HIGGS

Hydrogen in Gas Grids

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

---

D5.4

Techno-economic validation: Main conclusions and recommendations

Date	May 2023 (M41)
Grant Number	875091
Author(s)	**Salvatore Oricchio[1]**, Christoph Steiner[1], Javier Sánchez[2], Vanesa Gil[2,3], Virginia Madina Arrese[4], Jon Zuñiga Palacio[4], Pablo Benguria Uribe[4], Hiltrud Schülke[5], Stefan Gehrmann[5], Alberto Cerezo Alarcón[6], Cristina Rodríguez Vilariño[6], Tobias Weide[7]
1	Eastern Switzerland's University of Applied Sciences (OST)
2	Fundación para el Desarrollo de las Nuevas Tecnologías del Hidrógeno en Aragón (FHA)
3	Fundación Agencia Aragonesa para la Investigación y el Desarrollo (ARAID)
4	Fundación Tecnalia Research & Innovation (TECNALIA)
5	Deutscher Verein des Gas- und Wasserfachs (DVGW)
6	Redexis
7	European Research Institute for Gas and Energy Innovation (ERIG)
	Author printed in bold is the contact person
Status	Started / Draft / Consolidated / Review / Approved / **Submitted** / Accepted by the EC / Rework [use bold style for current state]

Dissemination level:

PU	**Public**	**RE**	Restricted to a group specified by the consortium*
PP	Restricted to other programme participants*	**CO**	Confidential, only for members of the consortium*

*(including the Commission Services)

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No. 875091 'HIGGS'. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

Document history

Version	Date	Description
0.1	2023-05-17	Document created (ORSA)
0.2	2023-06-08	Section 1, 2, 3.1, 4.3
0.3	2023-06-16	Section 3.2, 3.3, 3.4, 3.5
0.4	2023-06-22	Section 4, Section 5
0.5	2023-06-27	Executive summary
1.0	2023-06-27	Draft completed
1.1	2023-06-28	Inputs Fha, Redexis
1.2	2023-07-10	Consolidated and revised version submitted

Table of Contents

List of Figures

List of Tables

No table of figures entries found.

Executive Summary

Introduction

This report contains the work caried out in Task 5.3, *Evaluation of results and compilation of recommendations*. Section 3 describes how a future gas[1] grid can be characterised at the transport level on the basis of H_2 content and the need for separation. Based on this characterisation, 4 possible gas grids are presented. For each of these 4 gas grids, the canvas business model was used as a reference model to develop business cases, which in turn could directly be applied to suit the aim of this report. Hence, it was used to explain how TSOs could build and operate a business with it in the future. Section 4 summarises again the main findings and results of all deliverables from WP5. Together they form a set of (main) recommendations from both a technical and an economic point of view.

Key findings

1. 0 - 2 vol.-% H_2 without the need for separation:

   Admixing low volumes of hydrogen into the existing gas grid is to facilitate the transition towards a cleaner and more sustainable energy system. By blending hydrogen with gas, the existing infrastructure can be leveraged and utilised as a means to distribute and deliver hydrogen to consumers. Further, low volumes of max. 2 vol.-% of hydrogen allows for a gradual transition, minimizing the need for immediate and extensive infrastructure modifications.

2. 2 – 30 vol.-% H_2 without the need for separation:

   The existing gas infrastructure can be retrofitted to transport also higher shares hydrogen. The blends allow both TSO and end users to continue using their existing natural gas appliances and infrastructure to a certain degree. On the other hand, some may need to change full appliances though. This minimizes the disruption to end-users and enhances consumer acceptance. Admixing hydrogen in volumes of up to 30 vol.-% provides a gradual transition pathway towards a hydrogen-based energy system. It allows for the adoption of hydrogen

---

[1] Unless otherwise stated, in the context of this deliverable the term “gas grid” always refers to the high-pressure gas grid at transmission level. Gas, in this context, refers to natural gas (mostly methane) in its synthetic form and/or biomethane the emphasise the need for decarbonisation of the gas grid.

technologies while benefiting from the established natural gas infrastructure, providing time for further developments in hydrogen production, storage, and distribution technologies.

3. 2 – 30 vol.-% H_2 including separation:

   The additional implementation of separation technology on the transmission level minimises the impact on end-users. The existing natural gas infrastructure can still be utilised to a large degree after being retrofitted to account for the larger portions of hydrogen in the grid.

   Separation technology can be implemented at strategic points in the transmission grid to extract hydrogen, enabling the distribution and/or storage of pure hydrogen depending on the application further downstream in the grid. Separating hydrogen at the transmission level promotes the integration of larger volumes of hydrogen, especially green hydrogen, into the energy system by balancing out supply and demand of renewable energy sources.

4. 100 vol.-% H_2:

   A retrofitted natural gas grid for 100% hydrogen offers a practical and cost-effective solution for the distribution and storage of hydrogen. By retrofitting the existing infrastructure, the extensive grid already in place can be leveraged, minimizing the need for extensive construction. The retrofit enables efficient transmission of hydrogen across regions, ensuring widespread access to clean energy. The integration of renewable hydrogen, produced through electrolysis, further enhances its sustainability. The transition to a hydrogen-based grid promotes energy diversification and aligns with global efforts to decarbonize the energy sector. Overall, retrofitting the natural gas grid for 100% hydrogen represents a significant step towards a cleaner and more sustainable energy future.

Main conclusions and recommendations

- Technical point of view:

  i. Compatibility assessment: Conduct a comprehensive compatibility assessment of the existing gas grid infrastructure to ensure it can safely handle hydrogen.

  ii. General system retrofit: Identify necessary retrofit or modifications to accommodate the admixture of hydrogen based on an inventory of the affected grid section(s).

  iii. Blending ratio: Determine the optimal blending ratio of hydrogen and gas depending on the local circumstances. Start with low percentages and gradually increase them.

iv. Hydrogen dedicated grid: In the long term, retrofit parts of the existing gas grid for the use of 100 % hydrogen. Transporting pure hydrogen in a dedicated grid is the most cost-effective option.

It is recommended to read the WP4 deliverables D4.2 and D4.3, as well as D4.4 once released, to get a better understanding of the tolerance of the transport grid to different levels of hydrogen.

- Economic point of view

  i. Hydrogen supply: Assess the availability, cost, and reliability of hydrogen supply in the region. The goal must be to be able to offer green hydrogen in a cost-efficient way compared to other generation sources, with full cost accounting. It is recommended to read D6.1 of WP6 to get the vision about hydrogen injection po-tential across Europe.

  ii. Regulatory environment: Push local and national regulations related to hydrogen blending. Some regions may start to offer incentives, grants, or favourable policies for hydrogen integration. D6.3 will be published at the end of the project, where this issues will be detailed.

Conclusion

The local conditions within the European gas grid make it difficult to give an overall forecast of the direction in which the gas grid will develop. It is likely that, at least in the short to medium term, different solutions will develop depending on local conditions such as supply, demand, existing infrastructure and legal requirements. In the long term, however, a holistic European solution is needed to further increase cooperation between regions of the EU and to have a resilient gas grid that can reliably and flexibly meet energy needs.

Ultimately, WP5 has not only shown that the transport of hydrogen in a retrofitted gas grid is economically competitive, but also a necessity in order to achieve the emission targets that have been set.

D5.4 serves as input for WP6 to develop the hydrogen injection potential scenarios in Europe.

1 Objective

The main objective of this Deliverable D5.4 is to elaborate the findings and results of Task 5.2 into a set of conclusions and recommendations that can also aim as input for WP6 tasks. Based on the deliverables D5.1 - D5.3, the aim is to shed light on how hydrogen could be effectively transported in a European high-pressure gas grid (HPGG) of the future.

