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Safe hydrogen injection management at network-wide level: towards European gas sector transition

Shimmer

Safe Hydrogen Injection Modelling and Management for European gas network Resilience

D4.5 Report and guidelines on operational control strategies for injection in networks for the relevant cases and positioning of optimal monitoring points in the network

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ABSTRACT

The SHIMMER project investigates the safe and efficient integration of hydrogen into European gas transmission and distribution networks. The study combines detailed simulations and operational analyses of two Transmission System Operator (TSO) networks in Italy, and Spain, and two Distribution System Operator (DSO) networks in Italy and Spain. Results show that hydrogen blending is a viable short-term decarbonization pathway, while pipeline repurposing may enable larger-scale hydrogen transport where infrastructure conditions allow. However, hydrogen injection introduces dynamic gas-quality and hydraulic effects, requiring network-wide monitoring, transient modelling, and coordinated operation between TSOs and DSOs.

The analysis demonstrates that hydrogen concentrations depend strongly on network topology, flow conditions, and pressure-driven interactions, leading to spatial and temporal variations in gas quality. To support effective monitoring, a clustering-based methodology for optimal gas-quality sensor placement is proposed, enabling accurate estimation of gas quality while minimizing deployment costs. The findings highlight the need for advanced modelling, real-time monitoring, optimized sensor deployment, and harmonized operational and regulatory frameworks. Together, these elements provide a foundation for the safe, reliable, and scalable integration of hydrogen into future European gas networks, supporting the transition toward a low-carbon energy system.

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List of Abbreviations

Table 1 List of abbreviations

Term	Explanation
SHIMMER	Safe Hydrogen Injection Modelling and Management for European gas network Resilience
EU	European Union
TSO	Transmission System Operator
DSO	Distribution System Operator
NG	Natural gas
H2	Hydrogen
IP	Interconnection Point
WI	Wobbe Index
RES	Renewable Energy Sources
UGS	Underground Gas Storage
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
ASME	American Society of Mechanical Engineers
MAOP	Maximum Allowable Operating Pressure
DN	Nominal Diameter
PV	Photovoltaic
GEM	Global Energy Monitor
WP	Work Package

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Executive Summary

This document presents key conclusions and recommendations for the integration of hydrogen into gas transmission (TSO) and distribution (DSO) networks, along with guidelines for optimal gas-quality sensor placement. The findings are based on detailed simulations and case studies, focusing on operational control strategies, system performance, and monitoring requirements under hydrogen blending scenarios.

Hydrogen Integration in Transmission Networks

Hydrogen integration in high-pressure transmission networks should be approached through a phased strategy combining short term blending and long-term infrastructure transformation. Hydrogen blending into natural gas pipelines is technically feasible and serves as an effective transitional solution. However, its scalability is inherently constrained by hydraulic limitations, including increased volumetric flow, higher gas velocities, elevated pressure losses, which are of particular concern in already saturated pipelines and increased compressor energy demand. These factors may limit allowable hydrogen concentrations independently of downstream gas quality standards.

In contrast, pipeline repurposing enables dedicated hydrogen transport at significantly larger scale, offering a more suitable long term solution in specific cases. However, this approach is only feasible where natural gas pipelines are no longer required or where parallel pipeline infrastructure already exists. Repurposing represents therefore a strategic reallocation of transport capacity between natural gas and hydrogen. Consequently, its feasibility depends not only on technical suitability but also on demonstrating, through system-level assessment, that the remaining natural gas infrastructure can adequately accommodate projected natural gas transport needs.

Operationally, hydrogen integration introduces dynamic and location dependent gas quality behaviour. Hydrogen does not propagate uniformly through the network; instead, its distribution is influenced by topology, flow conditions, and mixing processes. As a result, compliance with gas quality limits cannot rely solely on injection point specifications but requires network wide, time dependent monitoring and assessment. In particular, both hydrogen concentration and derived indicators such as the heating/calorific value or Wobbe Index and its rate of change must be considered. Moreover, variable hydrogen injection may generate local pressure and velocity fluctuations which, in addition to influencing hydrogen transport and gas-quality evolution, may worsen repeated mechanical loading on pipelines and components, making hydraulic dynamics relevant for integrity assessment.

The presence of multiple distributed hydrogen injection points further increases system complexity. Injection capacity and local hydrogen concentrations depend strongly on the interaction between injection rates and local flow conditions. High flow corridors dilute hydrogen effectively, while low flow regions may experience elevated and highly variable concentrations. Consequently, hydrogen injection must be treated as a location specific service, requiring local assessments and coordination mechanisms among producers. This includes the implementation of dynamic allocation rules, curtailment strategies, and integrated forecasting and monitoring tools.

Additionally, underground gas storage (UGS) plays a critical role as an operational flexibility asset, supporting hydrogen dilution and balancing variable renewable hydrogen production if operation (seasonal way of work) allows it. However, in the main transmission pipelines, where flow conditions can be bidirectional, hydrogen may accumulate during flow reversal conditions when the upstream gas mixture already contains 5% hydrogen, thereby requiring enhanced monitoring and adaptive injection strategies.

Overall, successful hydrogen integration in transmission systems requires a holistic, system level approach, combining advanced transient modelling, real time monitoring, coordinated operation, and harmonized technical standards. These procedures should be aligned with established technical standards (e.g. ASME

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B31.12) and emerging European frameworks (e.g. EN 1594, EN 17649), ensuring a harmonized approach to hydrogen readiness across transmission systems.

Hydrogen Integration in Distribution Networks

In distribution networks, hydrogen integration is governed by hydraulic interactions, network topology, and time dependent behaviour, making gas quality control inherently more complex than in transmission systems.

A key finding is that pressure regulation at entry points acts as a primary control mechanism for hydrogen distribution. In multi entry networks, the relative contribution of each supply point and thus hydrogen concentration distribution is determined by pressure driven flow balancing. As a result, gas quality emerges from system hydraulics rather than being directly controlled at injection points. Adjusting pressure setpoints enables DSOs to dynamically manage hydrogen propagation and spatial exposure across the network.

This leads to the formation of gas quality zones, where different parts of the network experience varying hydrogen concentrations, ranging from pure natural gas to fully blended mixtures or intermediate compositions due to in network mixing. Such variability can persist even under steady state conditions and is further influenced by transient effects, particularly under seasonal demand changes.

The interaction between transmission and distribution systems is also critical. Hydrogen introduced at the TSO level propagates into DSO networks through multiple entry points, creating complex and non-uniform concentration patterns. Therefore, hydrogen management at the distribution level requires close coordination between TSOs and DSOs, including shared operational strategies and data exchange.

Hydrogen propagation in DSO networks is inherently time dependent, with significant delays between injection and arrival at consumers. These delays are especially pronounced under low demand conditions, potentially extending over weeks. Consequently, steady state analyses alone are insufficient, and transient modelling is essential to accurately capture system behaviour.

The presence of multiple supply sources with different gas compositions results in quasi steady conditions characterized by spatially non uniform gas quality. This has direct implications for end users, as varying hydrogen concentrations affect the energy content of supplied gas. If billing is based on volume, this may lead to inequitable costs for consumers receiving hydrogen enriched gas. Therefore, hydrogen integration strategies must explicitly address fairness and energy-based billing considerations, as these apply to both DSOs and TSOs. While this is a common problem either for DSOs and TSOs, the gas quality monitoring throughout distribution networks is far less adopted than at transmission level and much more complex given the much-meshed topology of urban level distribution systems.

In summary, effective hydrogen integration in DSO networks requires pressure-based control strategies, system-wide monitoring and modelling, coordination with upstream transmission systems, and consideration of consumer impacts.

Optimal Gas Quality Sensor Placement

The integration of hydrogen introduces significant challenges for gas quality monitoring due to dynamic, spatially heterogeneous gas composition. While comprehensive monitoring is desirable, the high cost of sensors necessitates an optimized approach.

The primary objective of sensor placement is to ensure that hydrogen concentrations throughout the network can be estimated within a predefined accuracy threshold, rather than measuring every point directly. This leads to a trade-off between accuracy and deployment cost, which must be explicitly managed.

A clustering based methodology provides an effective solution. By analysing simulated gas quality profiles, network nodes can be grouped into clusters with similar behaviour. A single sensor located at a representative node can then approximate the gas quality of all nodes within that cluster, provided that the estimation error

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remains within acceptable limits. Nodes exhibiting unique or highly variable behaviour may require dedicated sensors.

Results demonstrate a strong nonlinear relationship between accuracy requirements and the number of sensors. Relaxed accuracy thresholds allow broad coverage with relatively few sensors, while tighter thresholds significantly increase sensor requirements, particularly in regions where gas quality variability is high.

Importantly, gas networks can be divided into regions with distinct variability characteristics. Stable regions require fewer sensors, while mixing zones and transition areas demand higher sensor density due to their dynamic behaviour. Therefore, sensor placement should be targeted rather than uniform, prioritizing areas of high variability.

Practical implementation must also consider installation constraints and operational robustness. Preferred sensor locations, such as pressure reduction stations or city gates, may not always coincide with optimal monitoring points. Therefore, strategies should balance theoretical optimality with practical feasibility and system resilience.

Finally, the effectiveness of sensor placement depends on the integration of monitoring with advanced modelling and estimation techniques, which can enhance accuracy and potentially reduce the number of required sensors.

Overall Conclusion

Hydrogen integration into gas networks requires a system wide transformation of operational, technical, and monitoring approaches. Key enablers include:

- Advanced transient modelling and simulation tools
- Real time gas quality and flow monitoring systems
- Coordinated operational frameworks across multiple stakeholders
- Adaptive regulatory frameworks incorporating dynamic gas quality metrics
- Optimized sensor deployment strategies balancing accuracy and cost

Together, these elements form a robust foundation for enabling safe, efficient, and scalable hydrogen integration, supporting the broader transition toward a decarbonized and integrated energy system.

About the project: The European natural gas infrastructure provides the opportunity to accept hydrogen (H_2), as a measure to integrate low-carbon gases while leveraging the existing gas network and contributing to decarbonisation. However, there are technical and regulatory gaps that should be closed, adaptations and investments to be made to ensure that multi-gas networks across Europe will be able to operate in a reliable and safe way while providing a highly controllable gas quality and required energy demand. Aspects such as material integrity of pipelines and components, as well as the lack of harmonisation of gas quality requirements at European level must be addressed in order to facilitate the injection of H_2 in the natural gas network.

In this context, the SHIMMER project (Safe Hydrogen Injection Modelling and Management for European gas network Resilience) was selected for funding as part of the 2023 Clean Hydrogen Partnership programme. SHIMMER aims to enable a higher integration of low-carbon gases and safer H_2 injection management in multi-gas networks by strengthening the knowledge base and improving the understanding of risks and opportunities in H_2 projects.

It will do this by:

- Mapping and assessing European gas T&D infrastructure in relation to materials, components, technology, and their readiness for hydrogen blends.

- Defining methods, tools and technologies for multi-gas network management and quality tracking, including simulation, prediction, and safe management of network operation in view of widespread hydrogen injection in a European-wide context.
- Proposing best practice guidelines for handling the safety of hydrogen in the natural gas infrastructure and managing the risks.

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1 Introduction

1.1 Purpose of the document

This report is a deliverable of the SHIMMER project Task 4.3, Operational strategies for injection and flow transport management, specifically Subtask 4.3.1, Operational network simulation. The report, titled "D4.5 – Report and guidelines on operational control strategies for network injection, including relevant case studies and the positioning of optimal monitoring points", presents the results and guidelines developed within this subtask.

In this report, several operational strategies are designed and evaluated to develop smart injection strategies and practical guidelines for operating gas networks across Europe. These strategies are derived from network and injection challenges identified in the case studies presented in deliverable D4.1 – Report describing the defined simulated test cases, realistic-scale test case(s), and available operational models, including required datasets and data formats [1].

The guidelines and recommendations for hydrogen injection into natural gas pipelines are divided according to the network ownership of Transmission System Operators (TSOs) and Distribution System Operators (DSOs), reflecting the fundamental differences between these two types of networks. The TSO networks evaluated in this report are operated by Enagás (Spain) and SNAM (Italy), while the DSO networks are operated by Redexis (Spain) and Inrete Distribuzione Energia (Italy).

Work package 4 has targeted objectives as following:

1) To determine system and engineering constraints that can reduce hydrogen acceptability in the networks
2) To study the fluid dynamic impacts on H2 blending
3) To map how contractual constrains will affect H2 admissibility
4) To establish general guidelines on how gas quality parameters will impact H2 admissibility
5) To establish optimal operational strategies and best practice recommendations for handling and control of H2 in the natural gas infrastructure

1.2 Intended readership

The SHIMMER project aims to advance knowledge and understanding of the risks associated with multi-gas networks, with a particular focus on hydrogen injection. This study addresses the integration of low-carbon gases and the safe injection of hydrogen into the transmission and distribution gas infrastructure across European countries.

The intended audience of this report and the corresponding added value for each group are as follows:

- **Technical standardization bodies:** To address existing knowledge gaps and provide technical input to support the development of future regulations for the integration of renewable gases.
- **Transmission and Distribution System Operators (TSOs and DSOs):** To reduce uncertainties related to the operation of future gas networks by assessing operational strategies for asset management and hydrogen injection.
- **Regulatory bodies:** To inform the development of regulations that support gas quality harmonization, define appropriate incentives, and establish a coherent market framework across European countries.
- **Gas technology providers:** To improve understanding of the current state of gas technologies and to provide insights into potential future product requirements and technology development opportunities.
- **Investors in the renewable gas sector:** To support Europe-wide investment decisions by contributing to the harmonization of renewable gas and hydrogen markets across Europe.

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Readers of this document are expected to possess a general understanding of transmission and distribution gas networks and the associated operational challenges. Beyond this foundational knowledge, no in-depth technical expertise is required. Technical terms used throughout the report are explained in a clear and accessible manner in the Background chapter 2.

1.3 Structure of this document

The current document presents the results of Task 4.3, Operational Strategies for Injection and Flow Transport Management, with a specific focus on Subtask 4.3.1, Operational Network Simulation. The report outlines the outcomes of the study, including general recommendations and guidelines for operational control strategies related to hydrogen injection into gas networks, as well as methodologies for determining the optimal positioning of monitoring points within the network.

