number of projects in recent years have shown that existing domestic appliances can cope well with hydrogen concentrations of at least 20% by volume. Even fluctuating hydrogen concentrations do not appear to have a detrimental effect (e.g. [13]).
- According to a document from the Prime Movers' Group on Gas Quality and H2 Handling Sub-group 2 Work, EUROMOT (European Association on Internal Combustion Engine Manufacturers) points out that gas engines can already be operated with up to 20% hydrogen by volume today or after retrofitting, but that rapid changes in gas quality in particular do affect operation negatively [14].

The rather critical attitude towards hydrogen blending above 5% is only in line with climate objectives if a dedicated hydrogen network is established at the same time, transporting 100% hydrogen and thus connecting regions with high H₂ production potential with regions with high H₂ demand. The European TSOs have presented such a plan with the European Hydrogen Backbone Initiative. The initiative consists of 31 TSOs, representing a significant part of the European transport network. Based on the survey and the information published by ENTSOG and the Backbone, together with the information available on hydrogen corridors, it can be concluded that the European TSOs prefer a separate network transporting 100% hydrogen on the one hand and natural gas with limited hydrogen admixture (0 - 5%) on the other hand.

In principle, the Gas Package will also allow for higher blending limits at border crossings in consultation with the neighbouring countries concerned, and the national right to apply higher blending in national transport networks will in any case remain unaffected. This is also viewed positively by the TSOs.

4.4 Techno-economic considerations

The techno-economic models developed in WP5 of the HIGGS project show that the question of the most cost-effective solution cannot be answered in isolation from local and European conditions. On the other hand, it is also shown that a very large number of plants for the separation of hydrogen from a hydrogen-natural gas mixture quickly leads to very high overall transport costs. Harmonisation of the blending limits, as currently planned at European level, is described in D5.4 as the most promising way forward.

This becomes clear when considering a border crossing point between two countries A and B with different blending limits ($A > B$) (s. Figure 10):

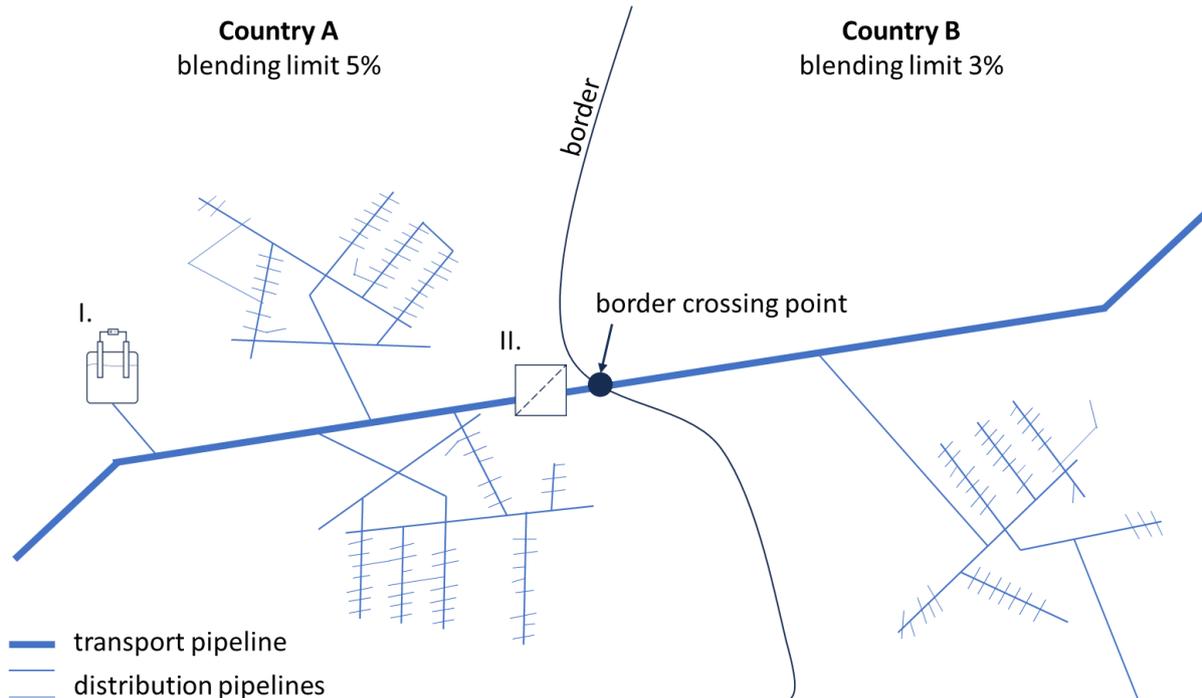


Figure 10. Border crossing point between two countries A and B with different hydrogen blending limits with an electrolyser (I.) and a membrane separation unit within a transport pipeline (II.)

I. Reduced incentive for injection

In country A, the incentive to inject into a transport pipeline leading to this border point is also low.

II.1 Membrane separation is very capital intensive

The membrane plants are only operated when the current hydrogen concentration at the border crossing point is higher than the blending limit in country B. This is only the case for a limited period of time due to the low incentive for feed-in described above and the already fluctuating hydrogen quantities.

II.2 Membrane separation is very energy intensive

Due to the high energy intensity, a high energy input is required to compensate for small differences in concentration.

II.3 Sub-optimal use of hydrogen after separation

After separation, hydrogen consumers would be required at the border crossing point, and these can operate with fluctuating amounts of hydrogen.

It should be emphasised that the above does not mean that the use of separation processes to remove hydrogen from hydrogen-natural gas mixtures is fundamentally uneconomical. On the contrary, suitable separation processes will be necessary to allow for targeted blending at certain points, to protect sensitive consumers or to stabilise the hydrogen concentration. However, the diverse use of membranes does not appear to be an economically viable alternative to a standardised and harmonised system for gas quality at EU level. This can be seen from the influence of the costs of

D6.3 Pathway and proposals summary to enable wider injection of H₂ in EU gas networks

membrane separation processes on the total transport costs determined in D5.3. Transport costs have been determined as

- 3-5 €/MWh/1000 km without considerations of membranes,
- 11-47 €/MWh/1000 km considering membranes at all city gates, and
- 7-11 €/MWh/1000 km considering the targeted use of membranes.

In addition, in D5.3, the levelised cost of hydrogen transport via an upgraded pipeline transmission system was calculated for different levels of blending. Figure 8 from this deliverable shows that the corresponding costs are almost constant up to a blend level of 40% by volume and then decrease rapidly towards a 100% hydrogen network. This calculation does not include any hydrogen separation processes, but the differences are due to the total cost of conversion, which is related to the energy content of different hydrogen concentrations in relation to the unit (€/MWh hydrogen/1000 km). This is an interesting result when looking at the gas network as a whole and comparing blending with pure hydrogen networks. However, this does not contradict the fact that in some places blending may have economic advantages in coexistence with a European hydrogen network. This is particularly true in regions where there are no parallel pipeline structures and where both hydrogen and natural gas need to be transported. In order to avoid the construction of new pipelines, blending could make sense in such a constellation.

In this context reference is made to a Marcogaz study on the 'Cost estimation of hydrogen admission into existing natural gas infrastructure and end use' for admixtures H₂ concentration 2, 5, 10, 15, 20, 25, 30 and 100 vol.% H₂, published in November 2023 [15]. The study aimed at, on one hand, estimating the level of H₂ acceptance in the existing natural gas infrastructure and end use, and, on the other hand, estimating the related costs of H₂ admission into existing natural gas infrastructure or end use equipment in Europe. The study disregards industrial uses.

5 Blending in the context of an emerging European hydrogen backbone

5.1 Initial situation and assumptions

Hydrogen currently plays a minor role in the European energy system. In recent years, however, the European Union and its member states have identified hydrogen as a key building block for achieving climate goals and greater energy independence. This requires, among other things, an infrastructural transformation to transport and distribute energy safely and reliably, without losing sight of the economic aspects. In this context, it is crucial not to neglect the transition from today's fossil structures when planning the vision of a common European hydrogen economy. The transition phase will differ significantly from the target state, as the availability of hydrogen in volume and the readiness of infrastructure and end-use applications for hydrogen will increase over time. In order to achieve a smooth transition, early and detailed planning is needed. To this end, the European Union and its Member States have started to establish a regulatory framework and to initiate and support projects to build production and import capacity, to address infrastructure issues and to convert industrial, commercial and domestic applications to hydrogen supply. In addition, industrial companies have launched numerous projects and initiatives to make the transition to a hydrogen economy. These include the European Hydrogen Backbone (EHB) initiative, a partnership of currently 32 energy infrastructure operators.

This initiative plans and publishes visions for a European hydrogen infrastructure based on existing and new pipelines. By 2030, the planned network will be more than 32,000 km long, increasing to more than 57,000 km by 2040 (EHB, 2023). Ultimately, an investigation of how the transition phase to a European hydrogen economy can be significantly supported by the blending of hydrogen to the natural gas transport network, as carried out in the HIGGS project, cannot be meaningfully carried out without taking into account the specific plans of the EHB. It is important to stress that there is no inefficient competition between these two approaches, as the transmission network operators that transport natural gas today are the same ones that will transport hydrogen in the future. As shown in Deliverable D6.2, there are reservations at EU level and among TSOs themselves, as well as among end users, against blending at transmission network level. The aim of this chapter is to explore whether there are gaps between hydrogen supply and demand that could be filled by blending and in which scenarios blending makes sense despite the critical framework conditions.

In order to approach these targets, national individual balances and an overall EU balance (+UK+Switzerland+Norway) on hydrogen production and demand are first established, based on Table 9 of D6.1. As blending may play a role especially in the transition phase, the year 2030 is initially chosen as the target year. The table shows a certain degree of uncertainty with regard to hydrogen production and demand, which is visible in a wide range in some countries. On the basis of the values, three scenarios can be distinguished that are described in D6.2:

1. Average Case (AC): For each country, the arithmetic mean of production and demand is calculated from the maximum and minimum values. The difference between these two averages gives the average trade balance.
2. Minimum Demand Case (MinDC): The difference between maximum production and minimum demand results in the smallest trade deficit for each country.
3. Maximum Demand Case (MaxDC): The difference between minimum production and maximum demand results in the largest trade deficit for each country.

5.2 Balanced capacity calculations to evaluate the fulfilment of demand by the EHB and the H₂ corridors

The aim of the European Hydrogen Backbone Initiative is to create a pipeline system connecting regions in Europe that have the potential to produce large quantities of hydrogen with regions that have a high demand for hydrogen. To this end, five major pipeline corridors are being planned across the European continent. They will also allow for pipeline imports from North Africa, Ukraine and the North Sea region.

- Corridor A: North Africa & Southern Europe.
- Corridor B: Southwest Europe & North Africa.
- Corridor C: North Sea.
- Corridor D: Nordic and Baltic regions.
- Corridor E: East and South-East Europe.

The corridors focus on connecting regions within the European Union with high production potential (Corridor B: Portugal and Spain; Corridor C: North Sea region; Corridor D: Scandinavia) and regions with high import potential (Corridor A: North Africa, Corridor B: North Africa; Corridor C: North Sea region and Corridor E: Ukraine/Eastern Europe) with regions with high H₂ demand, especially in Central and Central-South Europe.

The question for the HIGGS project is whether the concretely planned hydrogen corridors are sufficient in terms of capacity to exploit the export potentials of the surplus regions and to cover the import needs of the regions with a quantitative deficit. For this purpose, information on the respective hydrogen corridors is collected in this chapter and compared with the requirements outlined above. The planning of the hydrogen corridors is taking place in a dynamic environment and, for the most part, has not yet been finalised. Assumptions must therefore be made at this stage. Some of these assumptions are uncertain and some are highly simplified, but the aim is to provide an objective picture of the extent to which the EHB can meet the hydrogen demand derived in D6.1 at the level of the EU27 Member States +Switzerland+Norway+UK.

- The corridors are assumed to have the capacities and start-up dates as shown in Table 3. Only public sources were used [16], [17], [18], [19] [20], [21].
- As this project does not focus on hydrogen imports from outside of Europe and production, it is assumed that the demand for hydrogen corridors A, B, and E can be met by imports. For Corridor C, it is assumed that the capacity can in principle be achieved by off-shore production, and for Corridor D by on-shore production in the transit countries, as planned. Imports via terminals may play a role here, but the calculations tend to assume a start after 2030.
- A balance sheet approach with a time horizon of one year is chosen. Accordingly, the flow of hydrogen through the pipelines is balanced, which is achieved in principle by virtual storage at the point of production and consumption. This smoothes seasonal effects of production and consumption.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

- For simplicity, it is assumed that generation and demand always occur along the course of the hydrogen corridors. Transport and distribution within the Member States is assumed to be given.
- In a first run of the calculation, the balance is only solved for Member States through which a corresponding corridor runs. The solution is done in the order of the Member States.
- A reduced capacity utilization rate of 85% is assumed.

Table 3: Publicly available information on the planned H₂ corridors [16], [17], [18], [19] [20], [21]

	Corridor	Countries	Capacity [Mtpa]	Start up
A	SouthH2	Italy, Austria, Germany	2	2030
A	sunsHyne	Italy, Austria, Slovakia, Czech Republic, Germany	2	2030
B	H2Med	Portugal, Spain, France, Ger- many	2	2030
C ¹	AquaDuctus	Germany	1	2030
D	Nordic Baltic Hy- drogen Corridor	Finland, Estonia, Latvia, Lithuania, Poland, Germany	unknown	2030
E	Central Euro- pean Hydrogen Corridor	Ukraine, Slovakia, Czech Re- public, Germany	unknown	2030
T ²	Terminal Imports		0	

¹ It is known that more projects are planned in the North Sea. For the sake of simplicity, we assume a pipeline system between Germany, Norway, Denmark, and UK.

² The import of hydrogen via import terminals will play an increasing role in the future. For the sake of simplicity, these calculations assume that imports via liquid hydrogen or hydrogen derivatives such as ammonia and methanol will only take place after 2030.

To address the uncertainty associated with the construction of these corridors, two scenarios are set up.

- **Scenario “As planned” (Scenario I)**
 - o A corridor: total capacity according to publicly known data of 4 Mtpa, equally divided between the two routes SouthH2 and sunsHyne.
 - o B corridor: total capacity according to publicly known data of 2 Mtpa.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

- C corridor: total capacity according to the publicly known data of 1 Mtpa.
 - D corridor: total capacity in line with the capacities of the A and B corridors: 2 Mtpa.
 - E corridor: a total capacity based on the capacities of the A and B corridor: 2 Mtpa.
- **Scenario „Pessimistic“ (Scenario II)**
- A corridor: total capacity is reduced by 25% compared to Scenario I.
 - B corridor: total capacity is reduced by 25% compared to Scenario I.
 - C corridor: total capacity is reduced by 25% compared to Scenario I.
 - D corridor: total capacity is reduced by 25% compared to Scenario I.
 - E corridor: Assuming that this corridor will not be realised by 2030.