Specifically, possibilities will be shown how

a. A gas network can be characterised at the transmission level

b. Various business models could be developed according to the possible characteristics of the HPGG

c. Gaps still need to be closed from different perspectives in order to enable the transport of hydrogen in a retrofitted HPGG.

Eventually, a set of main recommendations (including a vision for 2050) from both a technical- and economic point of view will be presented on the possible futures of the European gas grid.

2 Introduction

In the HIGGS project, an experimental R&D platform has been built to conduct tests on the integrity of gas transmission network infrastructure under the influence of hydrogen admixture. The testing loop includes state-of-the-art components and materials of gas pipelines and is designed to work up to 80 bar with various blending levels but also 100% hydrogen. A hydrogen purification prototype based on membrane technology for the separation of H_2/CH_4 on behalf of different end-use applications is also integrated in the design.

In addition to the construction and commissioning of the plant, as well as carrying out and analysing various tests (e.g. varying the H_2 concentration and using different pipeline steels), further research is carried out with regard to legal, regulatory, technical and economic aspects of the blending of hydrogen into the existing gas grids.

In WP5, *Techno-economic modelling and validation, enablers and interoperability*, the main objective is to develop operational strategies and business cases for grid operators and to illustrate how hydrogen blending in the gas grid can contribute to the overall goals of decarbonising the European energy system. Moreover, the influence of higher H_2 fractions on the economics of the gas transport value chain will be assessed in the project and compared to other common methods, considering gas producers, transport companies up to delivery to the gas distribution networks. For this purpose, a numerical model will be compiled for representative cases in Europe in order to describe technical operation and business impacts. The model will allow analysing the different technological adaptions of the grid, which strongly depend on the blending level, as well as the operational strategies for the future grid with hydrogen injection.

This report contains the work caried out in Task 5.3, *Evaluation of results and compilation of recommendations*. At the same time, it also represents the conclusion of the activities in WP5. The Task is led by OST (formerly HSR) and runs form month 20 to 42 of the project lifetime. Project partner participating in the form of providing input to this deliverable are Tecnalia, Redexis, DVGW and FHa.

Section 3 describes how a future gas grid can be characterised at the transport level on the basis of H_2 content and the need for separation. Based on this characterisation, 4 possible gas grids are presented. For each of these 4 gas grids, the canvas business model was used as a reference model to develop business cases, which in turn could directly be applied to suit the aim of this report. Hence, it was used to explain how TSOs could build and operate a business with it in the future. It is also shown which gaps still need to be closed and/or which questions still need to be clarified in order to make this possible.

Section 4 summarises again the main findings and results of all deliverables from WP5. Together they form a set of (main) recommendations from both a technical and an economic point of view. Finally, the project team describes its vision of a European gas grid in 2050 that is in line with the set greenhouse gas emission targets.

3 Business cases and operation strategies

In a gas grid, the transportation and integration of hydrogen and therefore the *hydrogen content* in the grid will play a significant role, along with the *need for hydrogen separation* from gas if/when higher vol.-% of hydrogen will be transported. This characterisation reflects the transition towards a decarbonised energy system and the increasing use of hydrogen as a clean and versatile energy carrier.

Furthermore, such a characterisation helps to describe possible features of future gas/hydrogen grids and to classify them relative to each other (as shown in section 3.1).

Finally, the possible gas/hydrogen grids will also differ in their business models and in the way they are operated. What is needed, which gaps need to be filled and which questions still need to be answered are described in sections 3.2 - 3.5.

3.1 Characterizing possible gas grids

3.1.1 Hydrogen content

It is imaginable, that the gas grid will witness an increase in the volume of hydrogen transported. This hydrogen content may vary, ranging from low percentages to higher concentrations, depending on the specific applications and regions, the energy consumption of the grid and the availability of hydrogen.

Traditionally, the gas grid has been designed for the properties of gas and as such, modifications may be required to accommodate higher hydrogen concentrations. The compatibility of materials used in pipelines and other infrastructure with hydrogen is a crucial aspect to ensure safety and prevent leaks. Additionally, end-use appliances such as boilers, furnaces and cookers may require modifications or replacement to handle higher hydrogen concentrations effectively

While there is ongoing research and development in this area, current industry practices typically limit the hydrogen admixture in the transmission grid to levels below 20 vol-% due to the aforementioned considerations. However, apart from HIGGS additional studies and pilot projects, such as ThyGA, are exploring higher admixture percentages, up to 30 vol-% and beyond, to assess the technical feasibility and safety aspects. [3, 10]

For this reason and in accordance with the simulations carried out in D5.3, the hydrogen content was divided into 3 ranges for the characterisation:

1. 0 - 2 vol.% H_2: Already possible today in many EU member states and is considered to be the status quo. Many applications downstream (distribution level and lower) can easily handle this amount of hydrogen. [10]

2. 2 - 30 vol.-% H_2: Here it is taken in consideration that many EU member states allow considerably higher proportions of hydrogen in the gas grid. However, the permissible proportions are very different not only for applications further downstream in the gas grid, but also within the EU (cross-border transport). Therefore, as shown in the next section, the question of hydrogen separation also arises.

3. 100 vol.-% H_2: This refers to a retrofitted gas grid that transports hydrogen exclusively. This could make sense where several parallel pipelines already transport gas.

3.1.2 Need for separation

To enable the integration of hydrogen into the gas grid, advanced technologies for separating hydrogen from gas will be employed. Especially when considering admixture levels between 2 – 30 vol.-% of hydrogen. This separation process will involve various methods, including pressure swing adsorption (PSA), membrane separation (as investigated in HIGGS for instance), or catalytic processes. These technologies will allow for the extraction of hydrogen from the gas stream, ensuring purity and enabling its utilization for different purposes.

For very small admixture levels (0 - 2 vol.-% hydrogen), no separation is envisaged at present for the reasons mentioned in the previous section. At least not at the transmission level. At the distribution level, separation of gas and hydrogen is conceivable for sensitive applications. The same applies to a 100 % hydrogen grid. Consequently, separation is only considered for blending in the range of 2 - 30 vol.-% hydrogen by volume in the following sections.

However, separation should not be considered as an either-or property in a future gas grid. In the map in Figure 1 shown in the next section, the need for separation is to be understood as a continuous and not a discrete property. Of course, a separation unit will either be present at each city gate or not. As shown in D5.3, the differentiated use of separation technology at certain city gates is much more efficient from an economic point of view than equipping every city gate with the possibility of separation as a matter of principle.

3.1.3 Mapping possible gas transmission grids

Figure 1 shows, how possible future gas grids are arranged relative to each other based on the properties of H_2 content and separation described above. The result is 4 possible scenarios, 3 of which do not require separation and only 1 of which requires separation. These 4 scenarios now also form the basis for the development of just as many business models, which will be described and evaluated in more detail in the following sections.