The document is structured as follows:

1. Background
2. Operational control strategies for hydrogen injection
3. Positioning of optimal monitoring points in the network
4. Conclusions

1.4 Stakeholder involvement

The stakeholders of this work package are organizations that share a common interest in the outcomes of the SHIMMER project and collaborate closely in the execution of its activities. These stakeholders primarily comprise research partners and transmission and distribution (T&D) gas network operators from various European countries. A comprehensive overview of the participating organizations is provided in Table 2.

Table 2 List of the research partners and transmission and distribution gas network operators that comprise the stakeholders of the current work package.

Organization	Background	Country
Netherlands Organization for Applied Scientific Research (TNO)	Research partner	The Netherlands
SINTEF	Research partner	Norway
Politecnico di Torino (PoliTO)	Research partner	Italy
ENAGAS	TSO	Spain
SNAM	TSO	Italy
GAZ-SYSTEM	TSO	Poland
GASSCO	TSO	Norway
INRETE	DSO	Italy
REDEXIS	DSO	Spain

Each stakeholder has a well-defined role within the work package. The network operators contribute by providing representative network models and measurement data for simulations, as well as by sharing their operational expertise to define realistic scenarios and support the derivation of meaningful conclusions. The research partners are responsible for developing the case studies, performing scenario simulations, analysing the results, drawing conclusions, and documenting all activities related to this work package.

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Regular meetings were held among all stakeholders to monitor progress, coordinate activities, and ensure alignment with the project's objectives and scope. The involvement of all stakeholders is essential to safeguard the quality, relevance, and reliability of the study's outcomes.

The active participation of the partners is reflected throughout the project. In particular, the research partners prepared this report, including the background information, methodology, scenario definitions, and research questions. The network operators supplied the necessary example networks and operational measurement data required for the simulations. Close collaboration was maintained during the scenario definition and data collection phases. Within this work package, TNO acts as the task leader on behalf of the research partners.

This collaborative approach ensures that the SHIMMER project benefits from a broad range of expertise, thereby supporting higher levels of integration and safer hydrogen injection management in multi-gas networks.

1.5 Relationship with other deliverables

The operational simulation strategies presented in this deliverable are developed based on the case studies defined in Task 4.1 – Definition of network models and case studies. And make use of the open-source tool developed within Subtask 4.2.4 – Open-source model of multi-component gas networks with quality tracking capability. The results and methods supporting these activities are documented in the following related deliverables:

- D4.1 – Report describing the defined simulated test cases, realistic-scale test case(s), and available operational models, including required datasets and data formats [1].
- D4.4 – Open-source fluid-dynamic model with gas quality tracking, released with a handbook and tutorials [2].

The operational strategies for gas quality sensor placement build upon insights obtained from Task 4.4 – Evaluation of gas quality measuring technologies for effective network management. The findings of this task are documented in the following deliverable:

- D4.7 – Report providing an overview of available gas quality measurement technologies and an evaluation of their performance, their ability to be integrated into control systems, and their compatibility with modelling tools [3].

1.6 AI tool

Artificial intelligence (AI) tools were used solely to assist with drafting, language refinement, and grammar checking during the preparation of this report. The AI tools were not used to generate or validate the technical content, analyses, results, or conclusions presented herein. All AI-assisted outputs were carefully reviewed, verified, and, where necessary, revised by the authors, who take full responsibility for the accuracy, integrity, and final content of this report.

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2 Background

2.1 Introduction

Hydrogen is expected to play a key role in the clean energy transition. It can be integrated into pipeline infrastructure through two main approaches: (1) injection into existing natural gas pipelines to create a hydrogen–natural gas blend, or (2) transportation via dedicated 100% hydrogen pipelines, either newly constructed or repurposed from existing gas infrastructure. Hydrogen blending in natural gas networks is widely regarded as a promising pathway to accelerate energy system decarbonization. However, it is not a consolidated industrial practice: substantial technical and regulatory gaps are still open but many research and demonstration projects are addressing them. Their findings should help define all the required adaptations needed and contribute to the estimation of the required investments, so to ensure that multi-gas networks across Europe can operate safely and reliably. At the same time, these networks must maintain a high level of gas quality controllability while meeting the required energy demand.

Several operational challenges for blending are anticipated in both TSO and DSO networks. At the TSO network level, the following challenges are identified:

- Sector coupling between power and gas networks, introducing line-pack management challenges under variable supply and demand profiles;
- Hydrogen blending and long-distance transport from EU neighbouring regions (e.g. North Africa), raising challenges related to compression capacity;
- Storage systems acting as dispatch and asset management challenges within integrated network operation;
- Multiple gas injection points within the network, necessitating advanced strategies for smart flow and pressure control.

At the DSO network level, specific challenges are addressed that require detailed gas quality tracking and control to ensure user safety. The following design and operational control challenges are addressed:

- Multiple pressure levels and multiple city gates;
- A complex meshed network with multiple injection points, injection levels, and supply profiles;
- A wide range of end-users (industrial and domestic), each with specific gas quality requirements and time-varying demand profiles;
- Limited local storage capacity and limited line pack;
- Optimal placement of gas quality sensors for effective monitoring and control.

2.2 Task description

This report belongs to Task 4.3 (Operational strategies for injection and flow transport management) focuses on the operational control of gas networks as defined in Task 4.1 (Definition of network models and case studies) and further optimized in Task 4.2 (Optimization of network design and needs for modifications). The objective of Task 4.3 is to evaluate and optimize network operation in a smart manner, with particular attention to security of supply, safe operation, compliance with gas composition constraints at end-user locations, and minimization of operational expenditure (OPEX).

Time-varying supply and demand profiles, the presence of storage facilities, and physical flow and pressure bottlenecks, have a huge impact on the network performance. Therefore, operational control strategies are needed, like: control of network equipment, storage assets, and optimal location and number of metering stations. To assess these impacts, key performance indicators (KPIs) are defined to quantify network performance, operational reliability and the availability of sufficient transport capacity for natural gas and hydrogen, capturing their variation across both geographical space and time.

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Specifically Subtask 4.3.1 (Operational network simulation) focuses on the design and evaluation of different operational strategies to develop smart injection strategies and operational guidelines for gas networks across Europe. These strategies are derived from the network and injection challenges identified in the case studies defined under Task 4.1.

This subtask will result in the following outcomes:

- Strategies for network monitoring and control enabling smart gas network configurations (e.g. dynamic pressure modulation at city gates or injection points);
- Guidelines for injection characteristics, such as pure versus blended hydrogen injection and redundancy requirements at injection stations;
- Guidelines for optimal injection location within the network (e.g. in systems with multiple city gates);
- Guidelines for the management and coordination of multiple injection locations;
- Guidelines for gas composition tracking within the network, including recommendations for the placement of monitoring sensors;
- Line-pack management strategies for transmission networks to support sector coupling, including mitigation of gas quality fluctuations over time.

2.3 Objectives

Subtask 4.3.1 aims to provide comprehensive guidelines for the operational strategies related to hydrogen injection into both TSO and DSO gas networks. The objective includes defining best practices for the safe, reliable, and efficient integration of hydrogen into existing gas infrastructure, while considering network performance, gas quality compliance, and operational flexibility. In addition, the subtask focuses on determining the optimal placement of gas quality sensors throughout the network to ensure accurate monitoring and effective management of hydrogen blending operations.

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3 Operational control strategies for hydrogen injection

This section of the report presents guidelines for operational strategies related to hydrogen injection into natural gas pipelines at both the TSO and DSO network levels. The section begins with a description of the considered scenarios and the associated operational challenges within these networks. It then continues with an explanation of the applied methodology, the selected network use cases, and the key findings for all investigated use cases.

3.1 Scenarios

Several scenarios for both TSO and DSO networks are developed to simulate hydrogen injection and blending strategies. These scenarios are used to assess optimal network configurations, identify necessary infrastructural adaptations, and determine effective operational management strategies, with the overall objective of ensuring the safe integration of hydrogen into gas networks. Each scenario is designed to investigate one or more specific challenges as described in Section 2.1.

TSO scenarios:

1) **Multiple and distributed injection of hydrogen with discontinuous production**
This scenario illustrates power–gas sector coupling through power-to-hydrogen technologies and hydrogen blending. Renewable overgeneration is converted into hydrogen at geographically distributed facilities and injected into nearby gas network points, resulting in multiple, time-varying hydrogen injection sources. Such conditions can lead to gas quality fluctuations, potentially exceeding admissible limits and causing "shadowing" effects, where upstream injections restrict downstream network access and result in hydrogen curtailment. A realistic case study is used to investigate these challenges, with simulation models identifying criticalities that subsequently inform the development of operational guidelines and mitigation strategies.

2) **Long distance transport of H2 either via NG+H2 mixture or dedicated hydrogen backbone (repurposed from previous gas infrastructure).**
This scenario represents long pipeline backbone infrastructures with few branches and limited looping, typically characterised by parallel lines rather than meshed networks. It is modelled using a pre-blended hydrogen–natural gas mixture, avoiding explicit modelling of hydrogen injection and admixing within the network. By simulating realistic end-of-line gas demand (or export flow) and varying the pressure set-points at the inlet (e.g. import terminals) following the prescriptions in ASME B31.12 [4] for pipeline repurposing to hydrogen or hydrogen blends, the impact of hydrogen content on pressure drops along the pipeline can be evaluated. This hydrogen blend import scenario is then compared to the decoupling of parallel natural gas pipeline for the conversion of one of them into a 100% hydrogen backbone. In this case, both the hydrogen backbone and the "residual" gas infrastructure are simulated to verify their transport capacity.

   The main objective is to evaluate how high hydrogen blending or the strategy of pipeline repurposing to hydrogen backbone affect transport capacity, particularly in terms of inlet pressure requirements and possible required reduction of the Maximum Allowable Operating Pressure (MAOP) as prescribed by ASME B31.12, potentially necessitating compressor set-point adjustments or transport capacity reductions.

3) **Injection and extraction of NG+H2 blends in Underground Gas Storages (UGS)**
From a gas infrastructure modelling perspective, underground gas storages can be represented as network nodes acting as sinks during charging phases and as sources during discharging phases of NG+H_2 blends. Their integration into gas networks is particularly relevant for hydrogen blending, as

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it introduces complex interactions related to charging and discharging rates, storage capacity, and varying hydrogen shares. The scope of this scenario is not to model the internal phenomena occurring within UGS, but rather to simulate the interaction between storage facilities and the gas network. This includes assessing the impact of hydrogen blending on storage behaviour, accounting for potential hydrogen losses or composition changes.

DSO scenarios:

1) **Multiple and distributed injection of hydrogen at different pressure levels**
Distribution networks are typically characterised by multiple pressure levels and are interconnected with higher-pressure transmission networks through one or more pressure reduction stations (city gates). This scenario represents cases in which distribution infrastructures receive hydrogen-blended natural gas from the upstream TSO network while simultaneously integrating distributed hydrogen injection directly at the distribution level, potentially at multiple pressure tiers.

   The objective of this scenario is to simulate hydrogen distribution across the different pressure levels of the network, assess interactions between multiple hydrogen sources, and evaluate control and modulation strategies to ensure a safe and efficient integration of hydrogen into distribution infrastructures.

2) **Multiple and distributed hydrogen injection with varying hydrogen shares and time-varying injection and consumption**
Building on the previously described infrastructure types, this scenario focuses on analysing the distribution of hydrogen concentrations within complex, highly meshed networks under diverse operating conditions. These conditions include varying injection and consumption patterns, spatially distributed demand, and different hydrogen blending ratios at multiple injection points. The objective is to assess the potential for defining network zones with relatively homogeneous gas quality and to identify representative locations for gas quality monitoring that can effectively characterise entire network areas.

3.2 Methodology

3.2.1 Gas network model

The operational guidelines and recommendations presented in this report are derived from detailed gas network simulations incorporating hydrogen injection and full gas composition tracking. The simulations are performed using gas network models capable of resolving pressure, flow, and gas quality dynamics simultaneously over time and space. Gas composition tracking enables the explicit modelling of hydrogen transport, mixing, and dilution effects throughout the network, allowing local hydrogen concentrations to be assessed at any point in the infrastructure.

The simulation framework accounts for time-varying injection and withdrawal flows, multiple hydrogen injection points, storage interactions, and operational control actions such as compressor set-points and pressure regulation. Gas physical properties (e.g. density and viscosity) are dynamically updated based on local gas composition, ensuring physically consistent coupling between gas quality and hydraulic behaviour.

This approach enables the identification of operational constraints related to hydrogen admissibility, including gas quality limit exceedances, pressure and capacity limitations, line-pack utilisation, and interactions between multiple injection sources. Simulation results are used to derive operational insights and to test mitigation measures such as coordinated injection strategies, pressure modulation, storage utilisation, and sensor placement concepts. The composition-tracking capability is therefore a key enabler for developing robust and safe operational strategies for hydrogen integration in both transmission and distribution gas networks.

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Several gas network simulators used by the consortium partners are described in Section 5.1 of Deliverable D4.1 [1]. In particular, TNO applied its proprietary gas network simulator with composition tracking, AURORA [5], which has been validated using real network use cases in the Netherlands. PoliTO, on the other hand, employed the open-source fluid-dynamic model with gas quality tracking SHIMMER++, developed and released as part of Deliverable D4.4 [2] and available online here: https://github.com/shimmerhydrogen/shimmer.

3.2.2 Fluid dynamic effects of hydrogen blending

From a fluid-dynamics perspective, the primary impact of hydrogen blending in natural gas pipelines arises from the significantly lower density of hydrogen compared to natural gas. At standard conditions, hydrogen has a density of approximately 0.09 kg/m³, whereas natural gas typically lies around 0.7–0.8 kg/m³. As hydrogen is blended into natural gas, the resulting mixture density decreases progressively with increasing hydrogen fraction.

A. Effect on volumetric flow rate
Gas networks are largely operated to meet energy demand rather than volumetric demand. Because hydrogen has a much lower volumetric energy density (10 – 11 MJ/m³) than natural gas (36 – 40 MJ/m³), blending hydrogen reduces the energy content per unit volume of gas. Consequently, to deliver the same energy flow rate to end users, the required volumetric flow rate (m³/h) must increase as the hydrogen share increases. This effect is particularly relevant in high-pressure transmission pipelines and in distribution networks operating close to their hydraulic limits.