The calculations are carried out for both the Average Case (AC) and the Maximum Gap Case (MaxGC) scenarios. The results are presented on a country-by-country basis in Figure 11 and Figure 12.



Figure 11: Hydrogen balances at national level with the assumptions of Scenario I in the Average Case. A green colouring of the Member State means that the hydrogen demand is covered; the red-der the colouring, the greater the shortfall.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks



Figure 12: Hydrogen balances at national level with the assumptions of Scenario II in the Average Case. A green colouring of the Member State means that the hydrogen demand is covered; the red-der the colouring, the greater the shortfall.

Based on the results of the two calculations in the average case, it can be stated that the hydrogen corridors in both scenario I and scenario II (with significantly reduced capacities of the hydrogen corridors) are dimensioned in such a way that the demand of the considered countries can be met. Individual red spots with hydrogen shortages in Belgium, Switzerland and South-East Europe can be explained by the fact that none of the corridors considered pass through these countries and the demand cannot be met by the respective domestic production in either MaxGC or AC. However, this has to be evaluated in the context of the overall EHB planning, which, in addition to the development of the corridors, also foresees a cross-border hydrogen network [22] (Figure 13A and B). Therefore, the transport capacities for this small and local shortfall are also covered according to plan.

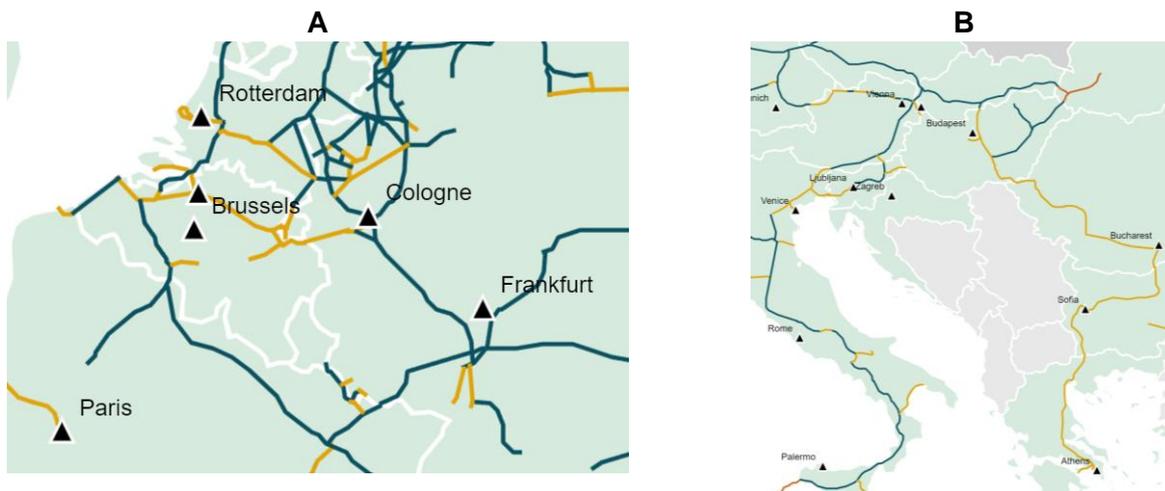


Figure 13: Extract from the EHB map for the year 2030, focusing on Belgium (A) and South-East Europe (B) [23].

The situation becomes more challenging when considering the MaxGC and thus the worst case scenario in terms of national self-sufficiency (Figure 14).



Figure 14: Hydrogen balances at national level with the assumptions of Scenario I in the Maximum Gap Case. A green colouring of the Member State means that the hydrogen demand is covered; the redder the colouring, the greater the shortfall.

Under the assumptions of Scenario I, the gap is particularly evident where there is a deficit in MaxGC and where no hydrogen corridor develops as planned. This concerns in particular the Netherlands (-43.6 TWh), Switzerland (-26.9 TWh) and Denmark (-13 TWh). A closer look at the planning of the EHB for 2030 shows that the Netherlands, Denmark, Norway and Germany will be connected via the backbone network as planned, regardless of the five main corridors [22] (s. Figure 15). The countries in south-eastern Europe with a somewhat smaller volume deficit will also be connected to a hydrogen network by 2030 as planned, in this case mainly by new pipelines. It can therefore be assumed in this calculation that the demand can basically be met by the capacities of the main corridors and the accompanying cross-border backbone network.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks



Figure 15: Extract from the EHB map for the year 2030, focusing on the Netherlands, Norway, Denmark and Germany [23].

The worst-case calculation, which combines the maximum national gaps of MaxGC with the pessimistic assumptions of Scenario II, is somewhat more critical (s. Figure 16). Under these pessimistic assumptions, there is a significant capacity gap for Germany (-105 TWh/a).

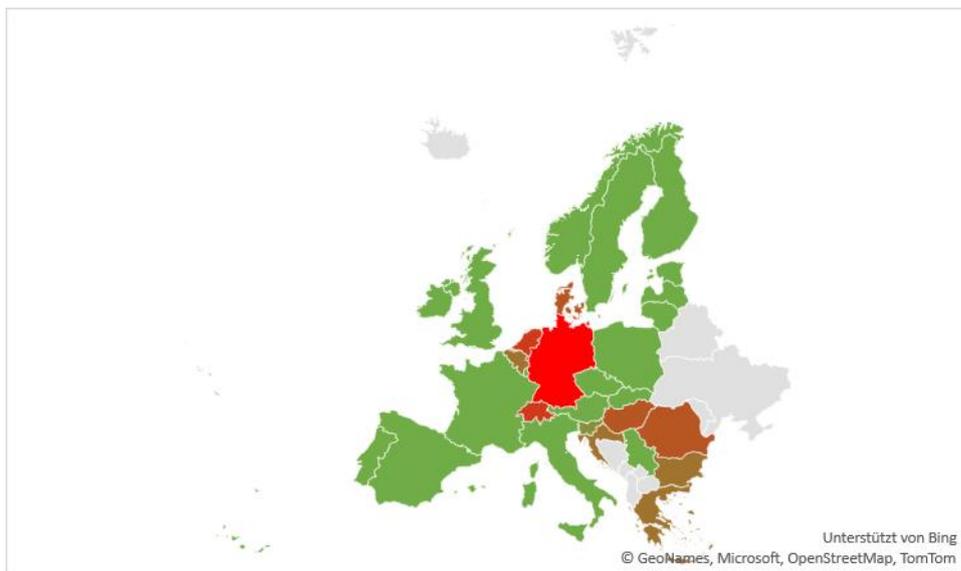


Figure 16: Hydrogen balances at national level with the assumptions of Scenario II in the Maximum Gap Case. A green colouring of the Member State means that the hydrogen demand is covered; the redder the colouring, the greater the shortfall.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

It should be noted that the calculations are scenarios and do not claim to be absolute. Neither the planning of the national hydrogen production and demand structure nor the planning of the corridors and the backbone or national hydrogen networks beyond them have been completed. However, these calculations can provide an indication of whether the capacities at the European level are sufficient to adequately transport hydrogen from regions with high production or import potential to regions with high demand, or whether there is a strategic need for accompanying measures through blending in the transport networks. If the framework conditions change significantly, for example due to massive delays in the construction of the backbone or due to significantly different production and consumption structures, the conclusion may change.

Looking at the results under the assumptions described above, it can be seen that in the two AC scenarios the corridors can transport enough hydrogen to meet the needs of the countries considered. Regions not connected by one of the corridors can be supplied by the rerouted and newly built hydrogen networks from neighbouring countries. If national self-sufficiency deteriorates due to a slow build-up of production capacity and/or rapidly increasing demand, the cross-border pipelines will have to support the corridors more strongly, independently of the corridors. At first sight, this does not seem problematic, as these pipelines are planned anyway and are also necessary to transport the hydrogen more densely. However, if, in the case of low national self-sufficiency, the capacities of the corridors are also significantly reduced or even entire corridors are eliminated, the situation changes. This is shown in the last scenario (MaxGC Scenario II) for a 25% capacity reduction of all corridors and the elimination of the corridor coming from Ukraine. In this case, a regional and, depending on the scenario, a continental shortfall cannot be excluded. In the case under consideration, there is a significant shortfall especially in the country with the highest hydrogen demand, Germany.

On the basis of these results, several questions arise:

A. Are the corridors reasonably dimensioned until the year 2030?

The results of the calculations indicate that the corridors are sufficiently dimensioned and adequately flanked by the hydrogen networks beyond them. If demand develops as expected, a partly delayed start-up or initially lower capacity utilisation can be compensated. Nevertheless, ambitious progress in planning and commissioning is needed. Adverse lock-in effects are not to be expected, as demand will continue to grow until 2040 and beyond to meet climate targets, and further capacity will be needed. Hydrogen imports via appropriate terminals will then play an increasing role, as will the further expansion of the European hydrogen network. According to the current plans of the EHB, the total length of the EHB will be about 32,500 km in 2030 and about 57,500 km in 2040.

B. Can hydrogen blending at transmission level help with delayed corridor build-up or rapidly increasing demand?

From a technical and balancing point of view, yes, in principle. But the question cannot be answered without further context. A closer look at the MaxGC Scenario II case shows that the quantitative shortfall, especially in Germany, is caused on the one hand by the discontinuation of corridor E and the reduced capacities of corridors A to D, and on the other hand by the assumed high demand for hydrogen with simultaneously low national production. Under these assumptions, if the rather negative attitude of German TSOs and customers towards blending (see D6.2) persists, it is likely that Germany will try to bring hydrogen into the country via other routes. On the one hand, there is an incentive to expand Corridor C from the North Sea further and faster, and on the other hand, there is an incentive for countries with high production and import potential to expand pipeline capacities towards Germany. In this case - with a strong increase in demand for hydrogen in Germany - a faster decline in demand for natural gas can still be expected, so that existing pipelines can be repurposed if necessary. Finally, in such a case there is an additional incentive to increase national production volumes and to accelerate the import of hydrogen or derivatives via terminals.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

On the other hand, blending may also be relevant at the transport network level in regions with different conditions. This may be the case, for example, if relevant capacities for the transport of pure hydrogen are lost and cannot be compensated by alternative routes or by the repurposing of existing natural gas pipelines. In this case, care must be taken at national level to ensure that unacceptably high concentrations of hydrogen are not reached at border crossings. Furthermore, if centralised hydrogen transport pipelines are lost, it is possible that several Member States will be affected in parallel, resulting in a regionally limited cluster with admixtures based on multilateral agreements.

C. Does this make hydrogen blending a marginal issue?

No.

In answering the question, a distinction has to be made between the transport network and the distribution network.

At the transmission network level, the strategic transport of hydrogen will most likely take place via dedicated hydrogen networks. Natural gas networks will initially remain in place and will gradually be converted to climate-friendly gases, up to and including climate neutrality. However, there are reasons for blending:

1. **National networks:** where single pipelines are located in individual regions so that parallel transport of hydrogen and natural gas is not possible, blending can help to bring hydrogen to consumers via the transport networks using processes compatible with H2NG blends. In some cases it may also be economical to separate the hydrogen and use the two base gases separately. A prerequisite for national blending is that spillover of increased hydrogen concentrations at border crossings can be excluded, so that stub lines are the main option to avoid costly separation from the transport network.
2. **Bi-/multilateral agreements:** The same applies as for national networks. In addition, the consequences of agreements on the scope of the Gas Package need to be analysed. Furthermore, the complexity of avoiding spill-over is increased in the case of cross-border flows.
3. **Biomethane:** The role of biomethane in Member States' plans varies according to circumstances and strategy. In significant parts of Europe, biomethane is part of the strategy to achieve climate-neutral gas networks. Depending on the development of national and regional transport and distribution networks, it also makes sense to transport biomethane via the transport networks. In this way, a mixture of hydrogen and methane can also be found in a climate-neutral network. Here, too, the European TSOs will undoubtedly adopt different strategies, also depending on the respective customer structure.
4. **Blending within the limits of the Gas Package:** Even with a blending limit of 2-5% in the transport networks, a considerable amount of climate-neutral hydrogen can be absorbed. On the one hand, customers and distribution networks are supplied with climate-neutral gas; on the other hand, such blending also contributes to the ramp-up of hydrogen production and can help to reduce the curtailment of hydrogen production plants and upstream renewable energy generation plants, thus contributing to an increase in the efficient use of energy.

The European distribution network is also extremely heterogeneous, depending on regional conditions, national and company strategy and network structure, so that a distinction has to be made. Overall, however, distribution network operators are much more open to hydrogen blending than

D6.3 Pathway and proposals summary to enable wider injection of H₂ in EU gas networks

transport network operators. This can be seen in the publications of ready4H₂, an initiative of 91 distribution network operators from 22 countries [24]. On the other hand, it is also demonstrated by numerous projects at the distribution network level that are dedicated to the topic of blending. Blending at distribution level is considered important for several reasons:

1. Speed
2. Flexibility
3. Size

The distribution networks can quickly contribute to the decarbonisation of many millions of households and SMEs through blending, and at the same time absorb local quantities of hydrogen that cannot be fed into the transport network for capacity reasons or due to surplus supply. Sensitive consumers need to be protected from the negative effects of high or fluctuating hydrogen concentrations. This can be done either by excluding the relevant pipeline sections from injection or by technical measures on site.

Another important aspect is that, in order to achieve climate neutrality, the distribution networks will to a large extent distribute both biomethane and hydrogen. Here, too, there will be mixtures of methane and hydrogen in the target state. At this point it is important to point out the considerable heterogeneity of the different regions within a country and across Europe. The solution spaces are different for densely populated conurbations than for rural and partly agricultural regions, and again different for industrial centres and mixed areas. A bottom-up approach is therefore important to ensure efficient and realistic planning of local gas networks. The issue of blending at distribution level is very important in this context.

6 Regulations, codes and standards

The European legal and technical framework, as it is illustrated in the HIGGS deliverable report D2.2 from June 2020 [25] and D2.3 [26] from December 2021, is considered and updated in this clause.

6.1 EC policies and legislation

Regarding **European policies** since the completion of the HIGGS Deliverable D2.3, the European Commission published the proposals for the revision of the EU Gas Directive (2009/73/EC, [27]) and the EU Gas Regulation (715/2009/EC, [28]) on 15 December 2021 as a part of the Green Deal and Fit for 55 [29]:

- “Proposal for a directive on common rules for the internal markets in renewable and natural gases and in hydrogen” COM(2021)804 and
- “Proposal for a regulation on the internal markets in renewable and natural gases and in hydrogen” COM(2021)803.