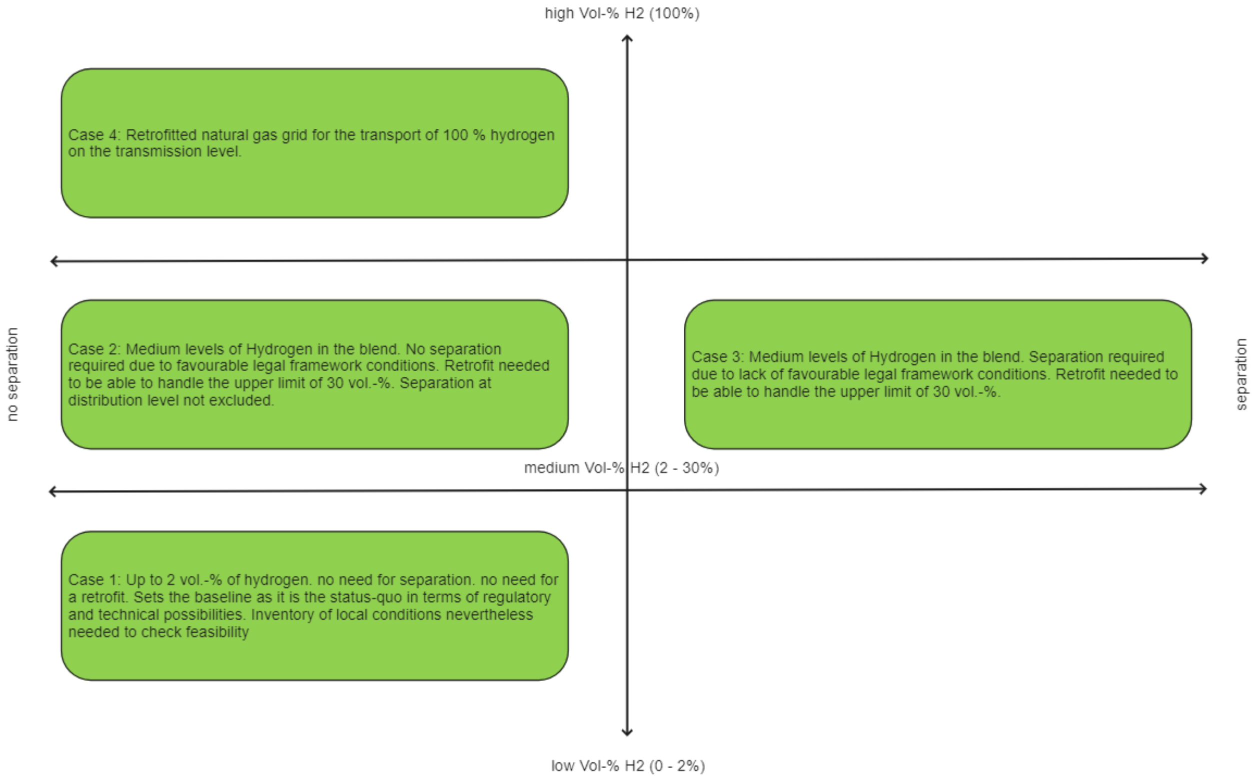

Figure 1: Mapping possible future gas grids

3.20 - 2 Vol.-% H_2, no separation

As already mentioned in previous sections, this type of gas grid represents the current status quo and sets therefore the baseline of what is possible today in most EU member states. Section 3.2 describes the business model resp. the operating strategy in detail. In order to avoid unnecessary repetitions and to improve the overview, only the essential differences and additions in the individual subsections compared to this section are described for the remaining business models, operating strategies and outstanding issues in sections 3.3 - 3.5.

3.2.1 Business model & operation strategy

3.2.1.1 Key partners

What are the key partners to get competitive advantage?

1. Gas suppliers: Collaborate with gas suppliers, both gas and hydrogen, to ensure a reliable supply of gas for transmission. Currently especially “first generation” (green) hydrogen suppliers.

2. Regulatory authorities: Maintain a close relationship with regulatory authorities not only to comply with regulations and obtain necessary permits and licenses, but also to give feedback on technological trends and needs.

3. Maintenance service providers: Partner with maintenance service providers to ensure the upkeep and integrity of the gas transmission infrastructure.

4. Technology providers: Collaborate with technology providers for advanced monitoring and control systems to optimize the efficiency and safety of the transmission network. Also to ensure H_2-readiness of gas contacted components and materials such as compressors, pipes and other mechanical equipment such as valves etc.

3.2.1.2 Key activities

What are the key steps to move ahead to the customers?

1. Gas transmission: Facilitate the transmission of gas from suppliers to customer by operating and maintaining the gas transmission grid.

2. System monitoring: Continuously monitor the gas transmission grid to ensure its integrity, reliability and safety. Further, ensure that the concentration of hydrogen is between the given limits of 0 – 2 vol.-% by monitoring.
3. Capacity planning: Analise market demand and plan for the expansion and/or modification of the transmission grid to meet future requirements.
4. Maintenance and repairs: Regularly inspect, maintain and repair the gas transmission infrastructure to ensure its efficient and safe operation.
5. Emergency response: Develop and implement emergency response plans to handle any disruptions or incidents in the gas transmission grid.

3.2.1.3 Key resources

What resources do you need to make it work?

1. Gas transmission infrastructure: Own and maintain a network of pipelines, compressors, pressure reducing stations and other equipment required for the transmission of gas.
2. Skilled workforce: Employ a team of engineers, technicians and operators with expertise in gas transmission systems.
3. Technological systems: Utilise advanced monitoring, control and communication systems to manage and optimise the gas transmission network.
4. Regulatory knowledge: Stay updated with regulatory requirements and compliance standards to ensure adherence.

3.2.1.4 Key value propositions

How will this make the customers life "happier"? What is the unique selling proposition (USP)?

1. Reliable gas transmission: Ensure a continuous and reliable supply of gas to meet the energy needs of customers, including industrial, commercial and residential customers. Reliable also in terms of accepting fluctuating hydrogen concentration (in the given range of 0 – 2 vol.-%) in order to buffer possible hydrogen overproduction.
2. Efficient operations: Optimize the efficiency of the gas transmission system, minimizing losses and reducing energy waste by providing also near real-time quality information. Therefore being able to direct the flow where needed.

3. Compliance and regulatory support: Assist gas suppliers and customers in meeting regulatory requirements and provide support during the permit and licensing processes.

3.2.1.5 Customer segments

Who are the customers and/or stakeholders?

1. Gas suppliers: Provide a reliable transmission infrastructure for gas suppliers and/or producers to transport their product to the market.
2. Customers: Serve industrial, commercial and residential customers who rely on gas for their energy needs. Additionally, their applications are able to handle blends of gas and hydrogen of up to 2 vol.-% without having to change equipment.

3.2.1.6 Customer relationships

How does the interaction with customers and stakeholders look like?

1. Service provider: Open communication on the status of the transmission services with suppliers and customers.
2. Regular meetings and updates on transmission grid status.
3. Customer support: Offer technical assistance, emergency response and support to address any concerns or issues related to the transmission system. Aim at long-term partnerships.

3.2.1.7 Channels

How are the customers going to be reached? How is the engagement with stakeholders going to look like?

1. Direct sales team: Engage with suppliers and customers directly through a sales team to understand their requirements and provide information about transmission services.
2. Regular industry meetings and conferences to foster knowledge sharing and networking
3. Online platforms: Maintain a website or online portal to provide information, updates and access to various services related to transmission such as information on status, quality and quantity of the blend being transported.
4. Public awareness campaigns about safety and transmission. Educate the public on hydrogen with emphasis on safety and benefits of using hydrogen

3.2.1.8 Revenue streams

What generates revenue?

1. Transmission fees: Generate revenue by charging fees to gas suppliers and customers for utilizing the gas transmission system based on the volume of gas transmitted.
2. Service agreements: Enter into service agreements with gas suppliers and customers for specific transmission services, such as capacity reservation or emergency response support. Further, provide maintenance and repair services for auxiliary systems related to transmission infrastructure.
3. Consultancy services for new pipeline projects or the expansion of existing pipelines.

3.2.1.9 Cost structure

What generates costs?