B. Effect on pressure drop
Pressure losses in gas pipelines are governed by frictional flow equations (e.g. Darcy–Weisbach, Panhandle, or equivalent formulations), which depend on gas velocity, density, viscosity, and pipeline characteristics. When hydrogen is blended into natural gas:
- The lower gas density leads to higher gas velocities for a given mass or energy flow rate.
- Higher velocities, combined with changes in Reynolds number and friction factor, result in increased pressure drops along the pipeline

3.3 TSO network use case

This section presents the lessons learned and key findings from fluid-dynamics simulations of hydrogen blending in natural gas pipelines at the TSO level. The analysed transmission networks are located in Italy and Spain.

3.3.1 Sicily, Italy

The Sicily use case concerns a section of the high-pressure transmission network in Italy representing a crucial Mediterranean hub for natural gas supply and the indicated entry gate for the southern corridor of the European hydrogen backbone. The network is the part of the Italian high-pressure network operated by the Italian TSO, SNAM. It consists of the complete transmission infrastructure covering the whole Sicily region. In the Italian (and European) context, this part of infrastructure is located at the international border, and it has two gas entry points from North Africa. These entry points feed the main transmission backbone transporting the gas out of the region towards the rest of the Italian peninsula. From the backbone system, few branches depart forming the regional transmission system which feeds the main urban and industrial centres of Sicily.

Beyond being a strategic corridor for gas supply to Europe, the Sicily use case is also relevant for the inclusion of:

- Parallel pipelines in the main backbone
- Compressor station and reducing gas station

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

These features will provide operational findings relevant for H_2-transport pipeline infrastructure.

3.3.1.1 Network geometry and assets

As shown in Figure 1, the island's transmission system is organized around a high-capacity backbone that runs from the Mazara del Vallo entry-point in the western part of the island to the Strait of Messina in the north-east. Mazara del Vallo is the Interconnection Point (IP) with Tunisia (part of the Transmed pipeline transporting the Algerian gas). A second entry-point is located more south, on the same coastline, in Gela and it is the IP with Libya (part of the Greenstream pipeline). This secondary import backbone, which is the final portion of the Greenstream, joins the main high-capacity backbone in Enna, where a gas compression station is located. The backbone includes two parallel pipelines between Mazara and Enna and three between Enna and Messina.

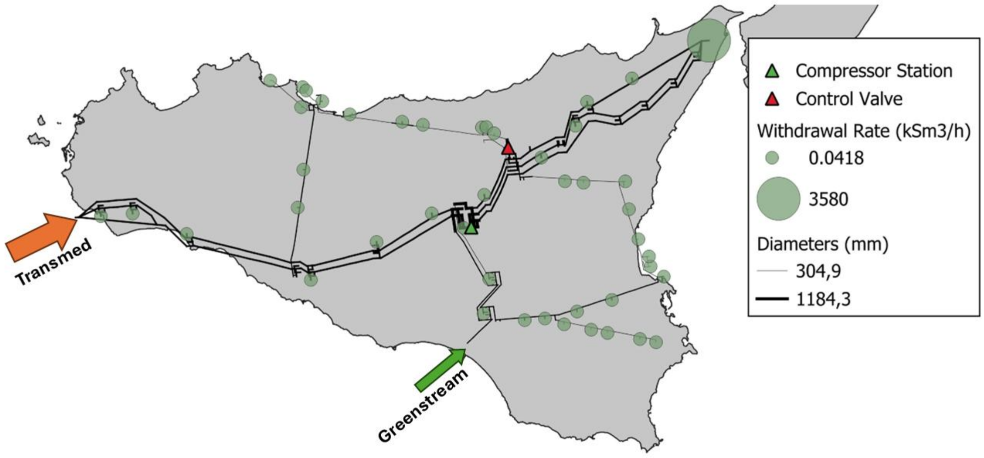

Figure 1 Sicily natural gas network and demand.

The northern portion of the island is served by two separate regional branches; the northernmost operated at lower pressure (24 bar_g) as it is connected to the main infrastructure via a control valve. The southern portion of the regional network originates from downstream the compression station, and runs parallel to the Greenstream towards south, feeding the regional southern loop. About 30 km downstream along the main backbone, a second branch breaks off to feed the south-east portion of the island. Both branches are hydraulically connected and form the southern loop.

The backbone is fed mainly at Mazara del Vallo by Algerian gas delivered through the Trans-Mediterranean (Transmed) pipeline; smaller volumes enter at Gela via the Greenstream pipeline from Libya. The ratio is around 8:1. Two further gas injection points are present as small national production of natural gas, located in Gagliano and Bronte, in the northern section. Gas is delivered to 45 exit points serving downstream distribution networks and large industrial users including a refinery hub in Augusta-Priolo, located in the second branch breaking off the main backbone to feed the south-east portion of the island, which hosts two world-scale refineries: Sonatrach Raffineria Italiana in Augusta and the ISAB complex in Priolo–Melilli.

3.3.1.2 Boundary conditions

The main characteristics of the Sicilian transmission system and the corresponding data sources are summarized in Table 3:

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

Table 3 Main characteristics of the Sicilian gas transmission system considered in the case study and corresponding data sources.

Category	Asset / Parameter	Value	Unit	Notes	Data source
Pipeline infrastructure	Main trunk system configuration	Single backbone with parallel sections	–	2 parallel pipelines between Mazara–Enna; 3 parallel pipelines between Enna–Messina	Authors' elaboration based on [6]
	Nominal internal diameter range	304.9–1184.3	mm	DN 350 on peripheral branches; DN 1200 on main backbone	Authors' elaboration based on [6]
	Pipeline roughness	0.012	mm	Uniform absolute roughness assumed	Industrial practice
	Maximum allowable operating pressure (MAOP)	75	bar-g	Transmission system	Authors' elaboration based on [6]
Entry points and supply sources	Mazara del Vallo (TransMed pipeline)	3.5	MSm³/h	Algerian gas import	[7]
	Gela (Greenstream pipeline)	0.40	MSm³/h	Libyan gas import	[7]
	Gagliano (domestic production)	7.97	kSm³/h	Northern Sicily	TSO – Snam communication
	Bronte (domestic production)	5.37	kSm³/h	Northern Sicily	TSO – Snam communication
Compressor stations and control devices	Enna compressor station	1	–	Mid-line pressure control	Authors' elaboration based on [6]
	Compressor outlet pressure set-point	60	bar-g	Reference operating condition	Authors' elaboration based on [6]
	Pressure control valve (northern branch)	1	–	Throttling to lower-pressure branch	Authors' elaboration based on [6]
	Valve outlet pressure set-point	24	bar-g	Northern regional branch	Authors' elaboration based on [6]
Operating scenario	Reference period	Winter 2023	–	Peak-demand steady-state snapshot	TSO
	Mazara del Vallo inlet pressure	64-75	bar-g	Actual operating set-point	[8]
	Gela contractual inlet pressure	70	bar-g	Minimum contractual value	[9]

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Major demand centres	Augusta–Priolo petrochemical hub	2 refineries	–	~198,000 bbl/d (Augusta); ~320,000 bbl/d (Priolo–Melilli)	[10], [11] [12]

3.3.1.3 Scenarios description

On the Sicily case study, the following scenarios have been studied:

1) Long distance transport of hydrogen
    a. Hydrogen blending vs. repurposing to dedicated hydrogen backbone;
    b. Import of blended hydrogen;
2) Multiple and distributed hydrogen injection from existing utility scale Renewable Energy Sources (RES).

In the following, scenarios description is given whereas the findings will be discussed in the separated paragraph.

Scenario 1.a: Long distance transport of hydrogen: hydrogen blending and hydrogen backbone

Two alternative pathways are analyzed and compared in this study: (i) hydrogen blending at 20 vol% within the existing natural gas infrastructure, and (ii) the repurpose of one parallel trunk line as a dedicated hydrogen backbone. Both pathways are described in compliance with ASME B31.8 and ASME B31.12 and are studied to quantify pressure profiles, flow velocities, compressor duties, and transport-capacity trade-offs under realistic operating conditions. Figure 2 summarizes the representative main scenarios which this study investigates; each scenario assumes a different level of infrastructure conversion, from minimal intervention (hydrogen blending) to a fully dedicated hydrogen corridor.

- Hydrogen Blending (20% H_2 + 80% CH_4, vol.): the existing network remains intact while a volumetric share of hydrogen is metered into the natural gas stream, keeping the total energy delivered to end-users unchanged.
- Gas Network Repurposing: a dedicated H_2 corridor is established by repurposing the northern parallel pipeline between Mazara and Messina in Figure 1. The following configurations are examined:
    - Reduced Natural Gas (NG) Network: Since the Mazara–Messina route is partially reassigned to hydrogen, the natural gas outflow from the Messina gateway is reduced to flow in remaining pipelines, while domestic demand in Sicily remains unchanged.
    - Hydrogen Backbone: the repurposed corridor carries 2.5 Mt/y of hydrogen (≈ 3.2 MSm^3/ h); a variant extends the hydrogen supply to the Augusta–Priolo petrochemical hub connecting it to North Africa import in coherence with European Hydrogen Backbone scenarios [13].

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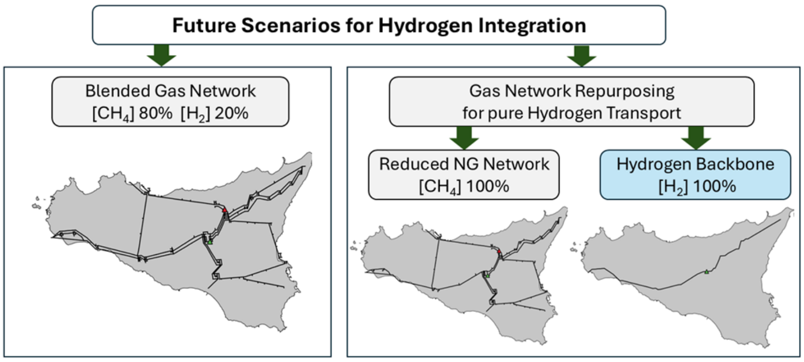

Figure 2 Qualitative Representation for Scenarios of Hydrogen Network-Integration.

In addition to the analysis of hydrogen blending and gas network repurposing, the main scenarios are further elaborated to ensure that mechanical integrity, reliability and safety of actual gas transmission systems, key thermofluidic-dynamic and operating parameters, such as pressure, flow velocity, and compressor duties, remain within prescribed thresholds. Therefore, pipeline assessment is considered by using ASME B31.8 for natural gas infrastructure and ASME B31.12 for hydrogen service and hydrogen blends, including Option A for pressure derating and Option B for underrated pipeline service . For the Sicily transmission network, currently transporting natural gas only, the certified MAOP is 75 bar_g, while flow velocities are limited to 20 m/s to avoid dynamic loading effects and fatigue failures. Overall, the following conditions are investigated:

(a) reference case: state-of-art operation with natural gas

(b) residual natural gas (NG) network after the repurposing: Gas network repurposing route

(c) hydrogen backbone with pressure derating (Option A): Gas network repurposing route

(d) hydrogen backbone without pressure derating (Option B): Gas network repurposing route

(e) hydrogen blending with pressure derating (Option A): hydrogen blending route

(f) hydrogen blending without pressure derating (Option B): hydrogen blending route

Scenario 1.a is investigated under steady-state conditions and aims at a comparative energy and hydraulic assessment of the considered long distance hydrogen pathways.

Scenario 1.b: Long distance transport of hydrogen: first import of 20% hydrogen blending from Mazara del Vallo entry point.

The Sicily infrastructure has been simulated under transient gas flow conditions without derating of pressure (ASME B31.12 Option B). Time dependent gas consumption profiles have been assigned to the exit points, using winter case data provided by SNAM. The two gas import points (Mazara del Vallo and Gela) have been assigned fixed pressure set points: 64 bar_g and 53.6 bar_g respectively while the other two gas entry points from domestic production (Gagliano and Bronte) have been set as constant gas flow rates injection point. Each gas inlet points have been assigned with the specific gas composition as shared by SNAM (see Table 4) and a steady-state equilibrium configuration of the network (in terms of pressure, flow rates, and gas composition) has been assumed as initial condition for the simulation.

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Table 4 Natural Gas composition (%vol) at each entry points of the Sicily network

	CH_4	C_2H_6	C_3H_8	iC_4H_{10}	nC_4H_{10}	iC_5H_{12}	nC_5H_{12}	C_6H_{14}	N_2	CO_2	He	H_2
	%	%	%	%	%	%	%	%	%	%	%	%
Mazara del V.	86.81	8.73	1.13	0.07	0.12	0.02	0.02	0.03	1.23	1.71	0.14	-
Gela	86.67	5.06	2.04	0.32	0.48	0.1	0.04	0.02	4.58	0.55	0.15	-
Gagliano	90.41	4.5	2.32	0.66	0.78	0.3	0.13	0.01	0.25	0.61	0.04	-
Bronte	89.59	4.97	2.9	0.8	0.93	0.2	0.09	0.03	0.18	0.26	0.04	-

At the initial timestep, the gas composition in Mazara del Vallo has been changed imposing 20% hydrogen share, thus modifying the composition as follows (see Table 5):

Table 5 Natural Gas composition (%vol) at Mazara del Vallo entry point with 20% H2 blending

	CH_4	C_2H_6	C_3H_8	iC_4H_{10}	nC_4H_{10}	iC_5H_{12}	nC_5H_{12}	C_6H_{14}	N_2	CO_2	CO	O_2	He	H_2
	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Mazara del V.	69.44	6.99	0.90	0.06	0.09	0.02	0.02	0.02	0.98	1.37	0.00	0.00	0.11	20.00

The compressor has been simulated as outlet pressure controlled which has been kept constant and equal to 60 bar_g.

A transient simulation of 24h has been run for simulating and tracking the first 20% blend reaching and travelling throughout the infrastructure. The relevance of this simulation is twofold:

1) It allows to track the gas quality perturbations on a real and complex infrastructure characterized by parallel lines which merge and fed by different gas sources which blend together.
2) Even though it shows the start-up of hydrogen blending import, it is anyways representative of the propagation times of any relevant gas quality perturbation.

Scenario 2: Multiple and distributed hydrogen injection from existing utility scale RES.