They both together set the basic legal frame for hydrogen blending with natural gas but also for pure hydrogen in the European energy market. More details on the requirements related to blending are given in D6.2 and chapter 4.1 of this document.

At the moment of drafting of this deliverable, the legal proposals are subject to interinstitutional negotiations of the EU Parliament and the EU Council (Trilogue).

The Green Deal and Fit for 55 policies were complemented by the **REPowerEU plan** [30] as a reaction of the military aggression of Russia against Ukraine in May 2022. It aims at European independency from Russian fuel imports and contains – among others - measures to accelerate the take-up of renewable and low-carbon hydrogen (see Figure 17). The plan focusses mainly on hard-to-decarbonise sectors such as transport (mobility) and energy intensive industry. To mention here is the increase of the general renewable target in the Renewable Energy Directive from 40% to 45% by 2030 and the strengthened ambition of achieving at least -55 % net GHG emissions by 2030 and climate neutrality by 2050. Furthermore, with this plan the EC put forward two delegated acts on the definition and production criteria of renewable hydrogen which create a joint basis for the take-up, meanwhile formally adopted on 20 June 2023:

- Delegated Act on a methodology for renewable fuels on non-biological origin [31].
- Delegated Act establishing a minimum threshold for greenhouse gas (GHG) emissions savings of recycled carbon fuels [32].

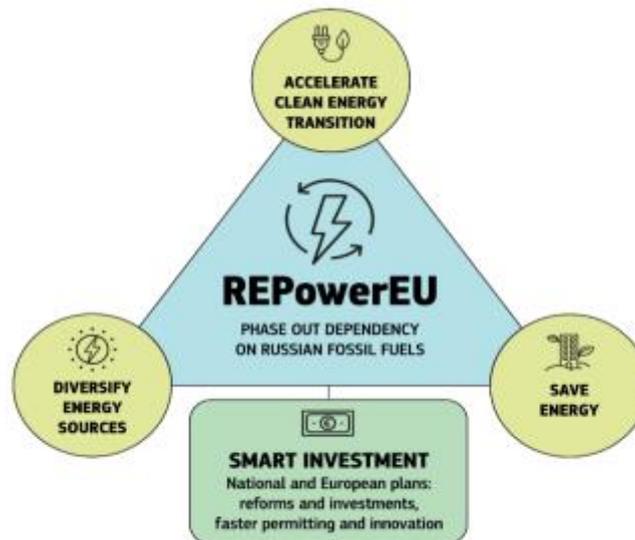


Figure 17. Overall objectives of REPowerEU goals [30]

With regard to this HIGGS project,

- the REPowerEU goals for hydrogen production volumes are considered in the derivation calculations of future average and maximum hydrogen balances at national level as input for the projection scenarios for 2030 (D6.2, chapter 4).
- the EC call on industry to accelerate the work on missing hydrogen standards, in particular for hydrogen production, infrastructure and end-use appliances builds a notable support for the standardisation activities on hydrogen in CEN and CENELEC [30].

A significant support to the practical development of sustainable networks across Europe for gas is given by the **regulation Trans-European Networks for Energy** (TEN-E; REG (EU) 2022/869 [33]) by providing financial and policy funding of EU projects of common interest (PCIs). The current version of the regulation gives a specific focus on hydrogen infrastructure, including transport and certain production technologies with electrolysis. It stipulates mandatory sustainability criteria for PCIs which – among others – allow the support of conversion projects for gas pipelines to convey hydrogen until end of 2027, but also natural gas or biomethane admixtures with hydrogen until end of 2029 are in the scope. New natural gas projects are generally not supported anymore.

The Commission will provide an implementation report on the progress of all PCI projects by 30 June 2027. Foreseen energy network plans including cross-border infrastructure will be provided by ENTSO-G and ENTSO-E.

6.2 National Hydrogen Strategies

In implementation of the EU policies and the planning of the countries for their decarbonisation of the energy system, the transport (mobility), industry and – in general - society, 18 of the 27 EU Member countries have a national hydrogen strategy (AT, BE, BG, HR, CZ, DK, EE, FI, FR, GE, HU, IE, LU, PO, PT, SK, ES, NL) ; 3 of the EU27 are in the draft stage (GR, IT, SE); 7 have no strategy yet (CY, LV, LT, MT, SI, RO). For the EFTA countries, 1 has a hydrogen strategy (NO), 2 have not (IS, LI). Even if different in the level of details they, they all express the national vision and ambitions for the development, research, production, infrastructure and application of hydrogen technology.

In all strategies it is expressed that hydrogen is a significant element of the transition of the energy systems and the achievement of the CO₂ reduction goals. All strategies aim at clean hydrogen for climate neutrality by 2050 at the latest, some acknowledge and include low-carbon hydrogen as transitional support achieving fast decarbonisation effects in parallel to the establishment of a robust climate neutral hydrogen systems.

In the most strategies hydrogen should be used in the sectors where no reasonable alternative for decarbonisation is given in terms of technology and economics. The most indicated sectors are industry, transport (mobility) and power. Hydrogen for heating (buildings) is an issue in many countries as well but not of the same priority than the others.

Whether blending of hydrogen with natural gas or biomethane will play a role in the countries and which role is not evident from all strategies.

In some strategies, as in the Irish [34], it is hinted to the significance of strategic decisions and the need of clear transition plans regarding the utilisation of pipelines to meet the energy demand at mid- and long term and on the other hand the orientation towards the future green hydrogen system. The use of blending shall not be instrumentalised to keep natural gas and/or gas networks longer in operation than strategically needed and it shall not hinder or delay the establishment of pure hydrogen end uses; the supply routes need to be planned with view to the locations of production and demand which might differ from the current situation with natural gas.

Countries that have no specific hydrogen strategy at the time of writing this report indicate strategic hydrogen in the National Energy and Climate Plans NECP.

The situation of national hydrogen strategies is meanwhile well documented on several websites that can be considered as reliable, as on those of the **Clean Hydrogen Partnership** [35] providing a European Hydrogen Observatory with national strategies, legal policies and many other valuable information (reports on the hydrogen landscape, scenarios for future hydrogen demand, costs and others) and the **Weltenergierat** on International Hydrogen Strategies[36] (excerpt s. Figure 18). Both websites only appeared in deep dive internet research for the smaller countries without evidence for the availability of hydrogen strategies. It is recommended to review the key terms for internet research to give more attention to the websites.



Key: dark green: published – light green: in draft stage – grey: no strategy

Figure 18. National Strategies in European countries as of September 2023 [36]

The national strategies are listed in in Appendix 9.1, where their relevant content is displayed.

6.3 European technical framework by standardisation

6.3.1 EU framework for standardisation

The EU policies of the Green Deal and related strategies and strategic plans are also implemented in the EU strategy and EU programme for standardisation:

The revision of the **EU Strategy on Standardisation** [37] in 2022 strengthens the consideration of European values, policy objectives and regulation in European and also international standardisation. It refers to EC’s ambitions, urgent topics and organisational supports regarding standardisation, including (among others)

- continuation of setting priorities in the Annual Union Work Programme for standardisation (AUWP)
- standardisation in support of the green transition and the “roll-out of the clean hydrogen value chain
- cooperation with the European Standardisation Organisations (CEN, CENELEC, ETSI) to optimise the development and adoption of standards

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Europeans leading role in international standardisation

- strengthening the use and consideration of European research results in standardisation.

The EU Regulation on standardisation (REG (EU) No 1025/2012) [38]

- sets the rules for the provision of European standards and European standardisation deliverables for products and for services, in support of Union legislation and policies.
- stipulates the relationship between the EU Commission and the recognised European standardisation institutes CEN, CENELEC and ETSI,
- stakeholder involvement in the standardisation and
- determines the financing.

With the yearly provided **Annual Union Work Programme for standardisation (AUWP)** EC expresses on one hand its political priorities for standardisation and on the other hand creates the legal basis for Standardisation requests from the EC to the European Standardisation Organisations CEN, CENELEC and ETSI and also for funding of standardisation and related pre-normative activities by the European Innovation Council and SMEs Executive Agency (EISMEA)¹. Standardisation for hydrogen topics has been in the programme since several years; The AUWPs for 2023 and 2024 (preliminary) request the hydrogen standardisation actions given in Table 4. There is no evidence for specific action related to blending.

¹ EISMEA supports and manages EU programmes in the fields of SME support, innovation ecosystems, single market, consumer policy and interregional innovation investments.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Table 4. Hydrogen standardisation with relevance to pipelines requested according to AUWP 2023 [39] and AUWP 2024 (preliminary) [40] – Actions on Energy transition and reduction

Actions for the development and revision of European standards or European standardisation deliverables supporting the green transition				
Ref AUWP (Action)	Title	Reference	European standards/European standardisation deliverables	Specific objectives and policies for European standards/European standardisation deliverables
2023(1) and 2024(14)	Hydrogen technologies and components	COM/2021/804 final, proposal regulation on the internal markets for renewable and natural gases and for hydrogen [41] COM/2021/557 final, proposal for directive as regards the promotion of energy from renewable sources [42]	Develop European standards on quality, technology and safety for the production and use of hydrogen.	Improving the development and maintenance of hydrogen infrastructure and components* in the single market
2023(2) and 2024(15)	Transport and storage of hydrogen	Regulation (EU) 2022/869 TEN-T, [33] ** COM/2021/803 final, proposal for directive on common rules for the internal markets in renewable and natural gases and in hydrogen [43]	Revise existing and develop new European standards for hydrogen quality and safety – relevant for injection into the dedicated hydrogen network, and end uses, including hydrogen-based fuels	Enabling and promoting the scaling up of transport and storage methods for hydrogen while ensuring the safety and operational efficiency of gas networks and avoiding inadvertent barriers, which will facilitate the replacement of fossil fuels and feedstocks in hard-to-decarbonise sectors.
<p>*aspect added in 2024 ** reference updated in AUWP 2024 due to revision of Regulation</p>				

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

As stipulated in the EC standardisation strategy, EC established the **High-Level Forum on Standardisation (HLF)**, chaired by EC, and started in January 2023. It aims at the identification of priority standardisation topics in support of the EU policies and legislation as well as the optimisation of the European standardisation system. The recommendations of the Forum are incorporated in the AUWP.

Following a multi-stakeholder approach, the HLF is composed of 60 members, i.e. stakeholders from the EU and EFTA countries, European Standardisation Organisations (CEN, CENELEC, ETSI), industry, civil society and science. The members of the Forum committed themselves by signing a pledge to support the education of a new generation of European standardisation professionals [44]. [45]. The Forum works with subgroups (so called Sherpas) unifying technical expertise and knowledge on standardisation on the topic in question and work streams elaborating on specific topics such as Clean Hydrogen led by Croatia.

European Clean Hydrogen Alliance (ECH2A) has been launched and promoted by the EU Commission in support of the EU Hydrogen Strategy in 2020, aiming at facilitating the large-scale deployment of clean hydrogen technologies. It is a measure towards industrial leadership and acceleration of the decarbonisation of industry in line with climate change objectives. The Alliance builds a platform for industry, national and local authorities, civil society and other stakeholders considering the full hydrogen chain from production, transportation to use. It currently counts about 1600 members. Its role is also to promote investments (see project pipeline below).

In an ECH2A report on barriers to the large-scale deployment of clean hydrogen in Europe from the perspectives of market, regulatory framework, infrastructure and technology [46], published in October 2021, the availability of standards was identified as a potential barrier to roll-out hydrogen technologies and applications. As a consequence, a dedicated Working Group elaborated the ECH2A Roadmap on Hydrogen Standardisation which the EC gave over to CEN and CENELEC for implementation (s. chapter 6.3.2) in March 2023.

This Roadmap refers to hydrogen as an energy carrier in the different forms and covers the complete hydrogen value chain. It clusters the parts of the chain and describes legal and technical frameworks. It contains a non exhaustive list of around 400 identified standardisation topics in the responsibility of about 50 CEN and CENELEC Technical Committees (in cooperation with about 29 ISO and IEC Technical Committees), giving evidence where standardisation is already in process, where existing standards might be revised and where standardisation need is still given. It also elaborates on criteria for prioritisation (see Key action 2). The clustered topics are set in the timeline by 2030 in line with EC policies. The Roadmap considerations are based on input from ECH2A members, sector activities, the CEN and CENELEC activities and (draft) EC Standardisation Requests.

Finally, the Roadmap issues six key actions (see box below), of which especially **Key action 3** is of high importance for the overall success of standardisation: “**Get broader stakeholder engagement in the standardisation process by sending experts to the relevant standardisation committees**”. In this respect the Roadmap gives valuable information on the status of standards and standardisation processes which can facilitate to get access and engaged in standardisation.

The quality of standardisation in general and thus for hydrogen including high-pressure transmission grids for hydrogen and its blends rely one-to-one on the contribution of expertise and experience from industry, academics, standardisers and further interested parties.

This includes that the results of the many significant research projects on European but also on country and company level can give real added value to standardisation. The challenge is to bring the relevant findings in the standardisation work. The commitment of the project partners and experts

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

and especially the willingness of the commissioning parties to make the results available is crucial here.

A broad involvement ensures the appropriate comprehensiveness and appropriateness of standards for purpose and support further on the acknowledgment and application in the daily practice.

Participation is possible via national standardisation bodies and stakeholder organisations.

The ECH2A Roadmap Key actions:

- “Key action 1: Integration of the identified standardisation topics list into the standard-setting process at EU level (CEN-CENELEC) and international level (ISO-IEC).
- Key action 2: Prioritise, as a first step approach, topics that are not yet directly addressed in specific standardisation committees; topics that need further technical understanding to allow for identification of standardisation needs; topics that are horizontal and therefore relevant for different segments of the hydrogen value chain.
- Key action 3: Get broader stakeholder engagement in the standardisation process by sending experts to the relevant standardisation committees.
- Key action 4: Call on the European Commission to support the hydrogen standardisation process by issuing standardisation request(s).
- Key action 5: Continuous support of the standardisation process by the WG on Standardisation.
- Key action 6: Strengthen the coordination of the overall process, including with relevant Horizon Europe Partnerships.

Excursus: In support of the establishment of the hydrogen market, the ECH2A also established a so called ‘project pipeline’ presenting hydrogen research projects in support of an integrated hydrogen value chain and across Europe. The projects nominated by May 2021, were assessed by the EU Commissions services regarding scope, maturity by end of 2030, geographic relevance, emission reduction and impact. The criteria are given on the ECH2A website. Out of the 1241 projects, 163 are related to transmission and distribution. Project titles and archetypes do not allow an interpretation how many projects and which of them are related to hydrogen admixtures with natural gas. [47]

CEN-CENELEC Co-ordination of the hydrogen standardisation

In the CEN and CENELEC standardisation for the whole hydrogen chain about 50 Technical Committees (TC) with more specific working groups are identified that elaborate relevant standards for products (gas quality, pressure regulators, seals, safety controls), functional systems (e.g. pipeline bound infrastructure) and services (e.g. safety management) related to hydrogen and hydrogen admixtures with natural gas. The resulting standards need to be coherent to ensure that products (components) fit into the systems, that the different parts/plants of systems are interoperable and last but not least that applications can use the conveyed gas/hydrogen qualities. Some topics are relevant for all parts of the chain and are just looked at from different perspectives of the different TCs (e.g. impact of hydrogen on materials, gas/hydrogen qualities).