1. Operational costs: Mainly the energy for compression along the pipelines and energy for preheating the gas at the pressure reducing stations.
2. Infrastructure maintenance: Incur costs for the regular maintenance, repair and expansion of the gas transmission infrastructure.
3. Workforce: Allocate funds for salaries, training and development of skilled personnel.
4. Technology investments: Invest in advanced monitoring and control systems to optimize network efficiency and ensure safety. Ensure to have hydrogen-ready infrastructure.
5. Regulatory compliance: Allocate resources to ensure compliance with regulatory requirements and standards.
6. Financing: Amortisation costs including interest.

3.2.2 Outstanding issues

Technological:

- Comprehensive measurement of hydrogen concentration in the gas grid to ensure gas quality.
- Suitability assessment standards to ensure the acceptance of the admixture at the customer.

	- The compatibility of materials used in the gas grid, potential leakage issues, and adequate storage and handling methods need to be further addressed to ensure safe and efficient hydrogen blending.
Regulatory:	- Standardisation of permitted hydrogen concentrations in the European gas grid. In the context of low vol.-% hydrogen currently 1, 2 and 5 vol.-% allowed in some EU states.[8] - EU-wide standards describing a. a hydrogen-capable gas grid in terms of materials and operating conditions, including measurable parameters for objective evaluation. b. How to meter and bill the hydrogen transported and what tolerance will be allowed.
Supply, demand and economics:	- According to [6], around 160 MW of electrolysers output capacity is currently installed in Europe. Hence the share of green hydrogen is correspondingly low. The supply of green hydrogen can therefore be further expanded without exceeding the given limits of hydrogen in the grid. - Demand does not play a major role at the transmission level for these quantities of hydrogen. According to [11], demand for hydrogen in these small quantities is more likely to be met by local production. . A better map of supply and demand capacities of hydrogen can be seen in D6.1. - A fair billing method must be introduced as proposed by [1] for instance. This considers the fact that the calorific value varies with the fluctuating hydrogen content.
Social:	- The public needs to be further educated about hydrogen. Awareness must be raised that hydrogen can easily be blended with gas in these low concentrations and thus greenhouse gas emissions can be reduced.

- Transparently explain the opportunities and risks of a gas-hydrogen mixture.

3.2.3 Bottom line

Admixing low volumes of hydrogen into the existing gas grid is to facilitate the transition towards a cleaner and more sustainable energy system. By blending hydrogen with gas, the existing infrastructure can be leveraged and utilised as a means to distribute and deliver hydrogen to consumers.

Further, low volumes of max. 2 vol.-% of hydrogen allows for a gradual transition, minimizing the need for immediate and extensive infrastructure modifications. It provides an opportunity to gain experience with hydrogen integration, assess technical challenges, and gradually increase hydrogen content in the infrastructure.

Overall, the admixing of low volumes of hydrogen into the existing gas grid offers a promising pathway for decarbonising the gas supply and facilitating the transition to a sustainable energy future and technologies mature.

3.3 2 - 30 Vol.-% H_2, no separation

If hydrogen is added to gas in proportions of 2 – 30 vol.-% , relatively constant transport costs can be achieved without the need for separation (see Figure 2). To achieve this, however, uniform permissible proportions of hydrogen in the gas grid are necessary, especially to enable transport across national borders. It should be noted that the lack of separation in the grid does not allow the (seasonal) storage of hydrogen. At least not at transmission level. Once the hydrogen is in the grid, it must be able to be consumed or transferred to the next lower levels in the grid where it is further processed.

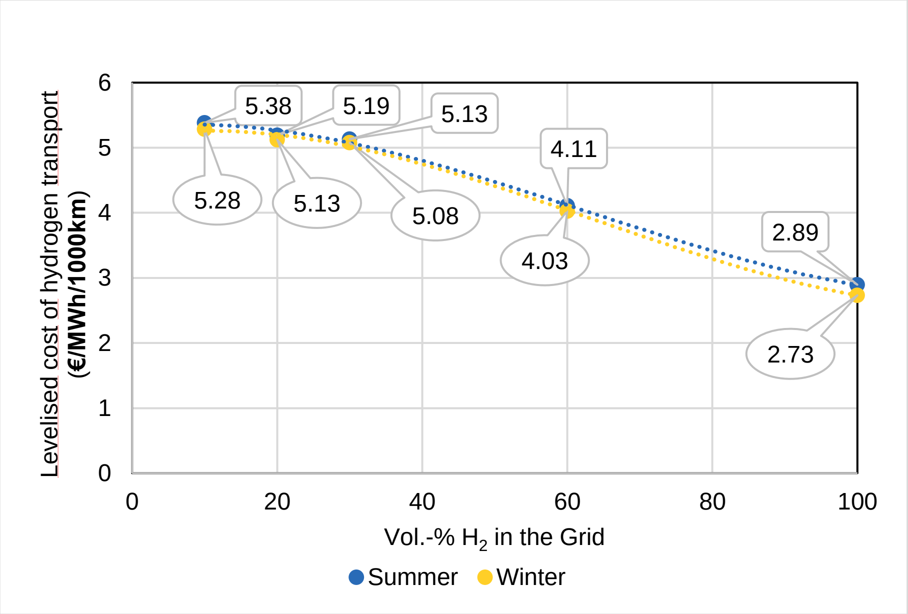

Figure 2: Levelised cost for hydrogen transport not considering separation [HIGGS D5.3]

Compared to section 3.2, only the main differences/additions are described in the following business model- and outstanding issues section

3.3.1 Business model & operation strategy

3.3.1.1 Key partners

What are the key partners to get competitive advantage?

1. Gas suppliers: In this business model, hydrogen is becoming more significant. It is therefore crucial to find partners who can reliably supply large quantities of hydrogen produced with little or no emissions in the long term.

2. Technology providers: H_2-readiness will no longer be sufficient, especially with regard to the 30 vol.-%. The retrofitting of the gas grid requires hydrogen-capable components, which have proven their hydrogen compatibility in high concentrations in experiments, such as those performed in HIGGS within the scope of WP4 (see deliverables D4.2 to D4.4).

3.3.1.2 Key activities

What are the key steps to move ahead to the customers?

1. System monitoring: Ensure that the concentration of hydrogen is between the given limits of 2 – 30 vol.-% by monitoring.

2. Buffer renewable energy supply: Implement and operate systems, that allow to feed renewable energy in the form of hydrogen into the gas grid if there is overproduction (as service).

3.3.1.3 Key resources

What resources do you need to make it work?

1. Favorable regulations: In order for this business model to be a success at the European level, regulations are needed that allow the transport of hydrogen across national borders. This means that homogenised hydrogen concentrations must be introduced throughout Europe, allowing high hydrogen concentrations of up to 30% by volume in the gas mix. This issue will be specially reviewed in D6.3 that will be ready by the end of the project.

3.3.1.4 Key value propositions

How will this make the customers life "happier"? What is the USP?

1. Gas transmission: Accepting fluctuating hydrogen concentration (in the given range of 2 – 30 vol.-%).

2. Buffer for renewable energy: Offer a buffer for renewable energy in order for power plant operators to run their facilities at the optimum operating point by converting overproduction to hydrogen, which in turn is injected into the gas grid and transported to destination.

3.3.1.5 Customer segments

Who are the customers and/or target audience?

1. Renewable energy producers: Operators of renewable energy power plants who want to deliver or have transported a surplus of energy production in the form of hydrogen.

2. Customers: Serve industrial, commercial and residential customers who rely on gas and or hydrogen for their energy needs. Additionally, their applications are able to handle fluctuating blends of gas and hydrogen of up to 30 vol.-%.