The Sicily infrastructure has been simulated considering the direct injection of hydrogen produced by a subset of utility-scale renewable generation plants, connected to the gas network in the nearest point. Figure 3 shows the location of all the photovoltaic and wind plants whose installed capacity is higher than 1 MW for solar and higher than 10 MW for wind generation. The data comes from GEM – Global Energy Monitor database [14]

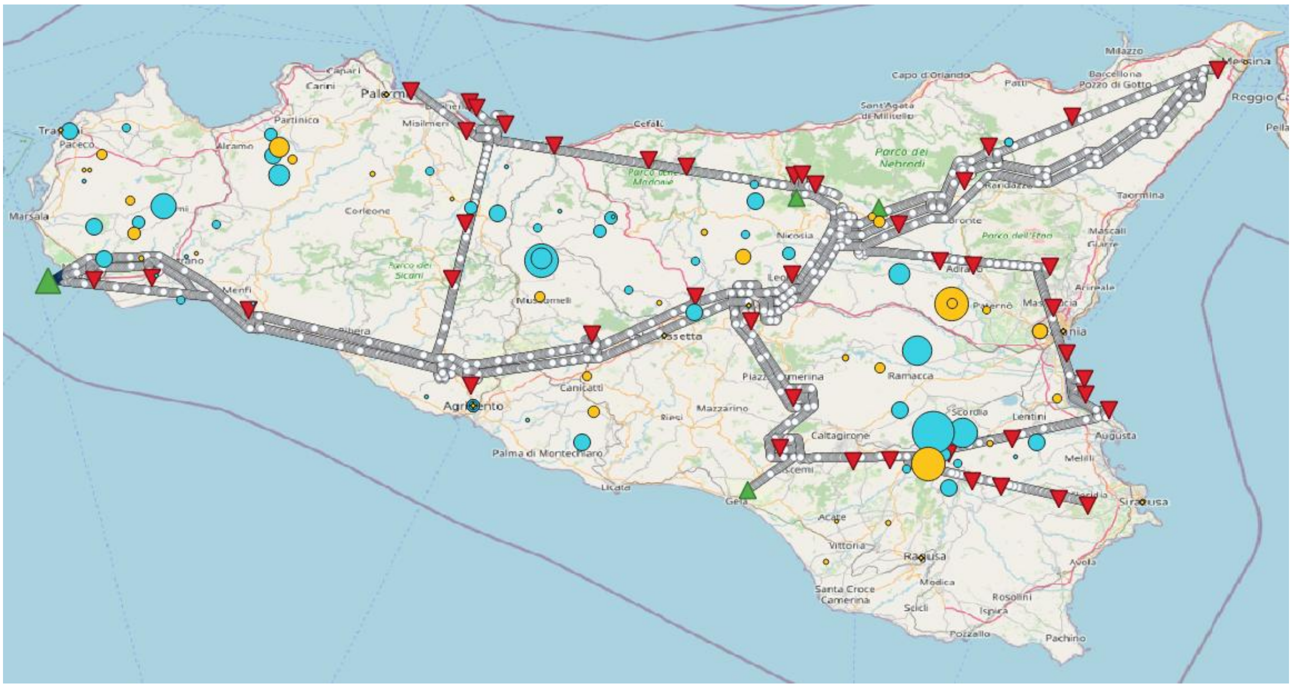

Figure 3 Localization of utility scale solar PV >1MW (Yellow)) and wind turbines installation >10MW (Blue) over Sicily. Bullet dimension is representative of the installed capacity. Data from GEM – Global Energy Monitor.

Among these, four RES installation has been selected for the distributed injection of hydrogen. Their main technical features have been summarized in Table 6.

Table 6 Main Technical features of chosen RES plants assumed to produce and inject hydrogen as distributed sources over the Sicily infrastructure.

#	RES type	Name of the plant	Province	$P_{el\ nom}$	H_2 flow rate (max)	injection point
				MW	kg/h	
1	Wind	Rocca Rossa (Alpiq)	Palermo	84	245.9	
	Wind	Rocca Rossa (Moncada)	Palermo	58	169.8	
	Wind	Rocca Rossa (*total*)	Palermo	142	415.8	main backbone (Mazara-Enna)
2	Wind	Regalbuto	Enna	50	146.4	regional branch (Sparacollo - Catania)
3	Solar	Fenix PV	Enna	245	717.3	regional branch (Augusta - Gela)
4	Wind	Mineo Militello Vizzini	Catania	101	295.7	regional branch

These plants have been chosen because they are among the largest installations and they are distributed on the territory so to provide representative distributed injection cases.

It has been assumed that the wind or solar net electrical production is fully converted into hydrogen by means of an electrolyzer whose average conversion efficiency is η_{LHV} = 65%.

By referring to typical meteorological year for wind speed and solar irradiance at the locations provided by the GEM dataset, the wind and solar hourly production pattern has been calculated and converted into hydrogen production flow rate.

Starting from the same boundary conditions as per the scenario before, a transient simulation of 24h has been run for simulating and tracking the distributed hydrogen injection throughout the network. A winter day has been selected for the hydrogen profiles. The simulation is set so that pure hydrogen reaches the gas network mixing nodes and directly blends within the natural gas flow rate. In Figure 4 the whole simulated infrastructure, including the four selected hydrogen production sites and their connections to the network is given.

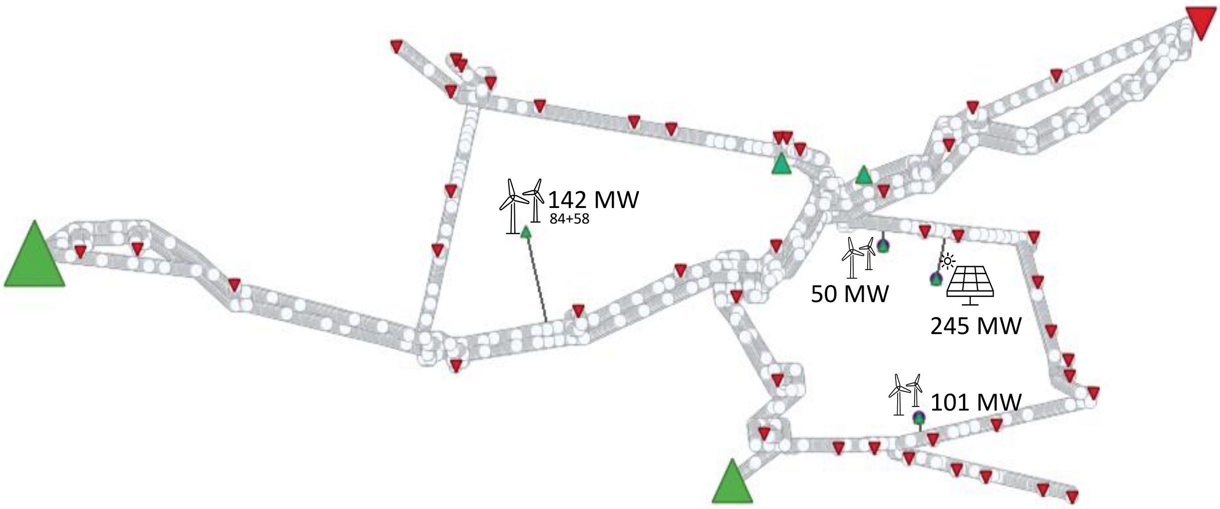

Figure 4 Localization of the hypothetical hydrogen injection from chosen distributed RES.

As of 2024, Sicily is the second Italian region in terms of installed wind capacity (19.2%) and the seventh as of photovoltaic installed capacity (7.2%). Considering the energy production, it is the second region for wind generation (29.7%) and the sixth for solar (8.2%). Overall, the regional electricity consumption is fairly low accounting for 5.9% of the total national consumption.

These features, even though not critical at the moment may motivate the interest towards Power-to-Hydrogen strategies and injection into the current gas infrastructure as a way of solving electricity network congestion, possible curtailments and, in general, energy system integration.

The relevance of this simulation is manyfold:

1) It enables the characterization of temporal variations in hydrogen concentration within the network at the injection point.
2) It demonstrates the role of injection point placement on local gas quality variation caused by hydrogen.
3) It captures the possible mutual interaction between multiple injection sources.
4) It allows the quantification of impacts on pressure cycles and flow velocities caused by the hydrogen injection.

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3.3.1.4 Findings

In this section the results from the simulations of the Sicily case study and the related scenarios are discussed and presented in form of key findings about the impact of hydrogen injection and hydrogen integration strategies on transmission networks.

Scenario 1.a: Long distance transport of hydrogen: hydrogen blending and hydrogen backbone

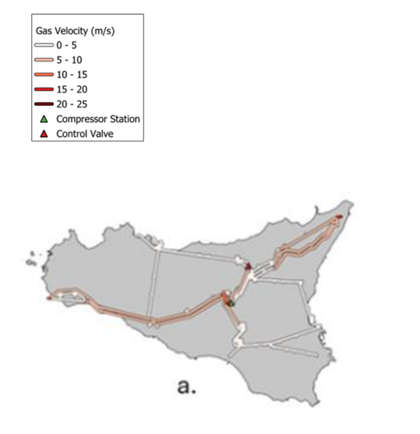
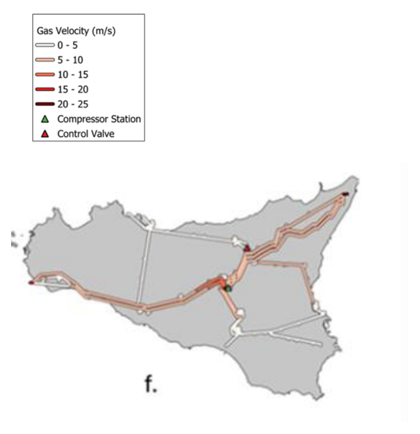
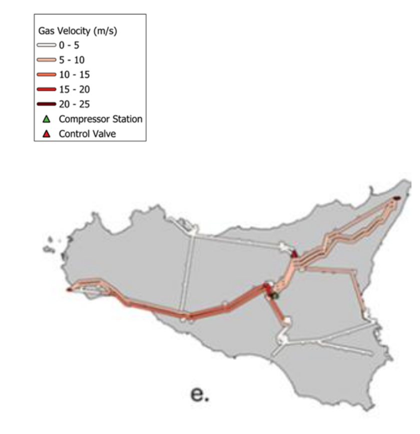
Blending introduces hydraulic and operational constraints, suggesting that blending limits should consider both end-user compliance and network operation

The steady-state analysis of the Sicily use case reveals significantly strategic difference of the two transport routes of hydrogen blending and repurposed gas network. A 20 vol% hydrogen blend in the existing gas system is technically feasible and can work as an early, transitional measure, but it is hydraulically penalized, non-selective for downstream users, and limited in scale. A repurposed dedicated hydrogen backbone is more scalable for pure-hydrogen delivery, as it enables the conversion of existing infrastructure towards hydrogen transport. However, since repurposing reallocates part of the natural gas transport capacity, its assessment requires evaluating the implications for the operation of the remaining natural gas network. In the Sicilian case, blending enables the transport of about 0.7 Mt/y of hydrogen, while the dedicated backbone enables about 2.5 Mt/y. Repurposing one trunk line reduces the available natural gas transfer capacity to mainland Italy by roughly 30%. The resulting natural gas transport capacity considered in the simulations (1041.6 GWh/day before repurposing) is comparable with peak transported flows observed at Mazara del Vallo, reaching up to 900 GWh/day over the last two years according to ENTSOG [7], highlighting the importance of assessing the operational margins of the residual gas system.

At equal delivered energy, adding hydrogen increases volumetric flow requirements, which in turn raises gas velocity, frictional pressure losses, and compressor duty. In the Sicilian case study, the baseline natural-gas configuration reaches about 16.8 m/s peak velocity and about 24 MW compressor demand. Under 20 vol% blending, peak velocities rise to about 24.0 m/s with pressure derating and 21.4 m/s without pressure derating, meaning that the blend exceeds the customary natural-gas practice range around 18–20 m/s even when the pressure penalty is eased. The most severe blended case also lifts recompression power at Enna to about 70 MW, versus roughly 24 MW today.

These findings are summarized in

Figure 5.

		
(a) reference case: state-of-art operation with natural gas	(f) hydrogen blending without pressure derating (ASME B31.12 Option B): hydrogen blending route	(e) hydrogen blending with pressure derating (ASME B31.12 Option A): hydrogen blending route

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Max velocity (m/s): 16.8	Max velocity (m/s): 21.4	Max velocity (m/s): 24
Compressor power (MW): 24.3	Compressor power (MW): 38.8	Compressor power (MW): 70

Figure 5 Summary prospect of the findings from scenario 1.a: hydrogen blending and hydrogen backbone comparison

This finding highlights the operational limitations of the blending option in terms of gas network management and suggests that gas-quality standards should consider not only final-user compliance, but also the feasible operation of transmission and distribution networks, including the definition of admissible blending limits. This finding is therefore related with gas quality and interoperability set in the EN 16726:2025 and it anchors the discussion on blended-gas compliance and interoperability. The finding also reconciles with gas quality traceability and guarantees of origin (GOs) system recently framed in EN 16325:2025 which includes hydrogen pure or in blends (in particular, the art. 5.3.10.2 includes the need to indicate in the GO, the point where the energy carrier is available for trading which could be a natural gas network for blends or a new and repurposed natural gas network for pure hydrogen) aligned with REDIII [15]. On the other hand, this finding calls for more advanced modelling analysis to better representing time-varying gas quality in line with the EN 16726-related governance including the Annex F for Rate Change of the Wobbe Index (Zero Flow Points, Intermittent consumption) as will be shown later.

For policy makers, regulators and standardization bodies, this finding suggests that the blending option should be framed as an early and transitional route for hydrogen uptake. Its limits are not only downstream users, but also within transport and distribution networks, where higher volumetric flows increase velocity, pressure losses and compression needs. Blending limits should therefore reflect hydraulic capacity, gas-quality interoperability and traceability, in line with EN 16726:2025 and EN 16325:2025.

For TSOs, DSOs and the gas industry, this finding remarks the need that hydrogen injection should be assessed against real network operation, including pressure margins, compressor duty, flow direction and gas-quality propagation. Blending can support early projects, but large-volume hydrogen transport requires dedicated or repurposed corridors.