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

The number of committees reflects the of complexity of standardisation topics and diversity of the needs of expertise. It should be noted that many products are used in different Sectors (e.g. pipes and seals used for gas or water).

For this overarching coordination of the European hydrogen standardisation and comprehensive approaches are needed beyond the regular direct liaisons work between the groups and beyond the coordination, consultations and investigations in the CEN and CENELEC Sector Fora², i.e. Sector Forum Gas infrastructure, Sector Forum Gas utilisation and Sector Forum Energy Management and energy transition, Sector Forum Rail).

Reflecting the needs and recommendations of CEN-CENELEC Technical Committees and representatives of national standardisation bodies at a joint internal workshop in October 2023, there is the intention to establish a coordination group that also considers aspects of cooperation with international standardisation in ISO and IEC and strengthening of the European voice on global level.

Additionally, EC Standardisation Requests in the field of hydrogen to CEN and CENELEC are highly appreciated. The draft standardisation request mentioned in D2.3 is still on a hold; a draft request for hydrogen quality in dedicated hydrogen systems is announced for 2024, after completion of the Gas Package.

6.3.2 Standards for gas transmission grids

Reminding the descriptions in D2.3 the technical standards for the design, construction, operation and maintenance as well as for products components and equipment in gas infrastructure can basically be applied for grids conveying hydrogen and its blends with natural gas (or biomethane); Amendment of the standards can be needed with respect to the hydrogen impact on:

- “materials such as embrittlement of steel, permeation through materials, suitability of elastomers and sealing materials), on
- safety aspects such as purging/venting, gas tightness, leakage, detection as well as on
- the technical system such as compression, metering”.

All these aspects need evaluation and testing.

The investigation of revision need of existing standards and the identification of additional standardisation needs to provide the appropriate and comprehensive set of standards is an ongoing process in the CEN and CEN-CENELEC Technical Committees and Sector Fora. Remaining challenges are further on the interdependencies between standards (e.g. products and components used to build systems need to be referenced in the dedicated standards) and the uncertainty which hydrogen concentrations can be expected in the natural gas admixture. For the latter, the CEN Technical Committees in the field of gas infrastructure and commercial and residential applications continue their work to enable hydrogen concentrations up to and including 20% and 100 % hydrogen. Regarding the pipework, it is to emphasise that generally the impact of hydrogen for example on material, sealings, valves and others is not different if they convey blends or pure hydrogen. Thus, at the time being for many revision projects the differentiation between hydrogen blends and for 100%

² The role of the CEN and CEN-CENELEC Sector Fora for hydrogen standardisation is described in D2.3. Clause 4.2.2.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

hydrogen is not obvious yet. However, the standards for high-pressure pipelines the focus is on 100% hydrogen.

The list of standards and Technical Committees relevant for the gas transmission infrastructure given in D2.3 is updated here below.

Table 5 focuses on the European standards for on land gas transmission network including standards for the pipelines, components, equipment and the connection to other grids and facilities.

There are also few offshore transmission pipelines in Europe for which EN 14161 (Petroleum and natural gas industries - Pipeline transportation systems (ISO 13623:2009 modified) and related reference standards apply. These are not specifically included in this table. In general it needs to be stated that European on land network operators are focussing on European standards for gas grids,. Reasons have been the limited European influence and control on technical contents in ISO but also the local/regional relevance of the pipework. In the contrary, for products and components international standardisation plays a significant and increasing role. Whilst in ISO a limited set of gas infrastructure standards have been available, there are divers intentions to extend the work, e.g. in ISO/TC 67 (Oil and gas industry including low carbon energies) and ISO/TC 197 (Hydrogen technologies). Further cooperation modes need to be discussed between CEN and ISO Technical Committees for purpose. However, also other (standardisation) organisations, such as ASME and EIGA are getting another notion in the European standardisation as well.

As far as evident, the relevance for hydrogen is indicated by an asterix (*) behind the standard reference number and the status of hydrogen inclusion is indicated as text below the document title.

Additionally, the available standards on hydrogen that can be applied for adaptation of the transmission grids for the transport of blends or conversion for pure hydrogen are integrated in Table 5 below.

Table 5: European standards for gas transmission grids (does not claim to be exhaustive)

Standard reference	Title	Current version	Responsible TC
Gas quality standards			
EN 16723-1	Natural gas and biomethane for use in transport and biomethane for injection in the natural gas network - Part 1: Specifications for biomethane for injection in the natural gas network	2016	CEN/TC 408
EN 16726*	Gas infrastructure - Quality of gas - Group H	2015/ 2018 Revision 2023 in CEN public enquiry	CEN/TC 234
CEN/TS 17977*	Gas infrastructure – Quality of gas – Hydrogen used in converted/rededicated gas systems	2023	CEN/TC 234
EN ISO 6145*, parts 1, 4 to 11	Gas analysis - Preparation of calibration gas mixtures using dynamic volumetric methods	2008-2019	CEN/TC 238 – ISO/TC 158
EN ISO 6974* parts 1 to 5	Natural gas – Determination of composition and associated uncertainty by gas chromatography Note: Part 4 is in fundamental revision giving guidance on gas analysis	2001-2018	CEN/TC 238 – ISO/TC 193

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Standard reference	Title	Current version	Responsible TC
EN ISO 6975*	Natural gas — Extended analysis — Gas-chromatographic method (ISO 6975)	2005	CEN/TC 238 – ISO/TC 193
EN ISO 6976	Calorific value, density, relative density and Wobbe indices from composition Note: Revision has started in 10/2023 under the Vienna Agreement with ISO lead.	2016	CEN/TC 238 – ISO/TC 193
EN ISO 13443*	Natural gas — Standard reference conditions	2005	CEN/TC 238 – ISO/TC 193
EN ISO 13734*	Natural gas – Organic components used as odorants – Requirements and test methods	2013	CEN/TC 238 – ISO/193
ISO 14687*	Hydrogen fuel quality – Product specification	2019	ISO/TC 197
ISO 19229*	Gas analysis — Purity analysis and the treatment of purity data	2019	ISO/TC 158
ISO/TR 16922:	Natural gas – Odorization	2013	ISO/TC 197

Functional standards for design, construction and operation of on-land gas transmission infrastructure with maximal operation pressure over 16 bar

EN 1594*	Gas infrastructure - Pipelines for maximum operating pressure over 16 bar - Functional requirements	2023	CEN/TC 234
EN 12327*	Gas infrastructure - Pressure testing, commissioning and decommissioning procedures - Functional requirements	2012	CEN/TC 234
EN 12732*	Gas infrastructure - Welding steel pipework - Functional requirements	2014	CEN/TC 234
EN 17649*	Gas infrastructure – Safety Management (SMS) and Pipeline Integrity Management System (PIMS) - Functional requirements (replacing CEN TS 16348)	2022	CEN/TC 234
EN 14161*	Petroleum and natural gas industries - Pipeline transportation systems (ISO 13623:2009 modified) Note: Applicable for offshore gas transportation system	2015	CEN/TC 12 – ISO/TC 67 SC 2

Functional standards for the conversion of gas pipelines for hydrogen use

WI 00234107	Gas infrastructure - Conversion of pipelines with maximum operating pressure over 16 bar for the use of hydrogen - Functional requirements	Working draft awaited 1 st Q 2024	CEN/TC 234
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D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Functional standards for components and equipment

EN 1776*	Gas infrastructure - Gas measuring systems - Functional requirements Note: Revision is in progress, even if availability for hydrogen-ready gas meters and other related issues is not fully given.	2015	CEN/TC 234
EN 12186*	Gas infrastructure - Gas pressure regulating stations for transmission and distribution - Functional requirements Note: Revision with EISMEA funding in 2023-2026.	2014	CEN/TC 234
EN 12583*	Gas Infrastructure - Compressor stations - Functional requirements	2022	CEN/TC 234

Product standards for components and equipment

EN 334*	Gas pressure regulators for inlet pressure up to 10 MPa (100 bar)	2019	CEN/TC 235
EN 682*	Elastomeric seals - Materials requirements for seals used in pipes and fittings carrying gas and hydrocarbon fluids	2005	CEN/TC 208
EN 1012-3	Compressors and vacuum pumps — Safety requirements — Part 3: Process compressors	2013	CEN/TC 232
EN 12261*	Gas meters - Turbine gas meters Note: Publication of revision expected for 2024	2018	CEN/TC 237
EN 12266-1*	Industrial valves - Testing of metallic valves - Part 1: Pressure tests, test procedures and acceptance criteria - Mandatory requirements	2012	CEN/TC 69
EN 12266-2*	Industrial valves - Testing of metallic valves - Part 2: Tests, test procedures and acceptance criteria - Supplementary requirements	2012	CEN/TC 69
EN 12405-1*	Gas meters - Conversion devices - Part 1: Volume conversion	2021	CEN/TC 237
EN 12405-2*	Gas meters - Conversion devices - Part 2: Energy conversion	2012	CEN/TC 237
EN 12405-3*	Gas meters - Conversion devices - Part 3: Flow computer	2015	CEN/TC 237
EN 13463-1	Non-electrical equipment for use in potentially explosive atmospheres — Part 1: Basic method and requirements	2009	CEN/TC 305
EN 13774*	Valves for gas distribution systems with maximum operating pressure less than or equal to 16 bar - Performance requirements	2013	CEN/TC 69

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

EN 13942*	Petroleum and natural gas industries - Pipeline transportation systems - Pipeline valves (ISO 14313:2007 modified/Cor 1:2009)	2009	CEN/TC 12
EN 14141	Valves for natural gas transportation in pipelines — Performance requirements and test	2013	CEN/TC 69
EN 14382*	Gas safety shut-off devices for inlet pressure up to 10 MPa (100 bar)	2019	CEN/TC 235
EN 14505	Cathodic protection of complex structures	2005	CEN/TC 219
EN ISO 4126*, parts 1 to 6	Safety devices for protection against excessive pressure — Note: no need to be revised for hydrogen, applicable to all applications	2013-2020	CEN/TC 69 – ISO/TC 185
EN ISO 10437	Petroleum, petrochemical and natural gas industries — Steam turbines — Special-purpose applications (ISO 10437)	2003	CEN/TC 12 – ISO/TC 67/SC 6
EN ISO 10439 parts 1 to 5	Petroleum, chemical and gas service industries — Centrifugal compressors (ISO 10439)	2015	CEN/TC 12 – ISO/TC 67/SC 6
EN ISO 13849-1	Safety of machinery — Safety-related parts of control systems — Part 1: General principles for design (ISO 13849-1)	2023	CEN/TC 114 – ISO/TC 199
EN ISO 17292	Metal ball valves for petroleum, petrochemical and allied industries	2015	CEN/TC 69 (ISO/TC 153)
ISO 3977* (all parts)	Gas turbines — Procurement	1997-2023	ISO/192
ISO 5168	Measurement of fluid flow — Procedures for the evaluation of uncertainties	2005	ISO/TC 30
ISO 13707	Petroleum and natural gas industries — Reciprocating compressors	2000	ISO/TC 118

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Standards for pipes and coating

EN ISO 3183*	Petroleum and natural gas industries — Steel pipe for pipeline transportation systems (ISO 3183:2019) Note: Including the normative reference to API 5L:2018 pipe (46th Edition, updated on 2020):	2019	CEN/TC 459/SC 10 (ISO/TC 67/SC 2)
EN 751-3+A1	Sealing materials for metallic threaded joints in contact with 1st, 2nd and 3rd family gases and hot water - Part 3: Unsintered PTFE tapes NoteL (Document in comments treatment after Public Enquiry)	2022+2023	CEN/TC 208
EN 10168	Steel products - Inspection documents - List of information and description	2004	CEN/TC 459/SC 12
EN 10204	Metallic products — Types of inspection documents	2004	CEN/TC 459/SC 12
EN 10288	Steel tubes and fittings for onshore and offshore pipelines — External two layer extruded polyethylene based coatings	2002	CEN/TC 459/SC 10
EN 10289	Steel tubes and fittings for onshore and offshore pipelines — External liquid applied epoxy and epoxy-modified coatings	2002	CEN/TC 459/SC 10
EN 10290	Steel tubes and fittings for onshore and offshore pipelines — External liquid applied polyurethane and polyurethane-modified coating	2002	CEN/TC 459/SC 10
EN 10301*	Steel tubes and fittings for on and offshore pipelines — Internal coating for the reduction of friction for conveyance of non-corrosive gas	2003	CEN/TC 459/SC 10
EN 12068	Cathodic protection — External organic coatings for the corrosion protection of buried or immersed steel pipelines used in conjunction with cathodic protection — Tapes and shrinkable materials	1998	CEN/TC 219
EN 12954	General principles of cathodic protection of buried or immersed onshore metallic structures	2019	CEN/TC 219
EN ISO 11114-4	Transportable gas cylinders - Compatibility of cylinder and valve materials with gas contents - Part 4: Test methods for selecting steels resistant to hydrogen embrittlement (ISO 11114-4:2017)	2017	CEN/TC 23 (ISO/TC 58)
EN ISO 12944 (parts 1-8)	Paints and varnishes — Corrosion protection of steel structures by protective paint systems	2017-2018	CEN/TC 139
EN ISO 15589-1	Petroleum, petrochemical and natural gas industries — Cathodic protection of pipeline systems — Part 1: On-land pipelines Note: Revision in process	2017	CEN/TC 219 – ISO/TC 67 SC 2
EN ISO 21809-1	Petroleum and natural gas industries — External coatings for buried or submerged pipelines used in pipeline transportation systems — Part 1: Polyolefin coatings (3-layer PE and 3-layer PP)	2018	CEN/TC 459/SC10 – ISO/TC 67