3.3.1.6 Customer relationships

How does the interaction with customers look like?

See section 3.2.1.6

3.3.1.7 Channels

How are the customers going to be reached? How can the product be promoted?

See section 3.2.1.7

3.3.1.8 Revenue streams

What generates revenue?

See section 3.2.1.8

3.3.1.9 Cost structure

What generates costs?

1. Infrastructure maintenance: Incur costs for the regular maintenance, repair and expansion of the gas transmission infrastructure. Particular attention should be paid to wear and tear of caused by the (permitted) high hydrogen content.

2. Technology investments: Ensure to have hydrogen-capable infrastructure.

3.3.2 Outstanding issues

Technological:	-	Materials and components must be developed and/or deployed that can cope with the high proportions of hydrogen in the mixture. Even under difficult conditions such as dynamic loads and fluctuating concentrations.

Regulatory:	- Standardisation and harmonization of permitted hydrogen concentrations in the EU member state's gas grids of up to 30 vol.% hydrogen. - Enable cross-border transport of hydrogen to link sources of green hydrogen with areas of high demand across Europe.
Supply, demand and economics:	- Regimes of direct financial support and/or fiscal incentives could aim at triggering the production of electrolyzers to produce capacity on an industrial level to achieve high levels of hydrogen in the grid [7]. - Demand for green hydrogen on the other hand must be increased by, among other things, closing the price gap with grey hydrogen through fiscal support and tariffs on the one hand, but also by setting targets for green gases as described in IRENAS's report [7].
Social:	- To show that even larger quantities of up to 30% by volume of green hydrogen can be added to the gas and that many applications can continue to be used in this way with only a few adjustments. Labels, such as " H_2-Ready" from the DBI, can have a confidence-building effect if clear standards are recognisable behind them.[2]

3.3.3 Bottom line

The existing gas infrastructure can be retrofitted to transport also higher shares hydrogen. Hydrogen can be injected into the gas grid at specific points, mixed with gas, and then distributed to consumers. The blends allow consumers to continue using their existing natural gas appliances and infrastructure with only little changes. This minimizes the disruption to end-users and enhances consumer acceptance.

By blending hydrogen with gas, we can utilize excess renewable energy, to replace part of the gas with hydrogen and consequently reduce the demand for gas. Eventually, contributing to the balancing of renewable energy supply and demand by injecting hydrogen into the grid.

Admixing hydrogen in volumes of up to 30 vol.-% provides a gradual transition pathway towards a hydrogen-based energy system. It allows for the adoption of hydrogen technologies while benefiting from the established natural gas infrastructure, providing time for further developments in hydrogen production, storage, and distribution technologies.

3.42 - 30 Vol.-% H_2, separation

In contrast to section 3.3, this business model additionally implements the separation of hydrogen from the gas. Separation technology is needed for certain consumers of gas when hydrogen has been blended in order to ensure proper operation of the processes downstream on a distribution- and/or consumer level. There are various technologies available, each of them with certain advantages and disadvantages as described in HIGGS D5.1. Furthermore, the use of separation technology opens up the possibility of storing hydrogen seasonally by separating it from the gas and storing it separately in designated facilities along the gas grid. When needed, the hydrogen can then be injected back into the grid.Business model & operation strategy

3.4.1 Business model & operation strategy

3.4.1.1 Key partners

What are the key partners to get competitive advantage?

1. Gas suppliers: In this business model, hydrogen is becoming more significant. It is therefore crucial to find partners who can reliably supply large quantities of hydrogen produced with little or no emissions in the long term (see D6.1 to get more information about availability of supply sources).

2. Technology providers: H2-readiness will no longer be sufficient, especially with regard to the 30 vol.-%. The retrofitting of the gas grid requires hydrogen-capable components, which have proven their hydrogen compatibility in high concentrations in experiments. In addition, it will be necessary to find partners who can offer separation technology on an industrial scale (see D4.2, D4.3 and D4.4 for more information about material evaluation and gas separation tests).

3.4.1.2 Key activities

What are the key steps to move ahead to the customers?

1. System monitoring: Ensure that the concentration of hydrogen is between the given limits of 2 – 30 vol.-% by monitoring.

2. Buffer renewable energy supply: Implement and operate systems, that allow to feed renewable energy in the form of hydrogen into the gas grid if there is overproduction (as service).

3. Seasonal energy storage: Implement and operate separation technology, to separate hydrogen from gas for seasonal storage. Transport the hydrogen via the grid to designated storage, separate it, store it and inject it back into the grid when needed.

3.4.1.3 Key resources

What resources do you need to make it work?

1. Technological systems: Separation technology that can be produced and purchased on an industrial scale. Ideally, separation technology that has a constant separation efficiency even with variable hydrogen content in the gas mix. For the separated hydrogen further storage- and injection facilities are needed.

2. Additional resources: Electricity and heat not only for the operation of the separation technology, but also for the hydrogen injection facilities as additional energy demand to the remaining components.

3.4.1.4 Key value propositions

How will this make the customers life "happier"? What is the USP?

1. Gas transmission: Accepting fluctuating hydrogen concentration (in the given range of 2 – 30 vol.-%).

2. Buffer for renewable energy: Offer a buffer for renewable energy in order for power plant operators to run their facilities at the optimum operating point by converting overproduction to hydrogen, which in turn is injected into the gas grid and transported to destination.

3. Seasonal storage: Offer a hydrogen seasonal storage system for the overproduction of renewable energy from corresponding operators by providing the whole process chain from gas/hydrogen-separation, seasonal storing and reinjection into the grid when needed. Hydrogen usage outside of the gas grid is also conceivable as a chemical feedstock for instance.

4. Stable gas quality downstream: With the use of separation technology at the transmission level, a consistent gas quality respectively composition can be achieved further downstream at the distribution level. Essentially, irrespective of whether the focus at distribution level is on gas or hydrogen.

3.4.1.5 Customer segments

Who are the customers and/or target audience?

1. Renewable energy producers: Operators of renewable energy power plants who want to:
    a. Deliver a surplus of energy production in the form of hydrogen and therefore reduce the need for gas.
    b. Store the surplus of renewable energy seasonally in the form of hydrogen by transporting it via the grid to the designated storage facilities.
2. Customers: Serve industrial, commercial and residential customers who rely on gas for their energy needs. Additionally, their applications are able to handle fluctuating blends of gas and hydrogen of up to 30 vol.-%.

3.4.1.6 Customer relationships

How does the interaction with customers look like?

See section 3.2.1.6

3.4.1.7 Channels

How are the customers going to be reached? How can the product be promoted?

See section 3.2.1.7

3.4.1.8 Revenue streams

What generates revenue?

1. Hydrogen storage fee: Generate revenue by charging producers of green hydrogen (seasonal storage) fees for separation storage and re-injection of the hydrogen into the grid.
2. Hydrogen broker: Take advantage of the fact that one has the means (pipelines) to transport and store large quantities of hydrogen at low cost. First, act as hydrogen broker and sell the hydrogen as raw material for industrial processes or as a fuel in the transport sector. Second, provide hydrogen as energy carrier to balance supply of energy when supply of renewable energy is low.

3.4.1.9 Cost structure

What generates costs?

1. Operational costs: Mainly the energy for compression along the pipelines and energy for preheating the gas at the pressure reducing stations. Additionally, both electricity and heat are required for the operation of the separation units.
2. Infrastructure maintenance: Incur costs for the regular maintenance, repair and expansion of the gas transmission infrastructure including separation technology. Particular attention should be paid to wear and tear due to the permitted hydrogen content of up to 30 vol.-%.
3. Technology investments: Invest in state-of-the-art separation- and the coherent hydrogen injection technology to ensure additional revenues from it. Ensure to have hydrogen-capable infrastructure.