Efficiency of infrastructure repurposing for hydrogen transport depends on asset-specific pipeline qualification, including material compatibility, weld integrity, fracture toughness and fatigue performance, to avoid conservative pressure derating and preserve the operating pressure envelope

The analysis shows that repurposing is a scalable route, especially if qualification of the pipeline compatibility with hydrogen replaces default pressure derating. It is shortly reminded here that Option A of the ASME B31.12 applies a conservative hydrogen material factor (Hf = 0.776) for eligible steels, reducing allowable operating pressure to account for hydrogen-related material degradation. In turn, Option B of the ASME B31.12 allows the full hydrogen material factor (Hf = 1.0) if pipe steel and welds are specifically qualified for hydrogen service through toughness testing, fracture assessment, fatigue crack-growth verification, and requalification of weld procedures when needed.

Under Option A, MAOP falls to about 58.2 bar-g, worsening hydraulic penalties. Under Option B, current-service pressure levels can be maintained with clear operational benefits as shown in Table 7.

Table 7 Key hydraulic findings of operated hydrogen backbone under Option A and B of the ASME B31.12

	Reference	Gas Network Repurposing

	CH_4 (a)	H_2 backbone Option A-ASME B31.12	H_2 backbone Option B-ASME B31.12
Hydrogen transported (Mt/y)	0	2.5	2.5
Max pressure (bar-g)	64	58	64
Max velocity (m/s)	16.8	16.8	15.9
***β* compressor**	1.17	1.1	1.04
Compressor power (MW)	24.3	17.7	5.4

The comparison of Options A and B is quite illustrative showing how pressure derating worsens hydraulic performance (note that Table 7 shows performance for hydrogen backbone but pressure derating applies also to blending scenarios as pressure derating used to be recommended also when hydrogen concentration in blends overcomes 10% in transmission systems), while performance-based qualification reduces those penalties and preserves much more of the current operating envelope. Strategies therefore should converge on harmonized qualification procedures for steel, welds, fracture resistance, and fatigue performance, because those procedures determine whether repurposed corridors can operate efficiently at scale. This finding therefore directly connects with the ongoing work of CEN/TC 234 (e.g., EN 1594:2024 on new/repurposed pipelines operating over 16 bar, EN 17649:2022 on SMS - safety management system and PIMS – pipeline integrity management system, EN 17928-1:2024 and EN 17928-3:2024 on injection stations) explicitly pointing to the need for a harmonized European framework for the design, operation, and maintenance of repurposed or new hydrogen pipelines. Like before, this finding calls for more advanced modelling analysis to better representing time-varying operation including pressure cycling, velocity pulsation for fatigue-sensitive qualification under the CEN/TC 234 integrity framework.

For policy makers, regulators and standardization bodies, this finding suggests how repurposing should rely on asset-specific qualification rather than default pressure derating. Where material compatibility, weld integrity, fracture toughness and fatigue performance are demonstrated, more of the existing operating envelope can be preserved. Harmonized procedures should build on ASME B31.12, EN 1594:2024 and EN 17649:2022.

For TSOs, DSOs and the gas industry, the finding remarks that qualification should guide hydrogen-readiness programs through material testing, inspection records, operational pressure-cycle history, defect assessment and component compatibility. This helps retain pressure capacity and avoid unnecessary compression, reinforcement or replacement.

Hydrogen backbone development should be planned together with a residual natural gas adequacy assessment, because repurposing increases hydrogen transport capacity while reducing the transfer capacity and flexibility of the remaining gas network.

Repurposing infrastructure effectively implies a reallocation of capacity. This shifts the discussion from purely technical aspects to broader energy and strategic considerations. Higher H_2 capacity and lower natural gas capacity are part of the same act of conversion. A correct approach would be to plan transport corridors with an explicit twin adequacy assessment for both hydrogen and natural gas. The analysis shows that reduced natural gas network (scenario b) only transports –27% energy throughput than actual case even rising the operating pressure at MAOP (75 bar-g) higher than actual operating pressure (64 bar-g). Overall energy

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throughput, considering both natural gas and hydrogen, slightly decreases (≈2-3%) including energy penalties for higher compression as shown in Table 8.

Table 8. Key energy and hydraulic findings in gas network repurposing scenario

Option B-ASME B31.12	Reference	Gas Network Repurposing	
	CH_4 (a)	H_2 backbone (d)	Reduced Natural Gas Network (b)
Hydrogen transported (Mt/y)	0	2.5	0
Energy transported (GWh/d)	1041.6	269.4	756.5
Max pressure (bar-g)	64	64	75
Max velocity (m/s)	16.8	15.9	16.5
β compressor	1.17	1.04	1.2
Compressor power (MW)	24.3	5.4	20.6

The findings suggest that repurposing should be considered as a strategic capacity-allocation decision rather than solely as an engineering retrofit. The analysis quantifies that converting one trunk line to hydrogen reduces gas transfer capacity to mainland Italy by roughly 30%. Therefore, the implications for the residual natural gas network should be assessed through an integrated approach considering available transport capacity, operational flexibility, infrastructure integrity and potential system evolution. This highlights that hydrogen corridor development cannot be considered independently from residual natural gas system planning. In practical terms, large-scale repurposing strategies should be evaluated together with complementary measures, such as alternative natural gas routing options, infrastructure reinforcement, demand evolution scenarios, or other flexibility solutions.

For policymakers, regulators and standardization bodies, this finding highlights that hydrogen backbone development should be considered as a system-transition decision rather than solely as a pipeline conversion exercise. Repurposing creates additional hydrogen transport capacity while reallocating part of the existing natural gas transport capacity; therefore, a parallel assessment of hydrogen system requirements and the capability of the residual natural gas network to accommodate expected flows is needed.

For TSOs, DSOs and the gas industry, the finding remarks that conversion planning should assess residual pressure margins, compressor needs, MAOP utilization, storage and LNG interaction, city-gate impacts and downstream customer protection. Hydrogen backbone deployment should therefore be planned together with the evolving role of the natural gas network.

Scenario 1.b: Long distance transport of hydrogen: first import of 20% hydrogen blending from Mazara del Vallo entry point.

Hydrogen blend propagation is topology-dependent: connected parallel pipelines, mixing nodes and changing flow ratios can delay, dilute or reshape the hydrogen concentration delivered downstream. The dynamic analysis of the 20 vol% hydrogen blend imported from Mazara del Vallo shows that hydrogen concentration may not propagate through the transmission network as a simple plug-flow front. Parallel pipelines (which are very common in long distance transport infrastructures), merging nodes,

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compression-station hubs and connections between different backbones modify both the arrival time and the shape of the hydrogen concentration profile. Therefore, even when the upstream blend is constant, the hydrogen share experienced downstream may be delayed, diluted, enriched or reshaped by the internal topology and operating conditions of the network.

This behaviour is already visible in the first section downstream of Mazara del Vallo, where the flow is split into three parallel pipelines and later partially recombined (see Figure 6).

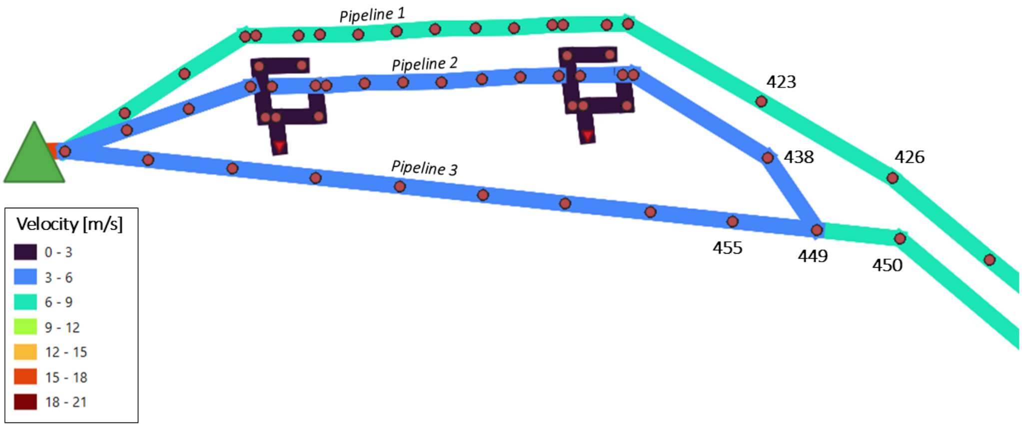

Figure 6 Close-up view of parallel line system of Sicily network just downwards Mazara Entry Point.

Different velocities in the parallel lines, approximately 6.8 m/s (pipeline 1), 3.8 m/s (pipeline 2) and 4.2 m/s (pipeline 3), generate asynchronous hydrogen-front propagation. The fastest line reaches 20 vol% hydrogen after about 100 minutes, while the corresponding downstream point in the slower line reaches the same concentration after about 160 minutes. At the merging node, the early arrival of the hydrogen front from line 3 mixes with residual natural gas still flowing in the other line, creating an intermediate blend of about 10.8 vol% before the concentration rises again towards 20 vol%. As a result, the downstream hydrogen front becomes less abrupt and assumes a two-step profile rather than preserving the original inlet shape. Figure 7 shows the hydrogen concentration variation in time at relevant nodes of this section of the infrastructure.

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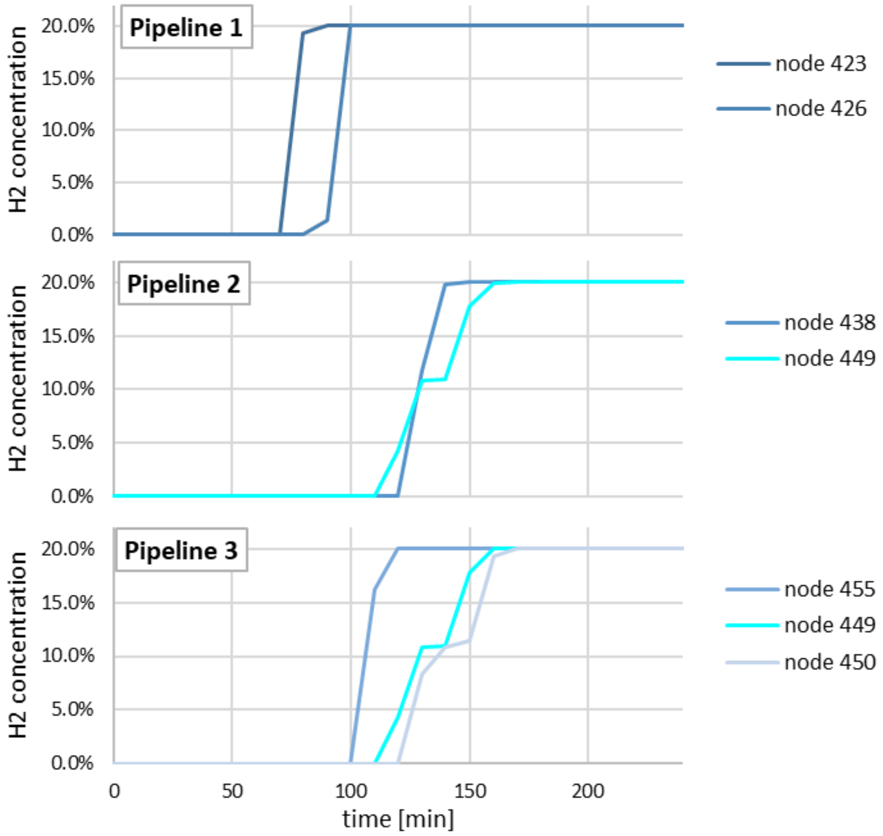

Figure 7 Hydrogen concentration variation at chosen nodes of the parallel lines of Sicily infrastructure shown in the previous figure.

Similar circumstances appear around the Enna Compression Station Hub and the Southern Loop Hub, where the Transmed and Greenstream systems interact (see Figure 8). At the Enna mixing node, the 20 vol% hydrogen front arriving from Transmed is mixed with natural gas from Greenstream, producing an initial blend around 14 vol% and then a gradual increase towards about 17 vol% as the Transmed-to-Greenstream flow ratio changes (see Figure 9 left – node 70). At the outlet of the compression station (node 115), the final hydrogen share reaches about 18.6 vol% after roughly three hours from receiving the first blend. Further downstream, the Southern Loop Hub redistributes part of the blended gas through interconnected lines, with concentrations stabilizing around 15 vol% at one mixing point (504 – see Figure 9 right) and around 9 vol% at another (531), before this modified blend propagates back north and perturbs the composition at Enna again.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

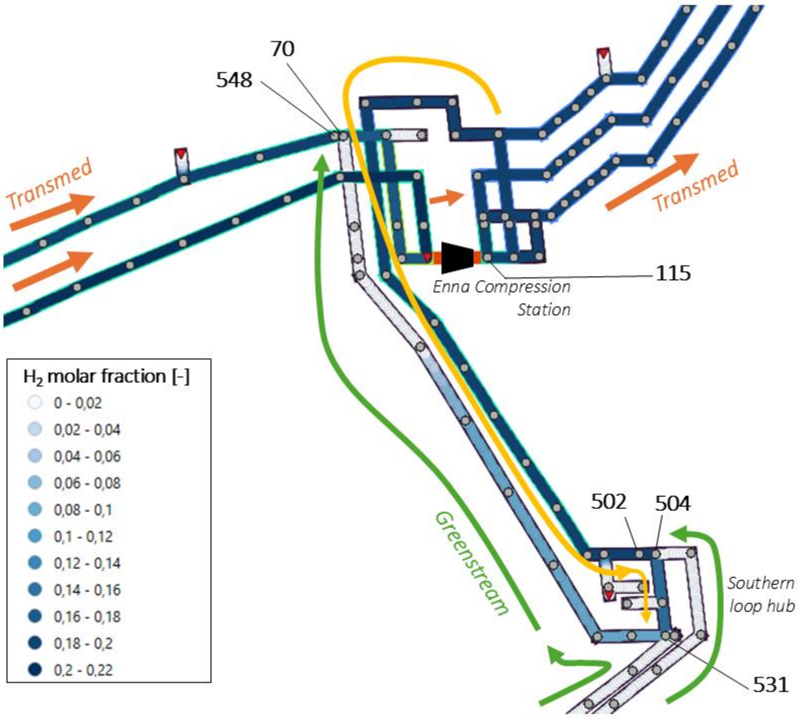

Figure 8 Close-up view of the piping systems around Enna Compression Station Hub and Southern Loop Hub.