Other relevant standards for the gas transmission grid

EN 837-1+AC	Pressure gauges — Part 1: Bourdon tube pressure gauges — Dimensions, metrology, requirements and testing	1996+1998	CEN/TC 141
EN 837-2	Pressure gauges — Part 2: Selection and installation recommendations for pressure gauges	1997	CEN/TC 141
EN 837-3	Pressure gauges — Part 3: Diaphragm and capsule pressure gauges — Dimensions, metrology, requirements and testing	1996	CEN/TC 141
EN 1127-1	Explosive atmospheres - Explosion prevention and protection - Part 1: Basic concepts and methodology	2019	CEN/TC 305
EN 1998-4	Eurocode 8 - Design of structures for earthquake resistance -Part 4: Silos, tanks and pipelines Note: in revision	2006	CEN/TC 250
EN IEC 31010	Risk management - Risk assessment techniques	2019	CLC/SR 56
EN ISO 15112	Natural gas - Energy determination	2018	CEN/TC 238
EN IEC 60079-10-1	Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres	2021	CLC/TC 31 (IEC/SC 31J)
EN IEC 60079-14	Explosive atmospheres - Part 14: Electrical installations design, selection and erection	2023	CLC/TC 31 (IEC/SC 31J)
EN 60079-17	Explosive atmospheres — Part 17: Electrical installations inspection and maintenance (IEC 60079-17)	2014	CLC/TC 31
EN 60079-20-1	Explosive atmospheres — Part 20-1: Material characteristics for gas and vapour classification — Test methods and data (IEC 60079-20-1)	2010	CLC/TC 31
EN 60079-29-1+A1+A11*	Explosive atmospheres - Part 29-1: Gas detectors - Performance requirements of detectors for flammable gases	2016+ 2022+2022	CLC/TC 31
EN 60079-29-2	Explosive atmospheres - Part 29-2: Gas detectors - Selection, installation, use and maintenance of detectors for flammable gases and oxygen	2015	CLC/TC 31
EN 60079-29-3	Explosive atmospheres - Part 29-3: Gas detectors - Guidance on functional safety of fixed gas detection systems	2014	CLC/TC 31
EN 60079-29-4	Explosive atmospheres - Part 29-4: Gas detectors - Performance requirements of open path detectors for flammable gases	2010	CLC/TC 31

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

EN ISO 80079-36/AC	Explosive atmospheres - Part 36: Non-electrical equipment for explosive atmospheres- Part 1: Basic method and requirement	2016/2019	CEN/TC 305
EN 61000-6-2	Electromagnetic compatibility (EMC) — Part 6-2: Generic standards — Immunity for industrial environments (IEC 61000-6-2)	2019	CLC 210
EN 61000-6-4	Electromagnetic compatibility (EMC) — Part 6-4: Generic standards — Emission standard for industrial environments (IEC 61000-6-4)	2019	CLC 210
EN 61508 (all parts),	Functional safety of electrical/electronic/programmable electronic safety-related systems (IEC 61508 (all parts))	2010	CLC/TC 65X
EN 61511 (all parts)	Functional safety — Safety instrumented systems for the process industry sector	2019	CLC/TC 65X
ISO 26142*	Hydrogen detection apparatus – Stationary applications	2010	ISO/TC 197
ISO/TR 15916*	Basic considerations for the safety of hydrogen systems	2015	CEN/TC 305 (ISO/TC 197)
prEN ISO 24078*	Hydrogen in Energy Systems – Vocabulary Note: In elaboration; Comments treatment after ENQ in 01/2024	Enquiry stage (ENQ)	CEN/CLC/JTC 6 (ISO/TC 197)
prTS xxx*	Safe use of hydrogen in built constructions Note: restart and change to TS in preparation	Project stage	CEN/CLC/JTC 6

Standards to ensure compatibility with the connection to equipment and grids, where available

EN 1473*	Installation and equipment for liquefied natural gas — Design of onshore installations	2021	CEN/TC 282
EN 1918-5*	Gas supply systems — Underground gas storage — Part 5: Functional recommendations for surface facilities Note: in revision with EISMEA funding 2023-2026	2016	CEN/TC 234
EN 12007 series*	Gas infrastructure — Pipelines for maximum operating pressure up to and including 16 bar (parts 1 to 4) Note: Under revision; hydrogen inclusion intended	2012	CEN/TC 234
EN 15001-1*	Gas Infrastructure — Gas installation pipework with an operating pressure greater than 0,5 bar for industrial installations and greater than 5 bar for industrial and non-industrial installations — Part 1: Detailed functional requirements for design, materials, construction, inspection and testing Note: Verification for hydrogen inclusion	2023	CEN/TC 234
EN 15001-2*	Gas infrastructure — Gas installation pipework with an operating pressure greater than 0,5 bar for industrial installations and greater than 5 bar for industrial	2023	CEN/TC 234

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

	and non-industrial installations — Part 2: Detailed functional requirements for commissioning, operation and maintenance Note: Verification for hydrogen inclusion.		
prEN 17928-1*	Gas infrastructure - Injection stations - Part 1: General requirements Note: Formal Vote in 1 st half of 2024	ENQ draft 2023	CEN/TC 234
prEN 17928-2	Gas infrastructure - Injection stations - Part 2: Specific requirements regarding the injection of biomethane Note: Formal Vote in 1 st half of 2024	ENQ draft 2023	CEN/TC 234
prEN 17928-3*	Gas infrastructure – Injection stations - Part 3: Specific requirements regarding the injection of hydrogen fuel gas Note: Formal Vote in 1 st half of 2024	ENQ draft 2023	CEN/TC 234
ISO/TS 19883*	Safety of pressure swing adsorption systems for hydrogen separation and purification	2017	CEN/TC 197

Note: For the adaption of the gas transmission grid for the use of hydrogen, several further documents are currently used by standardisers and operators such as:

- ASME B 31.12-2019 - Hydrogen piping and pipelines – Revision intended!
- EIGA Doc. 121/14 - Hydrogen Pipeline Systems
- EIGA Doc. 122/11 - Environmental Impacts of Hydrogen Plants
- EIGA Doc. 210/17 - Hydrogen Pressure Swing Adsorber (PSA) Mechanical Integrity Requirements
- NASA SAFETY STANDARD, NSS 1740.16,; Hydrogen and hydrogen systems, Guidelines for hydrogen system design, materials selection, operations, storage, and transportation (12 FEB 1997) [S/S BY ANSI/AIAA G-095-2004].

* The standards marked with an asterisk behind the standard reference have been already identified as relevant for the use of hydrogen in gas systems in the context of the potential EC Standardisation Request.

6.3.3 Standardisation need identified in HIGGS WP 4

During the practical realisation of WP4 the following aspects are identified to be covered in European standardisation. The list does not preempt if the topics are already subject to investigations or standardisation at an early stage.

- 1) Development of pre-normative testing guidelines towards carbon steel pipelines qualification for hydrogen service:** Harmonized methodology describing an experimental procedure to assess the hydrogen sensitivity of non-steel metallic materials under potential injection scenarios in the distribution gas grid (blend or full retrofitting) that will aim as pathway towards the development of qualification procedures.

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

A major issue is the European wide aligned methodology to quantify hydrogen embrittlement and – once the degree of embrittlement has been determined – how to evaluate the related suitability of the materials for use with hydrogen.

- 2) **Assessment of the applicability and complexity of the existing standards or codes for the qualification of metallic materials for hydrogen service.**
- 3) **Identification of gaps of knowledge or areas of future needs in the existing standards, codes and regulations for materials testing and qualification for hydrogen service**, for example:
 - how to test components with complex geometries or small sizes (such as the API 5L steel pipes considered in HIGGS).
 - what strain rates should be used in the SSR tests. The different codes and standards for testing in hydrogen gas, indicate quite different strain rate values.
 - how to test weld junctions
 - what frequency value should be used in fatigue testing...

In this context and when evaluating the hydrogen compatibility of metallic materials in service with hydrogen gas, it is important to distinguish between the standards for materials testing:

- SSRT,
- constant displacement fracture toughness and fatigue tests,
- and the standards for components/system qualification of materials for hydrogen service.

The following documents should be considered for steel qualification/validation for hydrogen service: ASME BPVC VIII-Article KD10 (high pressure vessels), ANSI CHMC-1 (compressed hydrogen applications) or ISO 11114-4 (transportable gas cylinders).

- **ASME B31.12 (2019): Hydrogen piping and pipelines.** Covers transmission and distribution pipelines conveying hydrogen from a production facility to the point of final use for hydrogen percentage above 10% (up to 100%). The ASME code B31.12 refers to article KD-10 for determining fracture resistance of pipeline steels in gaseous hydrogen.
 - The project SyWest H2 (see section 3) investigated the European pipelines against the ASME B31.12 criteria for hydrogen piping and pipelines with the positive result that the tested steel pipelines are suitable for hydrogen. It also addresses the frequency values in fatigue testing. DVGW transferred the technical findings in a national DVGW Code of Practice G 464 which currently is subject to integration in the new standardisation project on the conversion of gas pipelines with maximum operating pressure over 16 bar for hydrogen (WI 002340106) and also in the next revision of EN 1594 for the design, construction operation and maintenance of high-pressure pipelines.
 - A second part of SyWest H2 project aims at investigating the application limit for the fracture mechanics, from when load changes need to be checked and when not. Here the AMSE lifetime cycle and the load change will be considered and the remaining load change potential identified, also with view to the high loads in high pressure grids. Results are expected end of 2024.

D6.3 Pathway and proposals summary to enable wider injection of H₂ in EU gas networks

- The transferability on more complex structure such as valves which are installed in the gas systems is in verification in a further DVGW project on the H₂ tolerance of valves (UKoBaRi H₂ [48])
- **ASME Boiler and Pressure Vessel Code. Section VIII-Article KD-10 (2021): Special requirements for vessels in hydrogen service.** The hydrogen embrittlement tests proposed in this standard are constant displacement CT-WOL (K_{IH}), fracture toughness, and fatigue crack growth rate (FCGR). However, recent results suggests that materials testing methods described in Article KD-10 are not as robust as originally believed. Especially with respect to the constant displacement CT-WOL test, that for low-strength steels (such as pipeline steels) provide non-conservative results. Also, article KD-10 requires fatigue crack growth measurements to be conducted at a frequency of 0.1Hz, which can require thousands of hours to perform. The qualification methods described in the standard apply to three heats of material both for the base, heats affected zone (HAZ) and weld metal which is very costly and time-consuming.
 - In this context reference is made to the following projects in process in mutual cooperation between CEN/TC 54 'Unfired pressure vessels' in cooperation with experts from CEN/TC 267 'Industrial piping and pipelines'
 - the proposed new part of the EN 13445 pressure vessels series – EN 13445-15 – for hydrogen applications (responsible: CEN/TC 54)
 - the work on a new part of the piping series – EN 13840-11 - also for hydrogen application (responsible: CEN/TC 267 'Industrial piping and pipelines')
- **ISO 11114-4 (2017): Transportable gas cylinders: Part 4-Compatibility of cylinder and valve materials with gas contents.** This is a materials performance standard specific for hydrogen pressure vessels constructed with steel having tensile strength greater than 950 Mpa. The proposed hydrogen compatibility tests in this code: disk rupture method, fracture toughness determinations and constant displacement CT-WOL, are often referred to as general test methods for evaluating hydrogen embrittlement but should be limited to steel transportable gas cylinders and not extrapolated to other applications.
- **ANSI/CSA CHMC 1 (2014): Tests methods for evaluating material compatibility in compressed hydrogen applications.** This standard provides guidance on evaluating tensile (SSRT), fracture and fatigue properties of structural metals in gaseous hydrogen. This document provides a quantitative method to determine appropriate safety factors for hydrogen service using fatigue analysis. The qualification methods described in the standard apply to three heats of material both for the base, HAZ and weld metal.

7 Pathway / Open points

The gas grid of the future will be able to transport and distribute climate-friendly gases and thus supply the heterogeneous customer structure with sufficient renewable energy. With its coarse-meshed transport network and fine-meshed distribution network, it will provide the ideal conditions for making an important contribution to achieving the climate targets of the EU and its member states. This will be achieved by ramping up hydrogen and expanding biomethane capacities.

However, on the way to the target state, which is also described in Vision 2050 in D5.4 of the HIGGS project, transitional states have to be passed through, which cannot be avoided due to the immense task. Capacities for the production and import of hydrogen must be built up, and the production and feed-in of biomethane must be expanded. Networks will also have to be redesigned and built to transport, distribute and store the necessary amounts of energy. End-use applications need to be adapted to the changed conditions. At the household level, for example, this concerns the conversion of heating systems to hydrogen heating, and at the industrial level, the conversion of energy-intensive processes to hydrogen, but also to a changed feedstock structure. The heterogeneous structures at different levels have to be taken into account. The different Member States have heterogeneous production and import potentials for climate-friendly gases, heterogeneous consumer structures, heterogeneous geographical and climatic conditions, heterogeneous population and housing situations as well as individual strategies and preferences. Nevertheless, a reliable and affordable energy supply is needed in all areas to maintain or increase prosperity, business locations and quality of life. For this reason, the target countries, and especially the transition countries, cannot be described in general terms for the whole of the European Union. Nevertheless, it is clear that a functioning and reliable gas network, which can be operated safely and economically, is needed. To achieve this, it must be harmonised - even if the basic conditions are heterogeneous. The HIGGS project provides important knowledge in this context by taking stock of the European transport networks and the current national hydrogen strategies and RCS, and by adding investigations into material compatibility and gas-tightness tests of valves. In addition, external influences from regulatory and policy frameworks are analysed and evaluated. However, there are still a number of open issues that are currently being addressed or should be addressed in the future.

The remainder of this chapter outlines some of these issues and provides examples of existing projects that are dealing with them.

7.1 Technical considerations

- (1) On the technical side, numerous projects have been carried out in recent years to answer relevant questions on the compatibility of materials with hydrogen. For example, for pipe materials in the transport network, the current state of knowledge is that the relevant steel grades used in Europe are suitable for the transport of hydrogen under typical operating conditions of a transport pipeline. When assessing suitability, the relevant regulations should be applied to ensure a very high level of safety (e.g. DVGW G 464:2023-03 in Germany [49]).

If unusual pipe materials that have not been analysed in previous projects are identified as part of a pipeline conversion to hydrogen blending or to 100% H₂, a specific assessment should be carried out.

- (2) There is also considerable experience with other gas network components and systems that can be used today. For example, Marcogaz published an update of its "Overview of available test results and regulatory limits for hydrogen admission into the existing natural gas infrastructure and end use" in 2023, which answers questions about the fundamental suitability of blending for many components [50]. There is also a database that assesses the H₂

readiness of a wide range of components and materials in the gas network at a detailed level, based on numerous research results and investigations [51].

If, despite the incorporation of the latest research results, there are uncertainties regarding the hydrogen compatibility of individual components in the context of a pipeline conversion to hydrogen blending or 100% H₂, specific investigations should be carried out, ideally with the involvement of the respective manufacturer.

- (3) Underground gas storage facilities are nowadays essential for maintaining security of gas supply in Europe and will be so in the transitional and target states with climate-neutral gases, in particular in order to economically balance seasonal fluctuations in demand. A distinction has to be made between storage types (aquifers, salt caverns, hard rock caverns and depleted gas reservoirs) and storage development (conversion of a natural gas storage facility or new construction). In addition to the technical questions, which have been and are being answered in numerous research projects (e.g. [52], [53], [54], [55], [56]) there are also important economic and strategic questions.