3.4.2 Outstanding issues

Technological:

- General materials and components, such as pipelines and compressors, must be further developed and/or deployed that can cope with the high proportions of hydrogen in the mixture. Even under difficult conditions such as dynamic loads and fluctuating concentrations.
- Further development of efficient separation technology, which is deployed on an industrial scale. Separation technology that is able to handle changing conditions and high proportions of hydrogen.

Regulatory:

- Despite separation, standardisation and harmonization of permitted hydrogen concentrations in the EU member state’s gas grids of up to 30 vol.% hydrogen is needed. It reduces the need for separation in the first place, thus reducing cost for transport.
- Enable cross-border transport of hydrogen to link sources of green hydrogen with areas of high demand across Europe.
- Further develop regulations restricting greenhouse gas emissions in energy sector, thus boosting need for seasonal storage facilities for hydrogen and therefore also the need for separation technologies.

Supply, demand and economics:	- Regimes of direct financial support and/or fiscal incentives could aim at triggering the production of electrolyzers to produce capacity on an industrial level to achieve high levels of hydrogen in the grid [7]. - Demand for green hydrogen on the other hand must be increased by, among other things, closing the price gap with grey hydrogen through fiscal support and tariffs on the one hand, but also by setting targets for green gases as described in [7]. - More decentralised storage facilities for green hydrogen are needed to create incentives for producers of renewable energy to convert excess production into hydrogen instead of throttling the plants.
Social:	- To show that even larger quantities of up to 30% by volume of green hydrogen can be added to the gas and that many applications can continue to be used in this way with only a few adjustments. Labels, such as " H_2-Ready" from the DBI for instance, can have a confidence-building effect if clear standards are recognisable behind them.[2]

3.4.3 Bottom line

The additional implementation of separation technology on the transmission level minimises the impact on end-users. Consumers can continue to use their natural gas appliances without significant changes, ensuring a smooth transition to the hydrogen-enriched gas grid while benefiting from reduced carbon emissions. The existing natural gas infrastructure can still be utilised to a large degree after being retrofitted to account for the larger portions of hydrogen in the grid.

Separation technology can be implemented at strategic points in the transmission grid to extract hydrogen, enabling the distribution and/or storage of pure hydrogen depending on the application further downstream in the grid. Separating hydrogen at the transmission level promotes the integration of larger volumes of hydrogen, especially green hydrogen, into the energy system by balancing out supply and demand of renewable energy sources.

3.5 100 Vol.-% H_2

A transport natural gas grid can be repurposed for 100% hydrogen, offering cost-effective distribution and storage solutions. By modifying the existing infrastructure, hydrogen transmission can occur efficiently across regions. This retrofitted grid would support the integration of renewable hydrogen produced through electrolysis, enabling the use of green hydrogen for various applications. Industries and residential areas connected to the retrofitted hydrogen grid can tap into a clean and reliable energy source, reducing their carbon footprint and dependence on fossil fuels.

3.5.1 Business model & operation strategy

3.5.1.1 Key partners

What are the key partners to get competitive advantage?

1. Hydrogen suppliers: Collaborate with green (or low emissions) hydrogen suppliers to ensure a reliable supply of hydrogen for transmission. Currently especially “first generation” (green) hydrogen suppliers (see D6.1 for more details about hydrogen supply across Europe).

2. Technology providers: Collaborate with technology providers for advanced monitoring, control and safety systems, and mechanical components such as compressors and valves for the use of pure hydrogen. Hence ensuring hydrogen compatibility of the whole transmission grid. On the other hand collaborate with research institutions to further improve materials, components and processes. D4.4 will contain details about hydrogen tolerance of components under 100 %H2 once re-leased by the end of the project.

3.5.1.2 Key activities

What are the key steps to move ahead to the customers?

1. Hydrogen transmission: Facilitate the transmission of hydrogen from suppliers to customer by operating and maintaining the hydrogen transmission grid.

2. System monitoring: Continuously monitor the hydrogen transmission grid to ensure its integrity, reliability and safety. Further, ensure that the quality of hydrogen fulfils the quality standards in terms of purity. Monitor flows to balance supply and demand of hydrogen.

3. Maintenance and repairs: Regularly inspect, maintain and repair the hydrogen transmission infrastructure to ensure its efficient and safe operation.

4. Emergency response: Develop and implement emergency response plans to handle any disruptions or incidents in the hydrogen transmission system.

3.5.1.3 Key resources

What resources do you need to make it work?

1. Hydrogen transmission infrastructure: Own and maintain a network of pipelines, compressors, pressure reducing stations, storage facilities, hydrogen injection systems and other equipment required suited for the transmission of 100 % hydrogen.

2. Skilled workforce: Employ a team of engineers, technicians and operators with expertise in transmission grids with focus on hydrogen.

3. Technological systems: Utilise advanced monitoring, control and communication systems to manage and optimise the hydrogen transmission grid.

3.5.1.4 Key value propositions

How will this make the customers life “happier”? What is the USP?

1. Reliable hydrogen transmission: Ensure a continuous and reliable supply of hydrogen to meet the energy needs of customers, including industrial, commercial and residential customers by including.

    a. a buffer for renewable energy in order for power plant operators to run their facilities at the optimum operating point by converting overproduction to hydrogen, which in turn is injected into the gas grid and transported to destination (consumption or storage).

    b. hydrogen seasonal storage system for the overproduction of renewable energy from corresponding operators by providing the whole process chain from hydrogen storing and reinjection into the grid when needed.

2. Compliance and regulatory support: Assist hydrogen suppliers and customers in meeting regulatory requirements and provide support during the permit and licensing processes.

3. Low carbon footprint: Hydrogen from renewable energy sources provides a low carbon emission energy supply in order to reach the customers emission targets.

3.5.1.5 Customer segments

Who are the customers and/or target audience?

1. Hydrogen suppliers: Provide a reliable transmission infrastructure for hydrogen suppliers and/or producers to transport their product to the market.
2. Customers: Serve industrial, commercial and residential customers who rely on hydrogen for their energy needs or as a feedstock.
3. Renewable energy producers: Operators of renewable energy power plants who want to:
    a. Deliver a surplus of energy production in the form of hydrogen and therefore reduce the need for gas on one side and avoiding throttling down their production of energy on the other hand.
    b. Store the surplus of renewable energy seasonally in the form of hydrogen by transporting it via the grid to the designated storage facilities.

3.5.1.6 Customer relationships

How does the interaction with customers look like?

See section 3.2.1.6

3.5.1.7 Channels

How are the customers going to be reached? How can the product be promoted?

See section 3.2.1.7

3.5.1.8 Revenue streams

What generates revenue?

1. Hydrogen storage fee: Generate revenue by charging producers of green hydrogen (seasonal storage) fees for the storage and re-injection of the hydrogen into the grid.
2. Hydrogen broker: Take advantage of the fact that one has the means (pipelines) to transport and store large quantities of hydrogen at low cost. First, act as hydrogen broker and sell the hydrogen as raw material for industrial processes or as a fuel in the transport sector. Second,

provide hydrogen as energy carrier to balance supply of energy when supply of renewable energy is low.

3.5.1.9 Cost structure

What generates costs?

1. Operational costs: Mainly the energy for compression along the pipelines and energy for precooling the hydrogen at the pressure reducing stations.
2. Technology investments: Invest in 100 % hydrogen-capable technology such as pipelines, compressors, storing facilities and injection technology to retrofit an existing grid to pure hydrogen transport.