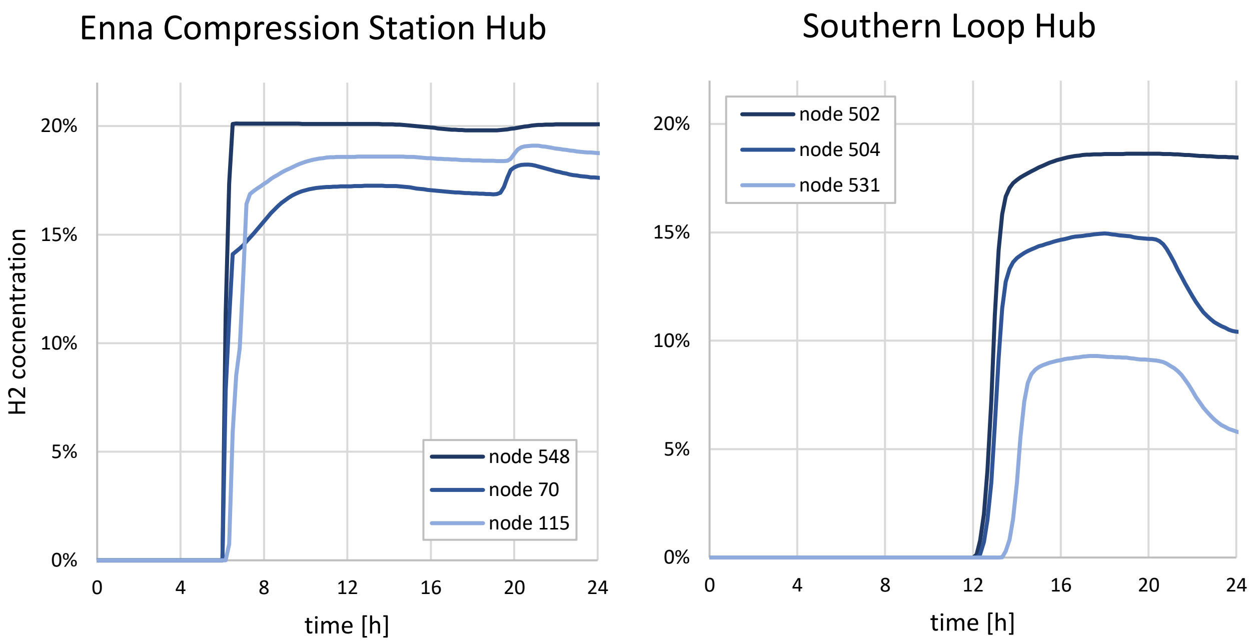

Figure 9 Hydrogen concentration variation at chosen nodes of the parallel lines of Sicily infrastructure shown in the previous figure.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

Figure 10 shows how the variation of the gas flow at Messina Exit Point affects the gas flows entering in node 70. The bottom-right graph displays the Transmed-to-Greenstream ratio at node 70: the contribution of the hydrogen-blended flux (Transmed flux) grows passing from a ratio of about 2:1 with respect to Greenstream flux to 5:1, thus causing the enrichment in hydrogen content of the mixture resulting from node 70.

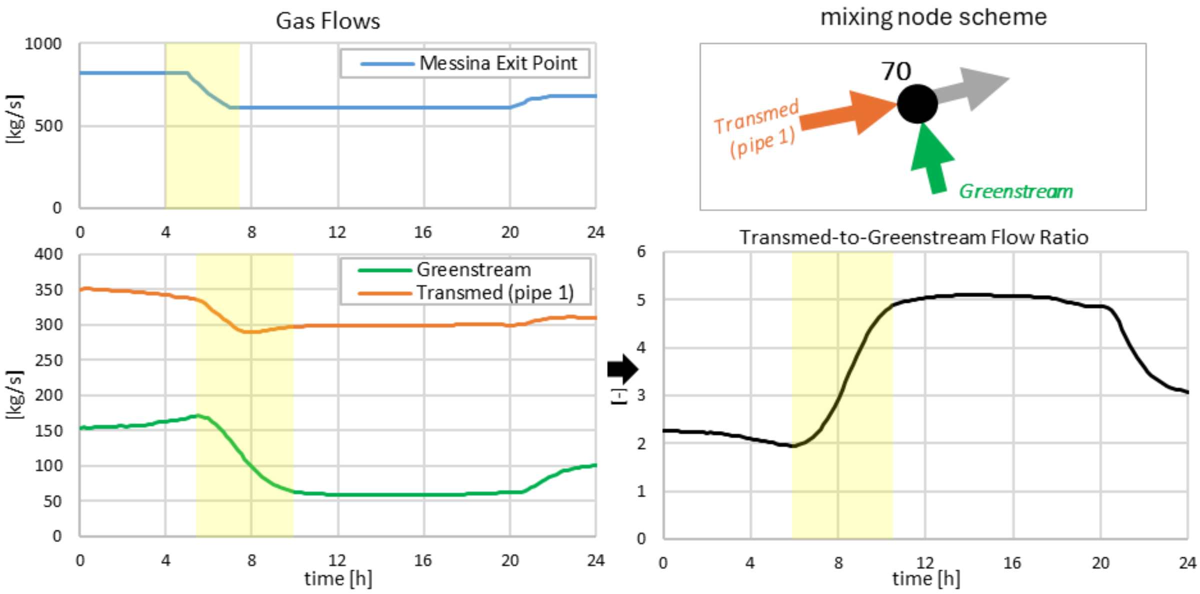

Figure 10 Gas flow variations at: Messina exit point (top-left), the pipe section of Transmed and Greenstream entering the mixing node 70 (bottom left); variation in time of Transmed-to-Greenstream flow ratio feeding the mixig node 70 (bottom right). Schematic of mixing node 70 (top right).

This finding shows that gas-quality management for hydrogen blending cannot rely only on the nominal hydrogen percentage at the entry point. The relevant variable for network operation is the time- and location-dependent gas composition delivered to each downstream node. This directly connects blending governance with transient gas-quality tracking, including the rate of change of gas-quality parameters such as Wobbe Index, and with the need to represent mixing nodes, parallel corridors, flow reversals and compression-station hubs in network models. It is worth highlighting that the management of Wobbe Index variation (both the ranges and its rate of change) is an open point extensively discussed in the recent European standard EN 16726:2025. In Annex F, examples of mixing facilities, that remind the ones here simulated, are given as a strategy to smooth the gas quality variations.

For policy makers, regulators and standardization bodies, hydrogen blending limits should not be defined only as static admissible percentages at injection or import points. They should also account for topology-driven propagation effects, dynamic gas-quality variation and the possibility that different users connected to the same transmission system experience different hydrogen shares over time. This reinforces the need for gas-quality interoperability rules, traceability mechanisms and dynamic compliance assessment in line with the broader framework discussed for blended-gas operation.

For TSOs, DSOs and the gas industry, hydrogen blending requires dynamic quality-tracking tools able to simulate and monitor hydrogen propagation across real network topologies. Operational planning should include mixing nodes, parallel pipeline systems, changing flow ratios, compression-station hubs and delayed downstream effects. Entry-point compliance is therefore necessary but not sufficient: operators also need to verify where, when and how hydrogen concentration changes across the network.

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Scenario 2: Multiple and distributed hydrogen injection from existing utility scale RES.

With reference to the network schematic of Figure 4 where the scenario of multiple and distributed injection is described, Figure 11 show the hydrogen production and injection profile throughout the simulated day and Figure 12 the corresponding hydrogen concentration formed at the injection point.

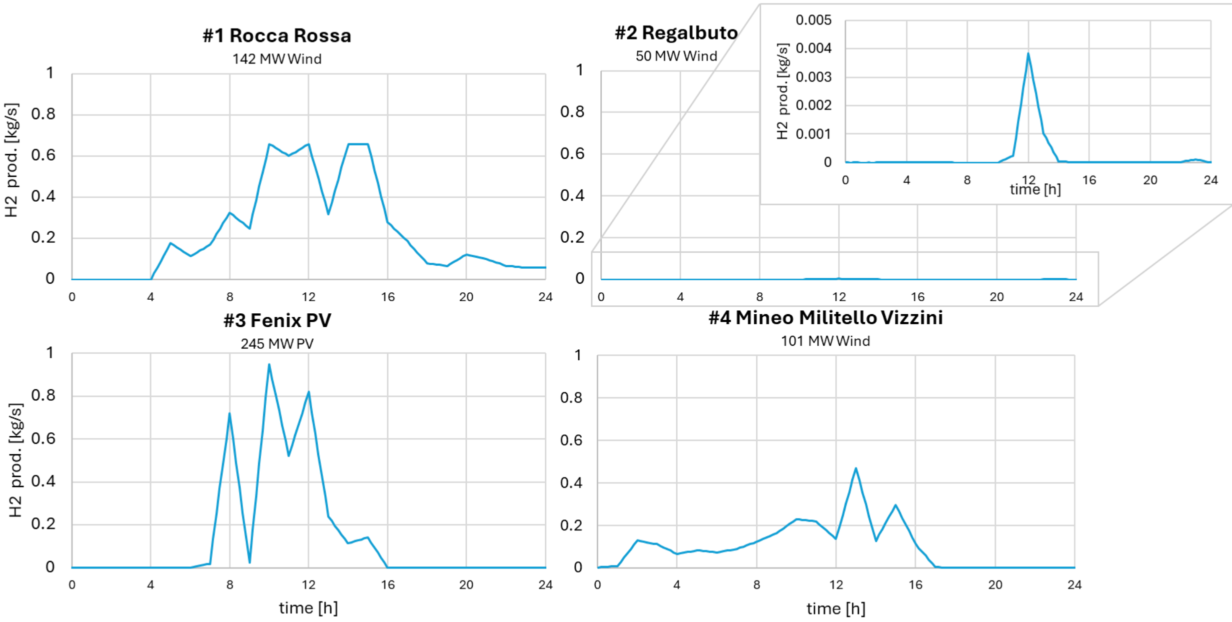

Figure 11 Hydrogen injection flow variations at the different injection points within the timeframe of simulation (winter day)

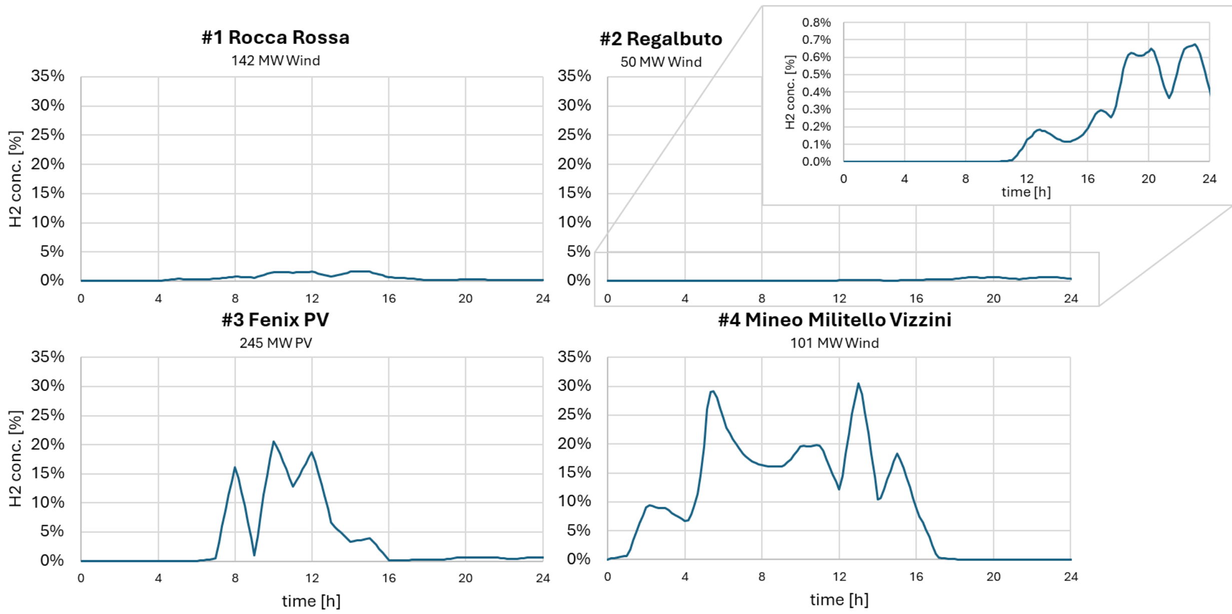

Figure 12 Hydrogen concentration variations at the different injection points within the timeframe of simulation (winter day)

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Distributed hydrogen injection is locally flow-constrained, because similar injection rates can generate very different hydrogen concentrations depending on network location

The distributed injection scenario shows that the hydrogen concentration resulting from renewable hydrogen injection is primarily governed by the ratio between injected hydrogen flow and local natural gas throughput. Similar hydrogen injection profiles can therefore lead to very different gas-quality outcomes depending on whether the injection point is located: on a high-flow transmission backbone or on a peripheral, low-flow branch.

In the Sicily case study, injection profiles of the same order of magnitude, with peak hydrogen flows around 0.5–1 kg/s, produce radically different concentration levels. Injection into a main trunk line leads to a maximum hydrogen concentration of about 1.6 vol%, while injection into lower-flow or more peripheral parts of the network can exceed 20 vol%. In the most critical case, associated with a large wind plant connected at a peripheral point (injection #4 – Figure 12), hydrogen concentration shows sudden peaks up to about 30 vol%. This indicates that hydrogen acceptability cannot be assessed from production capacity alone but must be evaluated against local gas-flow conditions and downstream gas-quality constraints.

This finding distinguishes two possible routes for blending.

- On high-flow sections of the transmission network, hydrogen injections can support sector integration by absorbing renewable electricity converted into hydrogen while keeping gas-quality perturbations limited. In this configuration, the large natural-gas flow dilutes the injected hydrogen, so blending mainly acts as a flexibility option for renewable hydrogen integration (e.g., for example in sector coupling scenarios) rather than as a controlled hydrogen transport pathway. If the objective is to deliver hydrogen downstream as a recognizable energy carrier within a defined concentration range, direct variable injection is not sufficient. This would require instead dedicated operational arrangements, including buffer storage, controlled blending and mixing facilities, coordinated production and injection schedules, and agreement with the network operator on admissible injection profiles.
- On low-flow peripheral sections, the strategy of direct injection may instead create significant and sudden hydrogen build-up: variable renewable hydrogen injection may produce fast and frequent gas-quality variations that are difficult to reconcile with stable network operation and downstream user acceptability. At the same time, these peripheral areas may be attractive for RES-based hydrogen integration because renewable generation is often geographically distributed. In such cases, however, blending can only be used if supported by buffer storage, controlled injection units, downstream demand coordination or deblending solutions. These additional requirements may significantly affect project feasibility.