A strategically appropriate placing of storage facilities in Europe must be converted or newly built to secure supply. The issue of parallel gas infrastructures for natural gas and hydrogen must also be considered in the context of the hydrogen ramp-up. The need for purification during withdrawal must be considered in terms of economic efficiency and the required gas quality. This applies in particular, but not exclusively, to the storage of hydrogen-natural gas mixtures. All these aspects need to be assessed in terms of overall strategy and economics, but also in the context of local conditions. Several studies are carried out or are ongoing on national level. Clarification on the further needs are needed.

- (4) Hydrogen injection stations are defined as new entry points to the gas system. They follow the methodology existing for the injection of biomethane, but with the particularity that hydrogen is a gas with much different properties to natural gas, needing for adapted procedures. Despite being an emerging topic, there are currently many manufactures providing turnkey project for the installation of an injection site, including the detailed engineering, materials and its construction. However, there is lack of legal and regulatory framework so that TSOs can operate their grids with confidence.

A strong national and international regulation for enabling hydrogen injection is still missing, hindering the operation of transport grids with renewable hydrogen.

7.2 Considerations regarding gas quality

- (1) Today's consumers of natural gas and future consumers of hydrogen operate a very heterogeneous range of processes, which means that questions about gas quality cannot be answered in a general way. One of the challenges will be to operate a gas network that is economically efficient and that meets the requirements of its customers in terms of gas quality. As some processes place high demands on the purity of natural gas and hydrogen and only accept low concentrations of individual impurities, but at the same time the gas network as a whole cannot be operated economically for everyone at these high purities, sensitive consumers must be protected by appropriate measures. From an economic point of view, it is necessary to develop technical or process-optimised solutions that also take into account seasonal fluctuations and can be designed for specific locations.

- (2) The sensitivity of individual processes is not only related to the pure level of hydrogen concentration in a blending, but also to the fluctuations in the blending and the associated fluctuations in the combustion properties of the gas. Technical or process-optimised solutions are conceivable, and storage facilities could play a role in smoothing the hydrogen concentration.

Appropriate measures must be found to protect vulnerable consumers while maintaining the economic framework. In this context, responsibilities and liability issues need to be clarified. Flexible solutions are needed to separate or purify hydrogen from different volume flows and pressure levels as required. Different approaches are being discussed for pipelines with blending to protect sensitive consumers. In addition to membrane systems, which are also being discussed in the HIGGS project, methanation to reduce H₂ concentrations [57] or reformers to reduce CH₄ [58] could be used.

- (3) The future hydrogen network will consist of newly constructed gas pipelines and repurposed natural gas pipelines. Newly constructed gas pipelines have the advantage that they are designed for hydrogen operation and do not store and slowly release impurities from previous operation with natural gas and possibly biomethane. Hydrogen networks that transport high purity hydrogen will need to consider and assess impurities introduced into the pipelines from existing pipelines and gas storage facilities, as well as from blending.

Studies are needed to further assess the influence of impurities from rededicated existing pipelines and gas storage facilities on hydrogen quality in new hydrogen networks. In this context, the (temporary) blending in newly constructed or cleaned pipelines is also relevant. Findings gathered in relevant research projects must be taken into account accordingly when repurposing pipelines. In this context, the work in Bad Lauchstädt and in the HyGrid2 project, for example, should be mentioned, which are providing the first important findings [59], [60].

- (4) For most Member States, the European gas distribution network is an important pillar of energy supply to SMEs and a strength of Europe as a business location. Supplying these industrial and commercial customers, as well as households, with climate-friendly energy is therefore extremely important both for the European economy and for climate protection. Distribution system operators and their customers are very open to the issue of blending and are actively developing plans at European level (Ready4H₂, [24]) and also at national level (e.g. Gasnetzgebietstransformationsplan within H₂vorOrt in Germany, [61]) to transform the natural gas grid into a climate-friendly grid that explicitly takes blending into account.

When planning the conversion of gas transmission networks to hydrogen, the needs and objectives of distribution system operators must be taken into account. An active exchange between TSOs and DSOs is necessary to ensure the development of a secure, economic, climate-friendly, efficient and sufficient supply, including the desire for blending at distribution level. Such an exchange must take place at regional level, without neglecting national or European strategies.

7.3 National and cross-border blending considerations at transport level

- (1) The sovereignty of Member States to operate gas networks with higher blends than those specified in the Gas Package for cross-border flows is likely to remain unaffected. This is likely to happen more at distribution network level. However, for various reasons, this may also happen at transmission network level. In this case, care must be taken to ensure that the local blending does not lead to an impermissible limit being exceeded at a border crossing

point, either in the same or a neighboring network. In Member States wishing to carry out national blending of hydrogen into the natural gas network, appropriate procedures shall be identified to avoid a spill-over effect of unacceptably high blending concentrations at neighboring cross-border interconnection points. This starts with the selection of suitable network sections and ends with the installation of purification systems upstream of a cross-border interconnection point.

At the level of Member States wishing to carry out blending, concepts should be developed on how to avoid spill-over at border crossing points through appropriate network selection or purification systems.

- (2) The statements made under 6.3 (1) also apply analogously to ensuring the legally compliant operation of cross-border gas flows in the case of bilateral or multilateral agreements with higher blending limits than those specified in the Gas Package. In such a case, the provisions of the Gas Package shall also be taken into account.

The statements made under 6.3 (1) also apply analogously to ensuring the regulatory-compliant operation of cross-border gas flows in the case of bilateral or multilateral agreements with higher blending limits than those specified in the Gas Package. In such a case, the provisions of the Gas Package must also be taken into account.

- (3) While 6.3 (1) and 6.3 (2) mainly deal with the addition of hydrogen to natural gas and thus the transition to a climate-friendly gas system, the future treatment of biomethane in the target state also needs to be considered. Biomethane is an important building block in the strategy of many Member States to develop a climate-friendly gas network and is therefore also part of the REPowerEU plan.

Member States need to develop concepts, possibly together with neighboring countries, on how to organise joint or parallel transport and distribution of hydrogen and biomethane.

7.4 EC, national policies and RCS

The European legal framework including the framework for high pressure transmission grids is developing with the finalization of the **Hydrogen and gas markets decarbonisation package** (Gas Package) and the availability of the revised Renewable Energy Directive (RED II/III), Energy Efficiency Directive (EED) and Emissions Trading Scheme (ETS). The adaptation of the European regulatory framework, i.e. Network Codes, based on the Gas Package has not yet started, but is – together with the Gas Package – of major importance for the cross-border transmission grid. With the national implementation of the legislation and regulation in the EU Member States adaptations and changes in the national hydrogen policies and strategies are awaited.

In general, the current national hydrogen strategies are rather high-level and focused at mid- and long terms. Blending – in various countries seen as a transition solution for the up-take of hydrogen especially in distribution grids - is not notably elaborated in the national strategies. In the context of this project, especially the possible European legal H₂ concentration thresholds at interconnection points and related market rules are crucial for the strategic national orientation for high pressure transmission grids. Only few countries give evidence on this in their hydrogen strategies.

The situation of national hydrogen strategies is meanwhile well documented on several websites that can be considered as reliable, as on those of the **Clean Hydrogen Partnership** [35] providing a European Hydrogen Observatory with national strategies, legal policies and many other valuable information (reports on the hydrogen landscape, scenarios for future hydrogen demand, costs and others) and the **Weltenergierat** on International Hydrogen Strategies [36]. Both websites only

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

appeared in deep dive internet research for the smaller countries without evidence for the availability of hydrogen strategies. It is recommended to review the key terms for internet researches to give more attention to these very informative websites.

The overall framework for European hydrogen standardisation is well set to achieve the hydrogen standards needed for the uptake of hydrogen in the energy systems:

- on EC level by the general EU standardisation strategy, EU regulation and organizational measures such as the Annual Union Work Programme for Standardisation and the High-level Forum for standardisation; here in addition dedicated Standardisation Requests from EC to the European Standardisation Organisations build streamlining support and are awaited by the standardisation community.
- in CEN and CENELEC by the ECH2A Roadmap on hydrogen standardisation combined with the Technical Committees' work programs.

Regarding the actual realisation of hydrogen standardisation, the current **establishment of CEN - CENELEC coordination** over the whole hydrogen value chain is a significant step to ensure efficient and comprehensive standardisation and coherent standards. It also contributes to clarification of Technical Committees' scope to avoid overlaps, controversial and/or double work. It is supported that Technical Committees and Sector Fora are contributing to the identification of further standardisation needs aiming at fulfilling the expectations of the industry and EC policies.

The **coordination should also lead to a open accessible list of ongoing standardisation work items**, indicating the scope, the formal status of work and the responsible CEN/CENELEC Technical Committee on one hand to be transparent, but also to facilitate contributions and involvement in the standardisation.

Especially the **CEN Technical Committees related to gas infrastructure, including high-pressure transmission grids**, and gas applications are actively working on the incorporation of hydrogen aspects to enable the uptake of hydrogen and – where appropriate - its blends. The current draft standard prEN 16726 is defining a H₂-concentration threshold in H-gas which will be basic for the grid as well as for gas applications. It needs to be confirmed or reviewed in the CEN Public Enquiry process.

Finally, the **quality of standardisation** in general including that for high-pressure transmission grids for hydrogen and its blends depends one-to-one to the contribution of expertise and experience from industry, academics, standardisers and further interested parties. In this respect, all relevant parties from industry, technical institutes and other interested parties shall identify:

- their expectations of standardisation and
- their possibilities to contribute to the standardisation by
 - direct involvement in the elaboration and revision of standards,
 - contribution of technical findings from the practice and especially from research and/or innovation,
 - constructive commenting in the course of consultations
 - stimulating new standardisation projects where need is seen from their perspective

A broad involvement ensures the appropriate comprehensiveness and appropriateness of standards for purpose and support the acknowledgment and application in the daily practice.

Participation is possible via national standardisation bodies and stakeholder organisations.

7.5 Availability of hydrogen

- (1) A demand-driven supply of hydrogen, including local production within the EU and imports, is essential for the large-scale use of hydrogen. This needs to be assessed in terms of time, cost, quality and quantity. Companies need planning certainty in order to plan the infrastructure, reorganise processes, complete the necessary research work, build up production and import capacities and create a suitable overall energy and raw materials system.

Infrastructural, technical, regulatory, systemic and economic framework conditions and financing instruments must be created or expanded to promote a demand-driven expansion of the hydrogen economy. Dependencies such as those that have arisen in the natural gas system must be avoided in the future by appropriate diversification of sources.

- (2) Initially, especially during the start-up phase of the hydrogen economy, the hydrogen network will not be able to cover the same area as the current natural gas network. This is due to the time required for the conversion and the parallel use of both natural gas and hydrogen. Companies and households that are not directly connected to a hydrogen network must be given a medium-term perspective of what a climate-friendly solution could look like. The first priority is certainly an ambitious and at the same time targeted expansion of hydrogen networks. This explicitly requires the coordinated planning of transport and distribution networks. On the other hand, the local hydrogen economy can be developed through local blending during the ramp-up phase. At the same time, well-designed certificate trading, which does not stand in the way of the development of dedicated hydrogen networks, can compensate for locational disadvantages for companies and households in the transition process.

Companies and households that are not directly connected to a hydrogen network must be offered the prospect of being able to use hydrogen at an early stage in order to avoid locational disadvantages. In addition to the ambitious and clearly formulated expansion of hydrogen networks, a sensibly designed certificate trade can be expedient.

- (3) When it comes to the availability of hydrogen, it is not enough to have enough hydrogen available on balance over the whole year; a sufficient supply must also be guaranteed at all times. In particular, the fluctuating production of renewable energy is likely to result in volatile national hydrogen production, which is also subject to seasonal influences. To a certain extent, imports can provide a relatively constant flow of hydrogen for the Member States concerned. This applies in particular to imports from the North Sea (offshore production), by ship from various countries of origin, or by pipeline from e.g. North Africa, which are then distributed throughout Europe. Sufficiently dimensioned hydrogen storage facilities can enable long-term storage of hydrogen in particular.

The conversion of natural gas storage facilities and, in some cases, the construction of new hydrogen storage facilities need to be coordinated at European level in order to compensate for seasonal fluctuations in production and demand. This will require demand-driven planning, taking into account the fact that there will be parallel network structures for natural gas

and hydrogen, which will also be reflected in dedicated hydrogen and natural gas storage facilities, especially during the ramp-up phase. In some cases, where strategically and technically feasible, storage of blends may also be considered.

- (4) Due to the fluctuations in hydrogen production in the European Union Member States described above, the quantities fed into and withdrawn from the hydrogen corridors also fluctuate.

Strategies need to be developed on how a stable supply of hydrogen to the Member States via the hydrogen corridors can work with fluctuating feed-in and feed-out quantities. Cross-border cooperation is particularly necessary.

7.6 Considerations regarding injection of hydrogen

- (1) If certain networks or sub-networks are to be used for blending and regional and decentralised generation plants feed into these networks, pre-defined blending limits must be complied with. These may be limits set by the Gas Package for cross-border interconnection points or limits set by agreements between neighbouring network operators. An appropriate authorisation for blending provides an incentive for the construction of hydrogen production facilities along the pipeline. Hydrogen production from electrolysis and renewables varies over time, as does gas consumption.

Solutions are needed that allow for constant hydrogen blending with fluctuating generation capacities and seasonal consumption patterns. This includes the question of which feed-in plant can supply how much hydrogen when hydrogen concentrations are close to the upper blending limit.

- (2) If 100% H2 pipelines are operated, the capacity of the pipeline may be fully utilised at times of high regional generation potential and the injection plants may not be able to reach their full generation potential.

The question that needs to be answered is which injection plant can inject how much when the capacity of a 100% H2 pipeline is exhausted.

- (3) Strategies for the injection of hydrogen have to be run in parallel with those of other renewable gases (i.e. biomethane, renewable, methane) so that there can be a fair competition aiming towards the final decarbonisation of the grid.

It is necessary to study the production capacity of each region, as well as the kind of customers and the amount and quality of gas consumed, and define the injection potentials accordingly.

7.7 Acceptance

- (1) The energy price crisis, triggered in particular by Russia's war of aggression in Ukraine, has caused concern among the population and industry. The emotionality with which the discussions have been conducted and the consequences of the relocation of industrial production capacity to regions outside the EU, or even its reduction, show that the needs and concerns of the population and industry must be taken into account when it comes to the energy transition as a whole, and therefore also when it comes to hydrogen and blending. Optimal solutions for the entire energy system must be found and made visible in order to achieve broad

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

acceptance. The issues of safety, security of supply, sustainability and affordability need to be communicated to the public in an understandable and effective way, taking into account the maintenance of prosperity and the strength of the EU economic area.