3.5.2 Outstanding issues

Technological:

- Comprehensive measurement and monitoring of hydrogen purity in the grid to ensure quality.
- The compatibility of materials used in the hydrogen grid, potential leakage issues, and adequate storage and handling methods need to be further addressed to ensure safe and efficient hydrogen usage.
- General materials and components, such as pipelines and compressors, must be further developed and/or deployed that can cope with the pure hydrogen. Even under difficult conditions such as dynamic loads.

Regulatory:

- EU-wide standards describing a hydrogen-capable grid in terms of materials and operating conditions, including measurable parameters for objective evaluation.
- Enable cross-border transport of hydrogen to link sources of green hydrogen with areas of high demand across Europe.
- Further develop regulations restricting greenhouse gas emissions in energy sector, thus boosting overall need for hydrogen.
- Governments can establish targets and regulations that mandate or incentivise the use of green hydrogen in specific sectors. These

	targets can include requirements for hydrogen in industrial processes, or procurement targets for hydrogen-powered vehicles. Clear regulations provide market certainty and encourage investment in green hydrogen technologies.
Supply, demand and economics	- Targeting specific sectors with high potential for green hydrogen utilisation can help drive demand. For example, promoting the use of green hydrogen in heavy-duty transportation, shipping, or industrial processes that are difficult to electrify can create significant demand and market pull. - Governments can invest in hydrogen infrastructure projects, such as building hydrogen refueling stations for transportation or creating hydrogen hubs near industrial clusters. Expanding the infrastructure network reduces barriers to entry and encourages the uptake of green hydrogen technologies. - Demand for green hydrogen on the other hand must be increased by, among other things, closing the price gap with grey hydrogen through fiscal support and tariffs on the one hand, but also by setting targets for green gases as described in [7]. - Regimes of direct financial support and/or fiscal incentives could aim at triggering the production of electrolyzers to produce capacity on an industrial level [7]. - More decentralised storage facilities for green hydrogen are needed to create incentives for producers of renewable energy to convert excess production into hydrogen instead of throttling the plants.
Social:	- Public acceptance and support is required. Education and awareness campaigns are necessary to inform the public about the benefits, safety measures, and potential environmental advantages of hydrogen as an energy source.

3.5.3 Bottom line

Repurposing a gas grid for 100% hydrogen would require addressing among other things infrastructure and materials compatibility, hydrogen production and supply, storage capacity and public acceptance.

A repurposed natural gas grid for 100% hydrogen offers a practical and cost-effective solution for the distribution and storage of hydrogen. By repurposing the existing infrastructure, the extensive grid already in place can be leveraged, minimizing the need for extensive construction. The repurpose enables efficient transmission of hydrogen across regions, ensuring widespread access to clean energy.

The integration of renewable hydrogen, produced through electrolysis, further enhances its sustainability. Industries and communities connected to the repurposed grid can benefit from a clean and reliable energy source, reducing their carbon footprint and dependence on fossil fuels.

The transition to a hydrogen-based grid promotes energy diversification and aligns with global efforts to decarbonize the energy sector. Overall, repurposing the natural gas grid for 100% hydrogen represents a significant step towards a cleaner and more sustainable energy future.

4 Main recommendations

In the previous section 3 it was shown how different the characteristics of the future gas grid can be. Here, it will be shown again in condensed form which points can be tackled in order to decarbonise the gas grid both in the short and long term. Although the points are numbered, the points are not necessarily to be understood in chronological order.

4.1 Technical point of view

i. Compatibility assessment: Conduct a comprehensive compatibility assessment of the existing gas grid infrastructure to ensure it can safely handle hydrogen. Hydrogen has different material compatibility requirements compared to gas, so it's crucial to evaluate the integrity of pipelines, valves, compressors, and other equipment such as pressure reduction stations at the city gates. A compatibility study is already being made within the scope of WP4 and the results can be seen in D4.2, D4.4 and the upcoming D4.4, with promising results with blends of up to 30 % H2 so far.

ii. General system retrofit: Identify necessary retrofit or modifications to accommodate the admixture of hydrogen based on an inventory of the affected grid section(s). This may include upgrading and/or replacing pipelines, installing hydrogen-specific equipment, implementing safety measures, and adjusting control- and monitoring systems.

iii. Blending ratio: Determine the optimal blending ratio of hydrogen and gas depending on the local circumstances. Start with low percentages and gradually increase them to ensure not only compatibility and safety, but also to gain experience in the process of operating a grid with such a blend. Factors such as the hydrogen supply availability, local regulations, and the end-use requirements need to be considered.

iv. Separation technology: As long as the permissible levels of hydrogen (> 2 vol.%) are not harmonised across the EU, separation of gas and hydrogen can be used selectively where applications further downstream cannot be adapted to the new mixture or can only be adapted slowly. A better overview is expected to be provided in coming WP6 deliverables. On the other hand, the use of separation technology at border crossings enables the transport of hydrogen across borders by adhering to permissible concentrations, which in turn further promotes the integration of hydrogen across Europe.

v. Hydrogen dedicated grid: In the long term, repurpose parts of the existing gas grid for the use of 100 % hydrogen. Especially where several pipelines run in parallel, retrofit individual pipelines as a first step. The demand for hydrogen in the EU and UK will be around 2150 - 2750 TWh by 2050, which corresponds to 20 - 25 % of final energy consumption. Domestic production potential (supply) in the EU and UK of green (and blue) hydrogen far exceeds this demand, as predicted by the EHB in [5]. In addition, as shown in HIGGS D5.3 and Figure 2 in this deliverable, transporting pure hydrogen in a dedicated grid is the most cost-effective option.

4.2 Economic point of view

i. Cost-benefit analysis: Conduct a comprehensive cost-benefit analysis to evaluate the economic viability of retrofitting the gas grid for hydrogen admixture depending on the local circumstances. Consider the costs of infrastructure upgrades, equipment modifications, safety enhancements, and ongoing maintenance against the potential benefits such as reduced carbon emissions or compliance with renewable energy targets. As shown in HIGGS D5.3, cost for transport of hydrogen are going to vary significantly depending on the business case chosen:

- approx. 3-5 €/MWh/1000 km without consideration of separation technology. Would correspond to the business cases in sections 3.2, 3.3 and 3.5 and the most cost effective solutions mainly due to lack of separation technology. On the flipside, it requires harmonised permissible levels of hydrogen across the EU or a dedicated 100 % hydrogen grid. It is seen as the most promising way to go.

i. Hydrogen supply: Assess the availability, cost, and reliability of hydrogen supply in the region. The goal must be to be able to offer green hydrogen in a cost-efficient way compared to other generation sources, with full cost accounting. Ergo, a price for CO_2 is needed. In order to compete with e.g. grey hydrogen, it must be possible to supply green hydrogen at 2 €/kg with a CO_2 price of at least 100 €/t. [9].

ii. Regulatory environment: Push local and national regulations related to hydrogen blending. Some regions may start to offer incentives, grants, or favourable policies for hydrogen integration, which can significantly impact the economics of hydrogen including the retrofitting of existing gas infrastructure.

iii. Stakeholder engagement: Engage with stakeholders, including gas grid operators, energy providers, industry partners, and local communities. Collaborative efforts and partnerships can help share the costs and risks associated with retrofitting, making the economic feasibility more attractive.

iv. Long-term planning: Consider the short- and mid-term viability and sustainability of hydrogen blending in the gas grid before eventually switch to a 100 % hydrogen grid. Evaluate future energy market trends, technological advancements, and potential scalability of hydrogen production to ensure the economic benefits can be sustained over time.