Overall, dedicated renewable hydrogen production and controlled injection facilities may be more appropriate than unmanaged direct injection.

For policy makers and regulators, connection rules for hydrogen injection should be based on local absorbability depending on local gas throughput and considering renewable hydrogen possible production ranges and pattern, downstream users, gas-quality constraints, temporal variability and the ability to trace renewable hydrogen within the gas system. Distributed hydrogen injection should therefore be treated as a location-specific service, with connection and operating conditions defined according to the hydraulic and gas-quality characteristics of each network area (including the consideration of sensitive users.

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For TSOs, DSOs and the gas industry, hydrogen-readiness assessments should include local hydrogen hosting-capacity maps, time-dependent gas-flow analysis, dynamic concentration forecasting and also mapping sensible users. Injection points on high-flow backbones can be suitable for low-impact sector coupling, while peripheral injection points require stricter control, storage, curtailment logic or dedicated hydrogen offtake solutions to avoid exceeding gas-quality limits.

Multiple hydrogen injection points require coordinated operation, because upstream injection consumes downstream blending margin with time delays

The simulation also shows that distributed hydrogen sources cannot be treated as independent injection points. Hydrogen injected upstream propagates through the network and modifies the initial gas composition available at downstream injection points. Even when the resulting interaction is small, it reduces the downstream margin for further hydrogen injection whenever concentration limits or gas-quality constraints apply.

In the Sicily case study, the hydrogen concentration profile generated at the upstream injection point (injection #1) is transmitted to downstream injection locations after further mixing through the network. The resulting hydrogen concentration observed at a downstream injection point (injection #2 – zoomed graph) remains limited, about 0.65 vol% in the analysed case, and is not critical for this specific scenario. However, the shape of the upstream concentration profile remains recognizable after propagation and admixing, showing that injection events can interact over both space and time. This effect becomes more relevant when injections are larger, more variable, closer to concentration limits or located in lower-flow sections of the network or closer to each other.

The coordination issue is therefore dynamic. Renewable hydrogen injection varies in time, while the network introduces transport delays, mixing effects and changes in flow direction or flow ratio. A downstream injection point may have available blending margin at one moment and lose it later because of an upstream hydrogen front arriving with delay. This creates a need for coordinated dispatch, connection priorities and possibly curtailment or storage rules among multiple hydrogen producers.

For policy makers and regulators, distributed hydrogen injection requires allocation mechanisms for gas-quality capacity. Where several producers share the same downstream network, hydrogen blending margins should be managed as a constrained network resource. Connection agreements should therefore define not only maximum injection capacity, but also priority rules, coordination requirements, curtailment principles and responsibilities for maintaining gas-quality compliance.

For TSOs, DSOs and the gas industry, multiple injection points require coordinated operational tools based on forecasting, real-time monitoring and dynamic simulation. Operators should account for upstream concentration propagation, transport delays, downstream blending margins and interactions between renewable production profiles. This is particularly important in networks where distributed RES-based hydrogen production is expected to grow and where local gas-flow conditions vary significantly over time.

Distributed hydrogen injection requires dynamic gas-quality assessment, because Wobbe Index rate of change may become critical even when absolute Wobbe Index limits are respected

The distributed hydrogen injection scenario shows that gas-quality compliance cannot be assessed only through static admissible ranges of hydrogen concentration or Wobbe Index. Variable hydrogen injection from RES-based production affects combustion-related gas-quality parameters, including Wobbe Index, Relative

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Density and Higher Heating Value over the time. In particular, the Wobbe Index rate of change becomes a relevant operational indicator, because final appliances and industrial users may be affected not only by the absolute value of gas quality parameters, but also by how rapidly those parameters vary over time.

This finding is directly connected with EN 16726:2025, which defines gas-quality requirements for Group H gases and introduces a Wobbe Index classification system for entry and exit points. Concerning the combustion properties, it only sets the following Relative Density limits: [0.45 – 0.7] while the Higher Heating Value is allowed to be obtained as the result of the relationship defining Wobbe Index. It is worth mentioning that hydrogen presence is allowed up to 2% vol. Concerning the Wobbe Index, the standard distinguish between Entry Point Wobbe Index range and Exit Point Wobbe Index classifications. As for entry range, the following range is recommended [46.44 – 54.00] MJ/m^3 15°C/15°C at 1013.25 mbar. This range is quite wide, even though some countries (e.g. Poland or Greece) have wider limits in their national legislations. As for exit points, the current standard suggests defining Wobbe Index Exit Point classes ("Class Specified") with narrower bandwidth (≤ 3.7 MJ/m3) over a narrower WI range [46.44 – 53.00] MJ/m^3 to be assigned to relevant exit points. The standard includes also the possibility to define "Class Extended" provided that downstream users will not be affected to the Wobbe Index high variability or appropriate mitigation measures are taken. It is worth mentioning that hydrogen contributes to reduce the WI, thus the critical limit might be the lower one. Overall, these bandwidths are intended to protect downstream users and support gas-quality interoperability (within the limits of the sensible appliances). However, EN 16726:2025 does not define quantitative thresholds for the rate of change of the Wobbe Index or other gas-quality parameters, although it explicitly recognizes that rapid variations of Wobbe Index and/or Gross Calorific Value may affect end-use applications such as gas engines and gas turbines.

In the Sicily case study, the Wobbe Index response was analysed for the two most impacted distributed injection points, namely the Fenix PV plant injection point (#3 – Figure 12) and the Mineo–Militello–Vizzini injection point (#4 – Figure 12). Although the simulated hydrogen concentrations exceed the admissible hydrogen content for conventional natural-gas grid injection, the analysis isolates the effect of variable hydrogen blending on Wobbe Index behaviour. As shown in Figure 13 – upper part, the Wobbe Index results show that, for the analysed winter day, the Wobbe Index remains largely within the recommended European range even at high hydrogen concentrations – the lower limit is reached for hydrogen concentration of about 30%. This is partly due to the initial natural-gas Wobbe Index being located in the upper part of the admissible range, which leaves some downward margin when hydrogen is blended.

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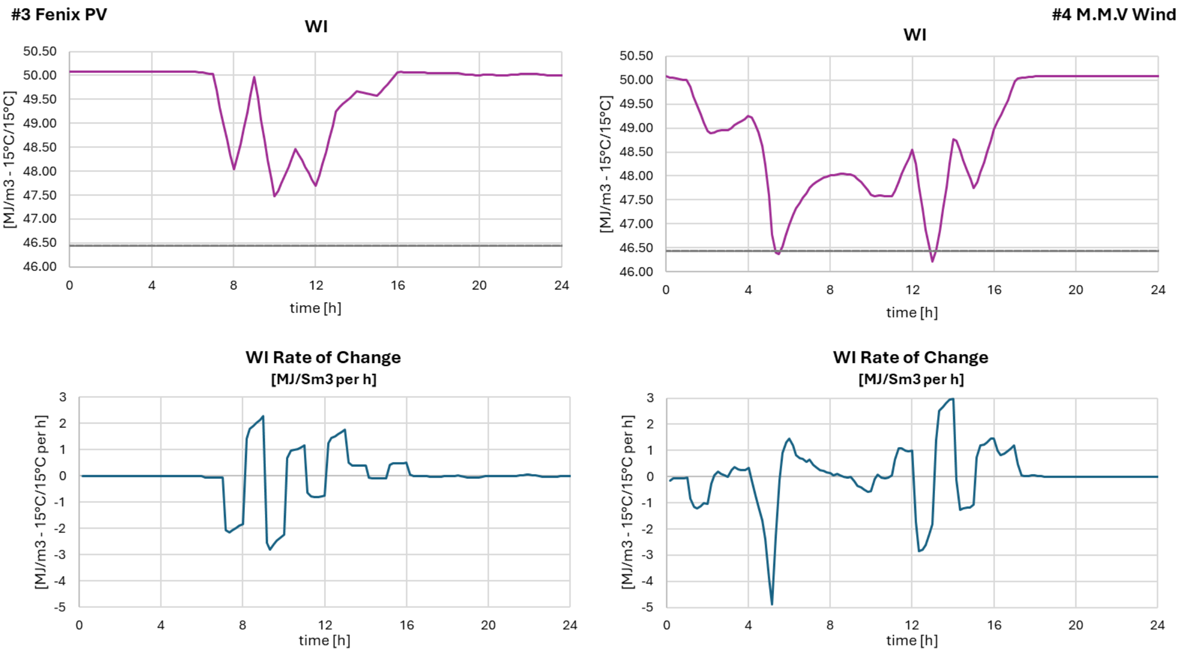

Figure 13 Wobbe Index variation and Rate of Change for the two most impactful injection cases – the grey line represents the EN 16726:2025 WI minimum limit.

However, absolute Wobbe Index compliance does not imply dynamic gas-quality acceptability. At injection point #3, the maximum Wobbe Index variation remains compatible with a “Class specified” exit-point bandwidth of 3.7 MJ/m³. At injection point #4, instead, the variation reaches about 3.88 MJ/m³, slightly exceeding that bandwidth. Also, Wobbe Index drops slightly below the minimum threshold of 46.44 MJ/m³. Moreover, these results refer to a winter operating day. During lower-demand periods, especially in summer, reduced natural-gas flow and potentially higher renewable hydrogen production may amplify both the Wobbe Index variation and its rate of change, particularly in peripheral network sections with low gas throughput.

The most relevant result is therefore not only whether the Wobbe Index remains inside a static admissible interval, but whether its temporal variation is compatible with downstream end-use requirements. The Wobbe Index Rate of Change for the two analyzed injection point is displayed in Figure 13 – lower part. According to the information given in ANNEX F of the EN 16726:202, a variation of 2 MJ/Sm^3 within 2h is already considered the maximum acceptable for some industrial users. What shown in Figure 13 indicates that such hydrogen concentration variation is very likely to be critical. It is then shown a new interoperability issue: a gas blend may be acceptable in terms of absolute Wobbe Index range, while still being problematic because of the speed and frequency of its variations.

For policymakers, regulators and standardization bodies, this finding suggests that future hydrogen blending frameworks may benefit from considering dynamic gas-quality aspects, in addition to static concentration or Wobbe Index limits. Although EN 16726:2025 recognizes the relevance of Wobbe Index rate of change (Annex F), it does not define corresponding acceptance criteria. As distributed hydrogen injection becomes more widespread, further discussion at the regulatory and standardization level may be warranted to determine whether additional guidance on gas-quality dynamics, information exchange and the management of sensitive end-users is appropriate.

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For TSOs, DSOs and the gas industry, the results highlight that the impacts of hydrogen injection may depend not only on steady-state gas quality but also on its temporal evolution. Where relevant, system studies may benefit from considering time-dependent gas-quality behaviour, including variations in Wobbe Index, local flow conditions and seasonal operating patterns. The appropriate methods for assessing these aspects, and any associated operational or regulatory implications, remain a subject for further discussion within the gas industry and standardization bodies.

Hydrogen injection may have limited impact on the global pressure profile, while amplifying local velocity dynamics downstream of the injection point

The comparison between the operation with and without hydrogen at injection point #3 is given in Figure 14. It shows that distributed hydrogen injection does not substantially alter the overall daily pressure profile of the line. In both cases, pressure follows the same daily trend, caused by the combination of the overall consumption profiles throughout the network, the transmission profile through the backbone (the outlet profile at Messina node) and the operational profile of the compressor.

However, the case with hydrogen shows a slightly higher and earlier pressure build-up, with the pressure range increasing from about 0.42 bar in the natural-gas case to about 0.51 bar in the hydrogen-blending case. This indicates that the injection modifies the hydraulic balance. In the case of hydrogen blending, this profile is transmitted upwards and downwards at the injection point, extending the local effect of blending to the overall line in which it happens. However, it does not cause a major shift in the global pressure regime. It is worth noting that the pressure profile in the injection case shows some fluctuations which are connected to the intermittent flow of hydrogen that is introduced inside the main natural gas flow. The amplitude of these is in the order of tenth of a bar in this specific case (where the hydrogen flux variation implies variation in the concentration in the range [0 – 20] %. However, the impact might increase as the injection takes place at lower pressure levels.

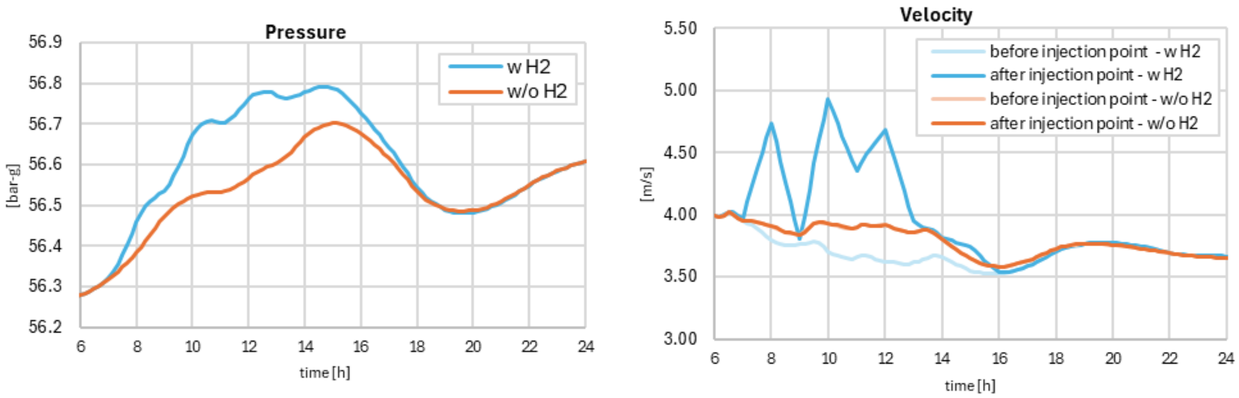

Figure 14 Impact of hydrogen injection on pressure and velocity profiles at the injection point. Results from injection point #3 are given here.