Sound strategies need to be developed at both EU and Member State level to ensure public acceptance.

8 Conclusions

The HIGGS project kick-off meeting in Aragon Hydrogen Foundation (Huesca, Spain) in January 2020 was less than four years ago, but the world has changed a lot since then. The coronavirus pandemic started almost at the same time as the project, and the Russian war of aggression against Ukraine started on 24th February 2022. Both events are primarily of social and political significance, but their impact on industry and the energy sector in the European Union cannot be overestimated. Both events also had a huge impact on the hydrogen economy. The European Union responded to the economic consequences of the coronavirus crisis at an early stage with the European Green Deal, which has been described as a "lifeline out of the coronavirus crisis", and numerous measures based on or accompanying it, in order to strengthen the European economy in the crisis situation on the one hand, and to take pioneering climate protection measures on the other. This approach was reinforced by the Russian war of aggression against Ukraine, which highlighted the problems of energy dependency. This was followed by the REPowerEU plan in May 2022, which, among other things, further addressed the diversification of Europe's energy supply and investment in renewable energy. In this way, the two catastrophic events acted as a catalyst for the transformation already underway towards the goal of climate neutrality. In this context, the issue of hydrogen and the implementation of a European hydrogen economy has also gained further momentum. In July 2020, the European Commission published "A Hydrogen Strategy for a Climate Neutral Europe". At the same time, the Member States of the European Union also published their own hydrogen strategies and numerous research and demonstration projects moved the state of the art towards technical feasibility at an impressive pace. In this dynamic environment, research projects also faced the challenge of having to deal with changing framework conditions. This also meant that the HIGGS project had to respond to discussions at the political, business, scientific and societal levels. In order to do this, the project also carried out appropriate research and analysis. In this way, the HIGGS project, with its key messages, can contribute to the success of a rapid and safe ramp-up of the hydrogen economy.

Key message #1

Blending hydrogen into the existing pipelines of the European gas transport network is technically feasible and safe up to 100% hydrogen.

The different tests performed in HIGGS showed no signs of damage in the different materials present in pipes, components or equipment that can be assigned to gaseous hydrogen. Besides, all the valves tested showed a coherent level of tightness for the new operating conditions. Combined with the results of other recent studies, in particular SyWeSt H2, the results of the HIGGS project reinforce the statement that hydrogen blending up to 100 mol% in the European gas transmission network is technically feasible and safe. Further specific investigations are required if exceptional materials are present or if open points are identified in the conversion process of transmission grids. For a European standardised certification system, certification criteria and procedures need to be established, e.g. in harmonised EU standards.

Key message #2

Hydrogen will play a crucial role in making Europe a climate neutral continent by 2045 and cross-border transport of hydrogen is necessary to enable Member States' national hydrogen strategies.

Numerous statements, strategies and legislative processes make it clear that hydrogen is a key element in achieving the European Union's climate goals. In addition to its use as an energy source in the various sectors, the material use of hydrogen in industry plays a decisive role in the sustainable development of European industry. The Member States have heterogeneous potentials for hydrogen

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

production as well as specific demand structures and strategies. Cross-border transport of hydrogen is necessary to meet the objectives of the respective hydrogen strategies.

Key message #3

Based on the current discussions on the Gas package and also on the prevailing opinion of the European TSOs with simultaneous planning of a hydrogen backbone, it is unlikely that blending above 2 - 5% by volume will play a major role in the cross-border transport of hydrogen.

The issue of blending at transport network level is viewed rather critically by the institutions of the European Union in the Gas Package currently being negotiated, and a blending limit for cross-border transport of hydrogen in the range of 2 to 5 per cent by volume is likely to be introduced. The introduction of a limit is justified by the need to avoid market segmentation due to different gas quality parameters. The relatively low value is derived from the presumed more efficient use of pure hydrogen compared to blending. This development could not be foreseen at the time of the project design and contradicted some of the objectives. Therefore, the objective has been partially adjusted in an amendment. It is important to emphasise that this unexpected development should in no way be interpreted as meaning that hydrogen has lost its importance in the EU's energy concept, but on the contrary that the ramp-up should be accelerated. Accordingly, the voices of the TSOs in the survey and in published statements can be interpreted as being in favour of a limited blending in the discussed range of up to 5% by volume. The planning of a European hydrogen network as part of the European Hydrogen Backbone with its hydrogen corridors should also be interpreted and evaluated in this context.

Key message #4

The addition of hydrogen to the gas network will be a decisive factor both in the transport network and especially in the distribution network.

Blending at transport level is likely to be possible up to a small percentage and will provide a degree of flexibility that is largely viewed favourably by TSOs. In addition, the Gas Package as currently discussed also allows for blending at national level. Given the heterogeneous infrastructure and heterogeneous conditions and strategies, it is possible that regionally limited blending will also take place at transmission system level. This is to be expected, for example, if parallel transport of hydrogen and natural gas is not possible during the ramp-up phase and customers can technically and economically realise the use of blending. The Gas Package also explicitly leaves open bilateral and multilateral agreements that allow higher blending limits.

In addition, distribution system operators in the EU are striving to gradually make their distribution networks carbon-neutral. Blending plays an important role in the ramp-up phase. And even in the 2045 target scenario, carbon neutrality will not be achieved by hydrogen alone, but also by biomethane, which will then be distributed together with hydrogen in some places.

Key message #5

H₂ concentration limits in European standardisation will allow blending in the grid at different levels.

In the revision of the CEN standard for H-gas quality the draft EN 16726 foresees a limit value of 2% hydrogen in natural gas (Group H) with the option to have higher hydrogen concentrations in regional and local grids according to the technical abilities of the grids.

D6.3 Pathway and proposals summary to enable wider injection of H₂ in EU gas networks

This standard will provide a reliable European specification complementary to the stipulations in the EC Gas Package for Interconnection Points and forthcoming European network codes on interoperability and also to national legislation.

Key message #6

National legal framework and national and European technical standards are (still) in development

1. The majority of EU Member States established their national hydrogen strategy or intend to publish it soon. Only few countries have set limits for hydrogen concentration in gas grids, if by legislation or codes of practice. For injection of hydrogen in transmission grids, it is assumed that the responsible parties have been waiting for the final concentration limits for cross-border interconnection points in the EC Gas Package.
2. European standardisation is currently investigating, revising and elaborating new standards to facilitate the use of the existing grids for hydrogen-natural gas blends (and pure hydrogen) and in gas applications. Numerous Technical Committees are involved; overall coordination will ensure the completeness and coherence of the standardisation. The European Commission supports standardisation with diverse instruments in a multi-stakeholder approach to optimise the standardisation for a fast delivery of solid standards.
3. Regarding blending of hydrogen in the gas grids, a hydrogen limit of 2% by volume is integrated in the draft standard for H-gas quality (EN 16726). In case of a hydrogen concentration in the EC Gas Package, an adaption of the standard might be needed to align with legislation.

9 Appendices

9.1 National hydrogen strategies

In the list of national hydrogen strategies, the date of issue, the key sectors for hydrogen use that are mentioned in the single strategy or other sources, the H₂ concentration limits in blending with natural gas and some general objectives are given. The information is collected with a focus to blending, it is not exhaustive.

Note: The main reference to the national hydrogen strategy is given in the row Date of issue, if any. This reference is applicable, besides other references are indicated with the statement. The indication of a reference at the bottom a box refers to all statements in that box.

D6.3 Pathway and proposals summary to enable wider injection of H₂ in EU gas networks

Country	Date of issue	Key sectors for H ₂	H ₂ concentration limits in blending with natural gas	Objectives in general, on production and import/export aspects
Austria AT	2022-06 [62]	H ₂ where no efficient decarbonisation alternative such as industry, transport, electricity/energy system	<ul style="list-style-type: none"> max. 10 mol-% of hydrogen injection into the gas grid according to Code of Practice ÖVGW G B 210 complementary to the EN 16726 and EN 16723-1 [63] there is no specific limit for transmission grids 	<ul style="list-style-type: none"> climate neutrality in 2040 priority use of renewable (electrolysers with green electricity, or biomass) and climate-neutral hydrogen (methane + CCUS) blending part of the plan but general focus on 100% hydrogen
Belgium BE	2021-10 [64]: Revision: 2022-10 [65]:	Industry, transport, with less priority also hydrogen and its derivatives in buildings and power	<ul style="list-style-type: none"> no legal hydrogen concentration limit in gas transmission grid 	<ul style="list-style-type: none"> priority use of renewable hydrogen but also low carbon for the transition phase leading in H₂ technology use the coast and terminals for import and transit hub for renewable gases in Europe cooperation and interconnection with neighbouring countries development of electricity and hydrogen grids in the North Sea and also the interconnection, initiation of projects, esp. for 2023 to 2025 Repurposing of gas grid, where available 2026: commissioning of 100-160 km of pipelines for H₂ [66] Interconnection with neighbouring countries FR, GE and NL (up from 2028). Draft law for regulator aspects; drafting of gas quality standard [35]

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Bulgaria BG	2023 [67]	Priority to industry, energy, and transportation (mobility) sectors	<ul style="list-style-type: none"> no legal hydrogen concentration limit in the transmission grid [68] 	<ul style="list-style-type: none"> hydrogen technologies on transport and use of green hydrogen in industry, energy and transport research and innovations Framework for education and training for new professions in relation to hydrogen technologies; EU and international cooperation. production capacity of 1.1 GW of green hydrogen by 2030 announced [36] The roadmap is applicable for the 2023-2026 period. Also the Integrated Energy and Climate Plan of the Republic of Bulgaria 2021-2030 [69] gives significant support to the development of the hydrogen market.
Croatia HR	2022-03 [70]	Priority on industry, transport (mobility) and buildings, less focus on power	<ul style="list-style-type: none"> no legal hydrogen concentration limit for gas transmission grids. [68] 	<ul style="list-style-type: none"> Availability of H₂ infrastructure for the hydrogen market by 2050. local hydrogen infrastructure near production facilities in a first step. blending in certain areas part of the planning (no specification if on transmission or distribution level) [35] production goal: 70 MW (electrolysers) by 2030 and 2,750 MW by 2050
Cyprus CY	no strategy published yet		<ul style="list-style-type: none"> no legal hydrogen concentration limit for gas transmission grids. [68] 	-

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Czech Republic CZ	2021-06 [71]	<p>Priorities in transport (mobility) – 2021-2025 and beyond, industry (2026-2030 and beyond) and buildings Use in power sector no priority.</p> <p>Timeline in 3 stages:</p> <ol style="list-style-type: none"> 1. 2021–2025 2. 2026–2030 3. 2031–2050 	<ul style="list-style-type: none"> • there is no legal hydrogen concentration limit, • but the assumption that the gas system is ready for transmission, distribution and storage of blends with 2% hydrogen in natural gas, up to 10% with slight technical modifications. (Limitations mainly due to end-users limitations). 	<ul style="list-style-type: none"> • availability of infrastructure for low-carbon hydrogen up to 2050 • use of large parts of the natural gas grid for transport hydrogen blended with natural gas, whilst converting gas pipelines and constructing new hydrogen pipelines. • construction of hydrogen pipelines and repurposing of natural gas pipelines is announced for stage 3 (2031-2050) <p>The strategy [71] dedicates a chapter to hydrogen transport giving arguments for the different means of transport. It identifies the transport in pipelines as the most efficient. The document evaluates the strengths, opportunities, weaknesses and threats of the transport possibilities including the ‘Transport of hydrogen through pipelines in a mixture with natural gas’.</p>
Denmark DK	2021-12 [72]	<ul style="list-style-type: none"> • 1st Priority to export • 2nd priority transport and buildings, • no specific focus on power 	<ul style="list-style-type: none"> • no legal hydrogen concentration limit in gas transmission grids [68] 	<ul style="list-style-type: none"> • establishment of 4 - 6 GW of electrolysis capacity by 2030 • focus on export of hydrogen and power-to-x technology • importance of cooperation with neighbouring countries, especially Germany <p>The hydrogen strategy is entitled Power-to-X strategy [72]; the Green gas strategy [73] gives relevant support to hydrogen.</p>

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Estonia EE	2023-03 [74]	-	<ul style="list-style-type: none"> no legal hydrogen concentration limit, but indication of 0.1 vol% limit in transmission grid. [35] 	<ul style="list-style-type: none"> focused on the hydrogen deployment period of 2021-2030. Research and development and project implementation, increase of renewable energy and provision of legal and technical framework by standards [35]
Finlan FI	2020-11 [75] 2023 [35]	<ul style="list-style-type: none"> Focus on industry, but also for transport (mobility) 	<ul style="list-style-type: none"> no information available 	<ul style="list-style-type: none"> carbon neutrality by 2035 under current preconditions and mostly in the present production facilities, the total potential for green hydrogen production is between 100 kt and 150 kt in 2030 when P2X technology is mature, large-scale production can be build, e.g. for fuels or carbon-free steel. repurposing of natural gas transmission pipelines is assumed possible, but more studies are needed. (50% less natural gas consumption over the last 15 years) <p>Note: As the text of the hydrogen strategy 2023 could not be identified, the strategy of Finland Business, the Finnish business organization for innovation funding and trade, travel and investment promotion, was taken as source:</p>

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

<p>France FR</p>	<p>2020-09 [76]</p>	<p>1st priority is industry (70% [77]) 2nd priority is transport (mobility/heavy duty) (cars, lorries, aircraft and decarbonised ships) (23% [77]) 3rd priority is research and innovation Further H₂ in Energy (7% [77])</p>	<ul style="list-style-type: none"> • no legal H₂ concentration limit; in network operators gas quality rules up to 6 mol-% hydrogen is generally permitted [63]; Reduction to 0.2 mol-% foreseen in line sensitive users connected to the grid and draft EN 16726, according to communication with GRTgaz and Francegaz. 	<ul style="list-style-type: none"> • installation of electrolyzers capacity with the production target: 6.5 GW of electrolyzers by 2030 <ul style="list-style-type: none"> ○ -> Goal 2030: 4 Gigafactories to cover 40% of the European market) <p>In February 2020, a French ordinance on hydrogen was published defining renewable, low-carbon and fossil hydrogen, intentions for decree on thresholds for each label, complying with RED II.[78]</p>
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D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