4.3 Vision 2050

In accordance with the strategic long-term vision of the European Union to reduce greenhouse gas emissions to net zero in all sectors of the economy by 2050 [4], the project team presents, in alignment with the vision in deliverable D6.1, its vision of what a climate-neutral gas grid could look like in 2050. As we move towards a decarbonised and sustainable energy future, it is crucial to envision a gas grid that aligns with the region's climate goals, enhances energy security and facilitates the integration of renewable and low-carbon gases. This vision outlines the key elements and principles that will guide the evolution of the European gas grid over the next three decades The gas grid will help to supply many households, businesses and commercial enterprises with climate-neutral energy and will thus play a decisive role in achieving Europe's climate goals

1. Renewable and low-carbon gas integration:

   By 2050, the European gas grid will support the efficient transportation and distribution of renewable and low-carbon gases, including biomethane, hydrogen and synthetic methane. On one hand, the grid will be designed and retrofitted to accommodate the injection and low-volume blending of hydrogen, enabling its seamless integration into the existing infrastructure. On the other hand, in parallel to the gas grids, new and/or retrofitted pipelines will transport 100% hydrogen from sustainable sources [9].

   The integration of hydrogen within the gas grid will contribute to enhanced energy independence for Europe. By utilsing domestic renewable energy sources and producing hydrogen locally, European countries can reduce their dependence on imported fossil fuels. This transition promotes energy sovereignty, strengthens regional energy security, and mitigates geopolitical risks associated with energy imports

2. Decentralised and flexible network:

   The gas grid of 2050 will be characterised by increased decentralisation and flexibility. It will incorporate a diverse range of supply sources, including small-scale biomethane plants, local hydrogen production facilities and Power-to-Gas systems. This distributed generation will enhance energy security, reduce transmission losses and create opportunities for local economic development.

3. Smart and digital infrastructure:

   The grid of the future will be a smart and digital infrastructure, leveraging advanced technologies for monitoring, control and optimisation. Real-time data analytics, IoT-sensors and predictive maintenance systems will enable proactive management of the grid, enhancing operational efficiency and reliability. Additionally, advanced metering and billing systems will support demand response mechanisms and facilitate consumer engagement.

4. Energy storage and flexibility:

   The European gas grid will play a crucial role in energy storage and flexibility. It will integrate large-scale gas storage facilities, including salt caverns and depleted reservoirs, to store excess renewable energy in the form of hydrogen. It will serve as a valuable energy reserve to be utilised during times of high energy demand or limited renewable energy availability. This will enhance the grid's flexibility and ensure a reliable energy supply throughout the year. By doing so it will enable a more efficient plant operation by avoiding the need to shut down power generation facilities during periods of low electricity demand. This approach maximises the utilisation of renewable energy assets and improves overall energy efficiency.

5. Cross-border cooperation and interconnectivity:

   As foreseen in the “Hydrogen and gas markets decrbonisation package”, to maximise the benefits of a unified European energy market, the gas grid will foster cross-border cooperation and interconnectivity [5]. Harmonised regulations and standards will enable seamless gas flows across national boundaries, facilitating gas trading and optimizing resource allocation. Interconnections with neighboring regions will enhance supply diversity and resilience.

6. Collaboration and stakeholder engagement:

   Achieving this vision requires collaboration among all stakeholders, including gas grid operators, energy companies, policymakers, regulators and the public. Continuous dialogue and engagement with these stakeholders will ensure that the gas grid evolves in line with societal expectations, environmental objectives and technological advancements.

7. Investment and financing:

   To realize this vision, significant investment will be required. Public and private investments will be channeled towards grid expansion, upgrading and retrofitting existing infrastructure, integrating new technologies and fostering innovation. Attracting financing from various sources, including public funds, private investors and international institutions, will be crucial to accelerate the transition and ensure the economic viability of the grid.

To conclude, a transformative and sustainable pathway for the evolution of the gas transmission infrastructure was shown. By embracing renewable and low-carbon gases, leveraging digital technologies, enhancing cross-border cooperation and prioritizing environmental sustainability, the gas grid will play a pivotal role in achieving Europe's long-term energy and climate objectives. This vision calls for collaborative efforts, innovation and bold action to create a resilient, efficient and future-proof energy network for the benefit of all European citizens.

5 Conclusions

Based on the findings in Tasks 5.1 to 5.3 and the corresponding deliverables D5.1 to D5.3, this deliverable shows what a future gas grid in Europe or in the European Union could look like. The approach of characterising the gas grid according to hydrogen content and the need for separation offers the advantage of considering different, conceivable development and expansion stages.

1. 0 - 2 vol.-% H_2 without the need for separation
2. 2 – 30 vol.-% H_2 without the need for separation
3. 2 – 30 vol.-% H_2 including separation
4. 100 vol.-% H_2

From a business and operational perspective, all four forms of the future gas grid discussed offer their specific opportunities and risks, but also many overlaps. What all the gas grid systems discussed have in common, however, is that there are still many gaps that need to be closed in one way or another in order to enable the integration of hydrogen in the European gas grid across the board. Two areas in particular should be emphasised:

- The legal barriers to the transport of hydrogen must be further reduced throughout Europe, and new laws should regulate, simplify and ultimately promote the transport of hydrogen in Europe.
- Supply and demand must be further expanded. Driving roles will be played by both the scaling of green hydrogen production capacities (electrolysis) and the need for seasonal storage of renewable energy.

The local conditions within the European gas grid make it difficult to give an overall forecast of the direction in which the gas grid will develop. It is likely that, at least in the short to medium term, different solutions will develop depending on local conditions such as supply, demand, existing infrastructure and legal requirements. In the long term, however, a holistic European solution is needed to further increase cooperation between regions of the EU and to have a resilient gas grid that can reliably and flexibly meet energy needs.

Ultimately, WP5 has not only shown that the transport of hydrogen in a retrofitted gas grid is economically competitive, but also a necessity in order to achieve the emission targets that have been set.

Bibliography & References

[1] Cadent Gas Ltd. and DNV. 2021. *NIC04 Future Billing Methodology Project Progress Report 5*.

[2] DBI. 2023. *H2-ready Label*.

[3] ENTSOG. 2021. *DECARBONISING THE GAS VALUE CHAIN*. *CHALLENGES, SOLUTIONS AND RECOMMENDATIONS*.

[4] EUROPEAN COMISSION. 2018. *A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*.

[5] EUROPEAN COMISSION. 2021. *on the internal markets for renewable and natural gases and for hydrogen*. *2021/0424 (COD)*.

[6] EUROPEAN COMISSION. 2023. *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS*. *on the European Hydrogen Bank*.

[7] IRENA. 2021. *GREEN HYDROGEN SUPPLY:*. *A GUIDE TO POLICY MAKING*. IRENA.

[8] Michael Walter et. al. 2021. *HIGGS D2.3*. *Final document review on specific technical,RCS barriers, enablers and innovations*.

[9] Rik van Rossum, Jaro Jens, Gemma La Guardia, Anthony Wang, Luis Kühnen, Martijn Overgaag. 2021. *Analysing future demand, supply and transport of hydrogen*. EHB.

[10] *THyGA | Testing Hydrogen admixture for Gas Applications*. https://thyga-project.eu/. Accessed 2 August 2021.

[11] VKU &DVGW. *Der Gasnetzgebietstransformationsplan (H2vorOrt)*. *Ergebnisbericht 2022*.

Acknowledgements

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No. 875091 'HIGGS'. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.