<p>Germany DE</p>	<p>2020-06 [79] Continuation in 2023-07 [80]</p>	<ul style="list-style-type: none"> • technology neutral approach • energy storage • benefit of hydrogen in industry, mobility (including air, sea traffic, heavy transport) and power sector mentioned, • chemistry (CatLab [funded by BMBF, 20-25]) • transport [80] 	<ul style="list-style-type: none"> • no legal hydrogen limit for gas grids • DVGW Code of Practice G 260 [81] determines hydrogen as a gas for public gas supply without indicating a hydrogen concentration. Thus, it enables in principle the admixture of more than 10 vol.% hydrogen and gives specifically guidance on limitations according to technical feasibility of the local/regional grid and sensitivity of end-uses and equipment. <p>The DVGW is – by legal presumption in the German Energy Act [82] – assigned to provide the Codes of Practice for hydrogen, as already the case for other gases for public supply (natural gas, biomethane).</p>	<ul style="list-style-type: none"> • Carbon neutrality by 2045 • focus on appropriate end use of green hydrogen at long-terms; additional low-carbon hydrogen for the transition phase • production target: min.10 GW by on- and offshore electrolyzers until 2030 – funding of flagship projects like H2Giga [83] and H2Mare [84] • determination of measures for the uptake of hydrogen by making available the hydrogen, providing the infrastructure, establishing hydrogen uses and setting the legal framework (including the reduction of bureaucracy in approval procedures) aiming at 2023, 2024/2025 and at 2030 (production, mobility, industry,) • establishment of a hydrogen core network (~11.000 km) connecting all major hydrogen feeders with all major consumers by 2032 – draft planning between transmission network operators and national regulatory body Bundesnetzagentur is in process 2023/2024 [85] • hydrogen builds significant element of the sector-coupling with electricity where renewable electricity cannot directly be used • focus on restructuring of chemical and steel industry and mobility sectors to facilitate hydrogen use • cooperation with neighbouring countries to enable the European Hydrogen Backbone by 2030 • establishment of National Hydrogen Council with experts from Business, science and civil society in support of the implementation and development of the strategy
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D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Greece GR	Draft 2022-11 [86]	-	<ul style="list-style-type: none"> no legal limit for hydrogen concentration in the gas grid [68] 	<ul style="list-style-type: none"> production target of 3,500 GWh (gigawatt hours) of hydrogen in 2030 from electrolysis, with a total capacity of 750 MW (megawatts), which will be powered by RES Renewable Energy projects, power 3 GW (80% photovoltaic and 20% windpower), planned hydrogen growth by 2030. production capacity of 3 Mtoe of green hydrogen in 2040 and export 1 Mtoe perspective to produce 7.4 Mtoe by 2050 and export 2.3 Mtoe of green hydrogen [87], [86]
Hungary HU	2021-05 [88]	<ul style="list-style-type: none"> industries: especially petrochemical, chemical industry and fertiliser/ammonia transport: mainly for heavy-duty vehicle, afterwards bus and waste collection aiming for an H₂ refuelling infrastructure 	<ul style="list-style-type: none"> no legal limit for hydrogen concentration in the gas grid. Pilot projects for min. 2% blending ratio in the natural gas system (where appropriate) aiming for higher percentage depending on research 	<ul style="list-style-type: none"> production goals for 2030: <ul style="list-style-type: none"> 20 thousand tons / year low-carbon hydrogen 16 thousand tons / year “green” and other carbon-free hydrogen 240 MW electrolyser capacity (powered with photovoltaic) use of green and carbon-free hydrogen to reduce CO₂ in industry and transport (mobility) building hydrogen valleys / hydrogen clusters Existing gas network should be connected to the European Hydrogen Backbone to facilitate export

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Ireland IE	2023-07 [34]	<ul style="list-style-type: none"> • industry, • power, • transport and • export. • Less importance on hydrogen for buildings 	<ul style="list-style-type: none"> • limit of 0.1% in natural gas set by Code of Operations of Gas Networks Ireland Annex G [89] [68] 	<ul style="list-style-type: none"> • creation of certainty for investors and availability of green hydrogen, 2 GW target of offshore wind, for the production of 2-4 TWh of renewable hydrogen by 2030 • further 20 GW of offshore production by 2040 and at least 37 GW by 2050, opening the opportunity to significantly ramp up renewable hydrogen production post 2030 • intention to become a net exporter of renewable hydrogen • stipulation of 21 actions in the areas hydrogen production, end uses, infrastructure, safety and regulation, research and cooperation and delivery and implementation • identification of 11 end-use priority sectors: 1) existing hydrogen users, 2) flexible power generation and long duration energy storage, 3) integrated energy parks for large energy users and 4) industrial heat and processing. • Ireland expects that blended gas will come into the country via the interconnectors and foresees to be prepared for that. • blending is low on the priority list (10 out of 11) it is seen as mitigation solution where excess production/end-use variability exists. Sufficient hydrogen storage and transportation technology is available. • based on technical and safety studies (Gas Networks Ireland) 'Injecting renewable hydrogen blends into Ireland's gas network' testing of 50% of the Irish transmission pipelines for blends with H₂ over 10% and 100% are intended. • at the same time, it is stated that blending shall not lead to delay of green hydrogen systems.
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D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Italy IT	Draft stage [90]	<ul style="list-style-type: none"> • industry (chemical, oil refining -> 'hard to abate' sectors characterised by high energy intensity and lack of scalable electrification solutions) power, transport, less buildings, no focus on export. • transport sector, especially heavy transport (e.g. long-haul lorries! 2% (5-7% possible) of long-haul fuel cell trucks by 2030, 80 % by 2050), in railways (esp. 	<ul style="list-style-type: none"> • legal limit of up to and including 2% hydrogen in natural gas set in 2022 [91], [68] 	<ul style="list-style-type: none"> • establishment of hydrogen valleys (both production (electricity to H₂) and consumption); Location for production side preferably industrial districts in regression (social aspects) • production targets: 5 GW by electrolysis production capacity by 2030; production of ~0.7 Mton green H₂ per year • conversion of 80% of infrastructure by 2040 • 20% energy demand covered by H₂ by 2050 • leverage and interconnecting existing/well developed gas network for import and export • (~70% of the gas grid is considered H₂-ready and internal technical procedures established [63]) • Goal 2030: 50% non electrifiable train routes converted to H₂ (exchange old diesel trains) by 2050
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D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

		Passenger transport)	
Latvia LV	No strategy published yet	<ul style="list-style-type: none"> no hydrogen concentration limit in the gas transmission grid [68] 	The published National Energy and Climate Plan published 2016 and 2020 indicate renewable hydrogen as long-term option for Latvia. Furthermore, cooperation between Latvia and Estonia is ongoing [92].

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Lithuania LT	No strategy published yet		<ul style="list-style-type: none"> the legal limit is set with $\leq 0.1\%$ for gas systems with pressure $P \geq 1.6$ MPa. Transmission network operators are allowed to increase the limit up to 2 mol% when issuing the conditions for connection of biogas plants to the transmission system; technical safety criteria of the transmission system as well as applicable metering standards shall be checked furthermore, higher hydrogen concentrations are possible for research projects; assessment of safety criteria of the grid, the equipment and needs of end-users is obligatory for the low pressure grids a gas system pressure $P < 1.6$ MPa, the limit of $\leq 2\%$ is set with the same option in case of research projects <p>[93]</p>	<ul style="list-style-type: none"> implementing the National Action Plan for the Strengthening of the Innovation Ecosystem in the Energy Sector approved on 10 September 2020, a Hydrogen Platform was established by agreement between the Ministry of Energy of the Republic of Lithuania and national research institutions, businesses and the public sector for the goal of developing hydrogen technologies in Lithuania, in 2020-11. <p>the platform supports and contributes to the strategy shaping and development of the framework, among other objectives [94].</p>
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D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Luxembourg LU	2021-09 [95]	<ul style="list-style-type: none"> • 1st Focus on industry • 2nd focus up from 2030 transport (mobility) and hydrogen system in an integrated approach with electricity, as far as electrification or other alternatives of decarbonisation are available. 	<ul style="list-style-type: none"> • no legal limit for gas transmission grids [68] 	<ul style="list-style-type: none"> • 7 strategic measure, including: <ul style="list-style-type: none"> - focus on renewable hydrogen with end of use of low-carbon hydrogen by 2030 - solution to decarbonise sectors which cannot be directly electrified, such as parts of industry, mobility, as well as to allow for sector coupling. - cooperation with EU Member States
Malta MT	No strategy		<ul style="list-style-type: none"> • No legal limit for hydrogen concentration in gas transmission grid [68] 	
Norway (EFTA)	2020-05 [96]	Industry and transport	<ul style="list-style-type: none"> • no legal hydrogen concentration limit in gas transmission grids [68] 	<ul style="list-style-type: none"> • solution for applications for which there are currently few or no other zero emission alternatives. • at the same time, hydrogen production and the development of hydrogen technology could contribute to value creation in Norway • there is no concrete statement on blending but it is presumed that export of hydrogen blended with natural gas could be an option

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Poland PO	2021-11 [97]	<ul style="list-style-type: none"> • industry, • power, • transport and • buildings, • export is not in the focus 	<ul style="list-style-type: none"> • no legal hydrogen concentration limit into the gas transmission grid [68] 	<ul style="list-style-type: none"> • renewable and low-carbon hydrogen • planning for infrastructure including repurposing of natural gas pipelines [97] • blending of hydrogen with natural gas is part of the strategy • objectives set for 2030 and 2040; foresees verification of achievements in 2025
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D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Portugal PT	2020-07 [98]	<ul style="list-style-type: none"> • export • industries (cement, refining, chemical, metallurgical, extractive, cement, glass and ceramics industries) • mobility (heavy road transport) • storage solution for energy • renewable fuels for energy sector or maritime transport and aviation sectors 	<ul style="list-style-type: none"> • no legal hydrogen concentration limit into the gas transmission grid [68] 	<ul style="list-style-type: none"> • carbon neutrality by 2050 (Goal set since 2016) with a roadmap to Carbon Neutrality 2050 (RNC2050 presented 2018) • production target: 2 to 2.5 GW electrolysers capacity by 2030 • production of green H₂ for domestic market (through renewable electricity) and for export by sea (port of Sines), and land (pipelines) • promote the injection of hydrogen into natural gas networks, establishing mandatory incorporation targets for this purpose. • H₂ vehicles for passengers and heavy duty and 50 to 100 refuelling stations by 2030 • strategic partnership with NL (Sines to NL and connect to industrial areas DE), DE, BE • focusing on the production and incorporation of renewable gases, including hydrogen, mainly in sectors where electrification is not cost-effective, like heavy-duty transport and the industry [36].
Romania RO	No strategy published yet		<ul style="list-style-type: none"> • no legal hydrogen concentration limit into the gas transmission grid [68] 	

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Slovak Republic SK	2021-06 [99]	<ul style="list-style-type: none"> • industry (petrochemical, steel as a partial or complete substitute for solid fossil fuels and coke produced from black coal, as well as in the production of cement), • transport, • buildings/heating in further investigation [36] 	<ul style="list-style-type: none"> • no legal hydrogen concentration limit into the gas transmission grid [68] 	<ul style="list-style-type: none"> • focus on national green hydrogen production, complemented by low-carbon hydrogen from fossil fuels and imports. • hydrogen use as a primary energy source in economy sectors in which the direct use of electricity is not cost-effective. • opportunities for decarbonisation in various areas and especially in those areas where the use of electricity or other decarbonisation solutions are not viable • blending of hydrogen in natural gas is part of the strategy; existing gas grids will be used for the blends and repurposed for 100% hydrogen.
Slovenia SI	No strategy published yet		<ul style="list-style-type: none"> • No legal hydrogen concentration limit, however the Gas Supply Act allocates the decision for gas quality requirements (including hydrogen) to network operators. The Gas Supply Act gives the indication that not more than 10% of hydrogen should be introduced into the gas network [100]. 	<ul style="list-style-type: none"> • national H₂ association built, also to urge the Government to establish a national H₂ strategy [101]

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Spain ES	2020-07 [102]	<ul style="list-style-type: none"> hydrogen-intensive industry (oil refining, fertilizers and chemicals, among others) and high-temperature processes transport: long-distance heavy transport, maritime transport, rail transport or aviation, public transport. energy storage sector coupling priorities: Homes and industries 	<ul style="list-style-type: none"> currently 5% renewable H₂ injection permitted Existing Gas network could tolerate 20% H₂ (investment could improve) [103] 	<ul style="list-style-type: none"> climate neutrality by latest 2050; focus on green hydrogen production 4 GW electrolyzers capacity by 2030, with estimation of 300-600 MW by 2024 two renewable hydrogen transmission axes in Spain (start of hydrogen backbone) [104] Export goal: 2 million tonnes of green hydrogen produced in Spain and Portugal (commissioned 2030) [104] creation of hydrogen valleys or clusters foreseen public information and awareness is part of the strategy preference for common EU standards for the gas grid
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D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

Sweden SE	No strategy published yet (Draft)	<ul style="list-style-type: none"> • no information 	<ul style="list-style-type: none"> • no legal hydrogen concentration limit into the gas transmission grid [68] 	
Switzerland CH (EFTA)	No strategy	<ul style="list-style-type: none"> • no legal hydrogen concentration limit into the gas transmission grid [68] 	<ul style="list-style-type: none"> • no legal hydrogen concentration limit into the gas transmission grid [68] 	

D6.3 Pathway and proposals summary to enable wider injection of H2 in EU gas networks

The Netherlands NL	2020 [105]	<ul style="list-style-type: none"> • industry • transport (mobility, including agriculture machinery) • buildings [106] 	<ul style="list-style-type: none"> • legal H₂ concentration limit in H-gas grids is 0.02 mol-%. For G-Gas the limit is 0.02 mol-% for transmission grids and 0.5 mol-% for the distribution grid [107], [68] • possibilities for physical blending and administrative blending by certification are subject to investigations from various grid and market perspectives. Physical blending up to 2% is already achievable with minor adjustments, increases to approximately 10-20% might be possible with further adaptations of the grid. 	<ul style="list-style-type: none"> • Focus on zero-carbon gases including green hydrogen; low carbon hydrogen is needed for the transition. • scale up electrolysis to approximately 500 MW of installed capacity by 2025 and 3-4 GW of installed capacity by 2030 • import targets for 2030 at two of its largest ports – Rotterdam (4.6 Mtpa) and Amsterdam (1 Mtpa); the target at Rotterdam increases to 18 Mtpa by 2050; first import as ammonia from 2024 [66] • revision of regulations for the future hydrogen market; the grids may have private and public parts (reference to NL four-year Hydrogen Safety Innovation) • need for guidelines and standards on safety aspect, preferably on European and international level • reuse of existing pipelines (85%) to connect ports and industries for H₂ by 2025 [106] • coordinated approach for hydrogen and electricity including placement of electrolysers in consultation with industry (Main Energy Infrastructure Programme) • blending is an option in the strategy as it facilitates offtake from green hydrogen projects and decentralized production • significance of European and international planning for overall development of the grids, production and import opportunities
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