The most relevant effect appears instead in the velocity profile downstream of the injection point. Upstream of the injection point, velocities remain relatively regular and slightly lower in the hydrogen case, following the same trends as the one observed in the case with no injection (in which velocities results unaltered before and after the injection. Downstream of the injection point, by contrast, hydrogen injection introduces marked velocity peaks during the central hours of the day, with the maximum velocity increasing from about 4.0 m/s

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in the natural-gas case to almost 5.0 m/s in the hydrogen case. The downstream velocity range therefore increases from roughly 0.44 m/s without hydrogen to about 1.4 m/s with hydrogen, showing that variable hydrogen injection can generate local flow oscillations that are not visible from pressure monitoring alone. These oscillations are due to the oscillating nature of the hydrogen flux in this specific case and they are formed at the injection point and transmitted further downstream: this is due to the addition of mass flow within the main natural gas flow. As for the velocity before the injection point, it differs from the non-injection case as a result of the altered pressure field.

This finding suggests that, for distributed hydrogen injection into transmission networks, the assessment may benefit from considering hydraulic behaviour in addition to gas-quality compliance. The simulations indicate localized variations in pressure and flow velocity downstream of the injection point, although the pressure fluctuations observed in the analysed scenarios remain limited. These results illustrate the dynamic response of the network to variable hydrogen injection and may support further investigations under different operating conditions and network configurations.

For policymakers, regulators and standardization bodies, these findings suggest that dynamic hydraulic behaviour could be considered alongside gas-quality aspects when evaluating future hydrogen injection scenarios. While the analysed cases do not indicate operational concerns for the transmission network, further studies covering a broader range of operating conditions and network configurations may help determine whether additional guidance on dynamic hydraulic behaviour would be beneficial for future hydrogen infrastructure planning.

For TSOs and the gas industry, the results provide additional insight into the hydraulic response of the network to distributed hydrogen injection. Although the simulated pressure and velocity variations remain within normal operational conditions for the analysed case, the methodology developed in this work may support the assessment of alternative scenarios involving different injection profiles, network configurations or operating conditions.

3.3.2 Ebro Valley, Spain

The Ebro Valley pipeline focuses on a high-pressure gas transmission network in Spain operated by the Spanish TSO, Enagás. The network supplies natural gas to the Ebro Valley region while also serving as a strategic connection between the Barcelona area, located to the southeast, and northern Spain near Bilbao, to the northwest.

The Ebro Valley network was selected because it contains several characteristics that make it a representative and insightful case study for assessing hydrogen injection in a gas transmission system. Its topology, operational behaviour, and data availability enable realistic simulations under different hydrogen injection scenarios. The main reasons for selecting this network are outlined below:

- **Connection to the wider Spanish transmission system**
  The network is integrated into the broader ENAGAS transmission system, with gas flow directions at the eastern and western interconnection points varying throughout the year. This creates a realistic framework for analysing how hydrogen injection interacts with changing boundary conditions and long-distance gas transport.
- **Presence of a large-scale underground storage facility**
  The network includes an underground gas storage site whose injection and withdrawal flow rates are of the same order of magnitude as the total regional demand, making it a dominant hydraulic and operational component of the system. This aspect is particularly relevant because the storage facility operates under a stricter hydrogen concentration limit, enabling the assessment of gas-quality constraints and associated operational risks.

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- **Complex topology for hydrogen injection analysis**
  The combination of long-distance transport, a major storage facility, and seasonally reversing flow directions makes the Ebro Valley network especially suitable for investigating the effects of localised hydrogen injection on gas-quality management under realistic TSO operating conditions.

In Spain's natural gas system, the hydrogen blending limit is generally set at around 2% by volume in the transmission system. An upper hydrogen concentration limit of 5% may be permitted in the system, provided that the gas TSO demonstrates, through hydraulic simulations, that the hydrogen content in all transmission system facilities and hydrogen-sensitive end-user equipment does not exceed 2%. The same 2% limit must also be respected at international interconnection points, unless a higher value has been explicitly agreed with the relevant operators [16].

3.3.2.1 Network geometry and assets

Below, Figure 15 illustrates the network geometry. It consists of pipelines operated at a nominal pressure of 72 bar, with a maximum allowable pressure of 80 bar. The pipeline system forms part of a larger transmission network operated by the TSO. For the present study, the Ebro Valley region is selected and modelled as a subsystem connected to the surrounding TSO network at two boundary points, to the East and West, representing neighbouring network areas.

Within the Ebro Valley region, there are 47 exit points, which represent either industrial consumers or connections to downstream distribution system operator (DSO) networks. In the northern part of the region, there is the Serrablo underground gas storage facility, which is based on depleted natural gas reservoirs. Serrablo has a total storage capacity of approximately 1100 Mm^3, with around 680 Mm^3 of working gas and a maximum withdrawal capacity of about 6.7 Mm^3/d.

For this study, a maximum hydrogen blending limit of 5%. is assumed for the transmission network. However, a stricter constraint of 2%. hydrogen is applied at the storage facility.

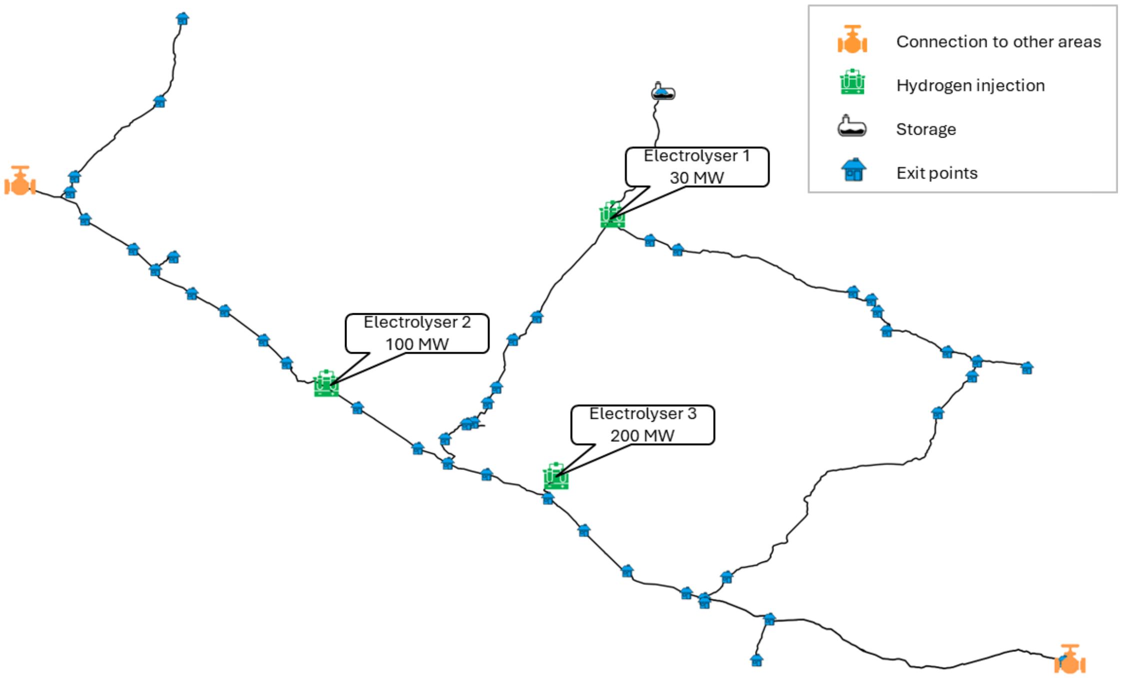

Figure 15 Ebro Valley TSO network use case

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A table summarising the network assets of the Ebro Valley system is provided in Table 9 below.

Table 9 Ebro Valley TSO use case assets

Asset	Properties
72 bar pipelines	738 km Max pressure 80 bar
Storages	1 underground storage total volume = 1 bcm
Connections to neighbouring areas	2 locations
Hydrogen injection	3 locations (30 MW, 100 MW, 200 MW)
Exit points	47 locations

3.3.2.2 Boundary conditions

To ensure realistic fluid dynamics simulations of the gas network, measured flow rates (Figure 16) and pressures within the system are used as boundary conditions in the gas simulator. Flow measurements are available for the 47 exit points, the two network connection points, and the storage facility, and are incorporated directly into the model setup. Pressure measurements are also used to validate the model prior to running the simulation scenarios.

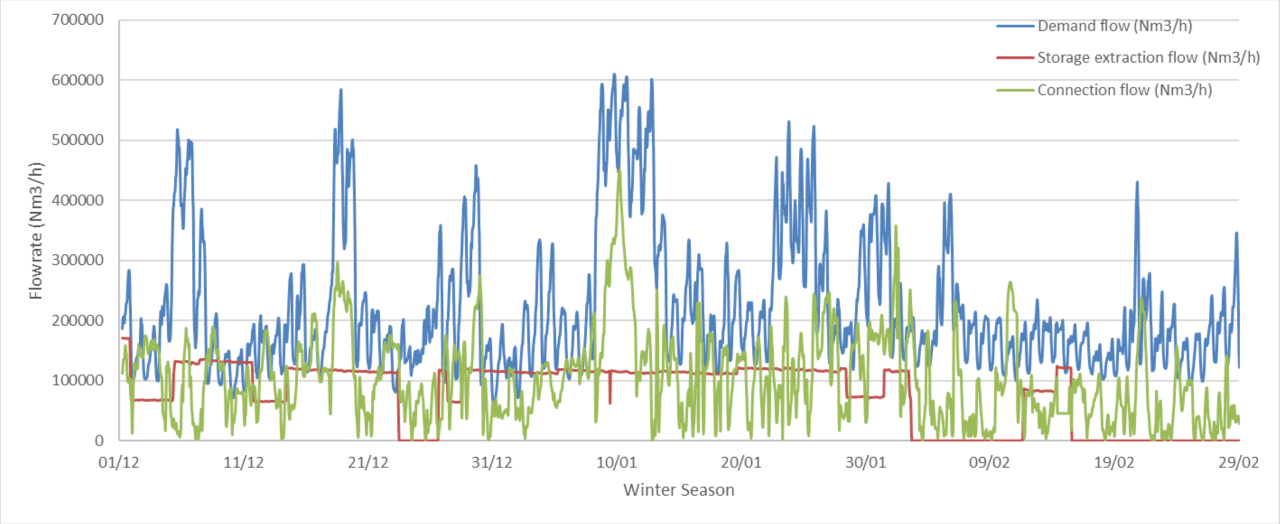

Figure 16 Flow measurements of Ebro Valley gas network during winter season

Hydrogen Injection points

Three hydrogen injection locations are considered in the Ebro Valley case study. These locations are indicated in Figure 15 using green symbols. The injection rates are derived based on an alkaline electrolyser, assuming that for a rated electrical power of 1 MW, the hydrogen output is approximately 200 Nm^3/h:

- Electrolyser 1: maximum capacity of 30 MW, corresponding to approximately 6 kNm^3/h

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- Electrolyser 2: maximum capacity of 100 MW, corresponding to approximately 20 kNm^3/h
- Electrolyser 3: maximum capacity of 200 MW, corresponding to approximately 40 kNm^3/h

For each simulation case, only one injection point is active at a time, while the remaining two are set to zero flow. Each electrolyser is assumed to inject 100% hydrogen directly into the grid and is controlled in such a way that the total hydrogen concentration resulting from mixing with the natural gas flow does not exceed the specified limit.

3.3.2.3 Scenarios description

This section describes the simulated scenarios developed to analyse the impacts of hydrogen injection at the transmission level. Based on the network configuration, assets, and boundary conditions described in the previous sections, a series of dynamic simulations was carried out using AURORA. The simulated scenarios are divided into two main groups, representing different hydrogen injection strategies and operating assumptions.

AURORA models transient gas flows and pressure behaviour while explicitly tracking gas composition, enabling the analysis of hydrogen transport, mixing, and concentration evolution throughout the network under both transient and quasi-steady operating conditions.

A. Full-capacity hydrogen injection scenarios

In the first group of scenarios, hydrogen injection is considered at one injection location at a time, with the corresponding electrolyser operating at 100% of its nominal capacity. The initial condition of the network is assumed to consist entirely of natural gas. Hydrogen is then injected as a pure stream at the selected location, while all other operating conditions follow measured seasonal behaviour, this is, it is assumed that there is not a limit for H2 concentration in NG. Simulations are performed for both summer and winter conditions.

These scenarios are designed to capture the transient propagation of hydrogen from a localised injection point into an initially hydrogen-free transmission network, as well as the subsequent evolution towards a near-stable operating state. They provide a conservative assessment of hydrogen impacts by evaluating network behaviour under maximum electrolyser output.

B. Curtailed hydrogen injection scenarios

The second group of scenarios investigates hydrogen injection under curtailed electrolyser operation. As in the previous group, the initial network condition consists entirely of natural gas. However, instead of operating at full capacity, the hydrogen injection rate at each location is dynamically determined based on the actual gas flow rate in the pipeline at the injection point. The injected hydrogen flow is calculated such that hydrogen represents 5% of the locally mixed gas flow, corresponding to the hydrogen concentration limit applied throughout the TSO network.

These simulations assess whether adjusting hydrogen production based solely on the local gas flow at the injection point is sufficient to maintain hydrogen concentrations within the permitted limits across the network and gives information about the hydrogen curtailments. The initial phase of each simulation captures the transient system response following the start of hydrogen injection. As the simulation progresses, the network approaches a near-stable operating state that becomes largely independent of the initial assumption of a hydrogen-free network.

3.3.2.4 Findings

In this section, the observations and findings from the simulations of the Ebro Valley network are presented and discussed for both winter and summer cases to cover injection and extraction of the storage.

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Curtailment of hydrogen injection is needed in order to satisfy the hydrogen concentration limit

In the TSO network, hydrogen is produced by an electrolyzer and injected directly into the network. Therefore, the hydrogen admixture concentration depends on the natural gas flow in the main pipeline perpendicular to the injection point. Below, we present the simulation results for the electrolyzer at Locations 1 over a one-month period in December for the winter scenario.

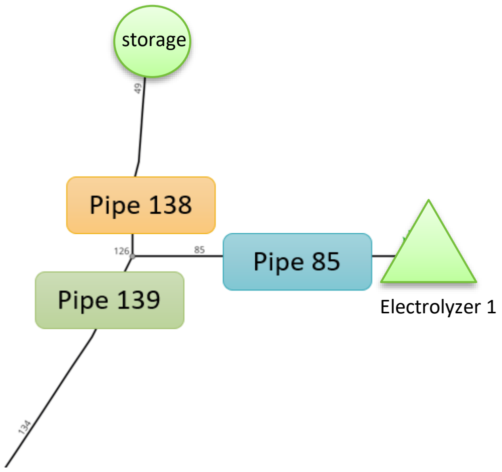
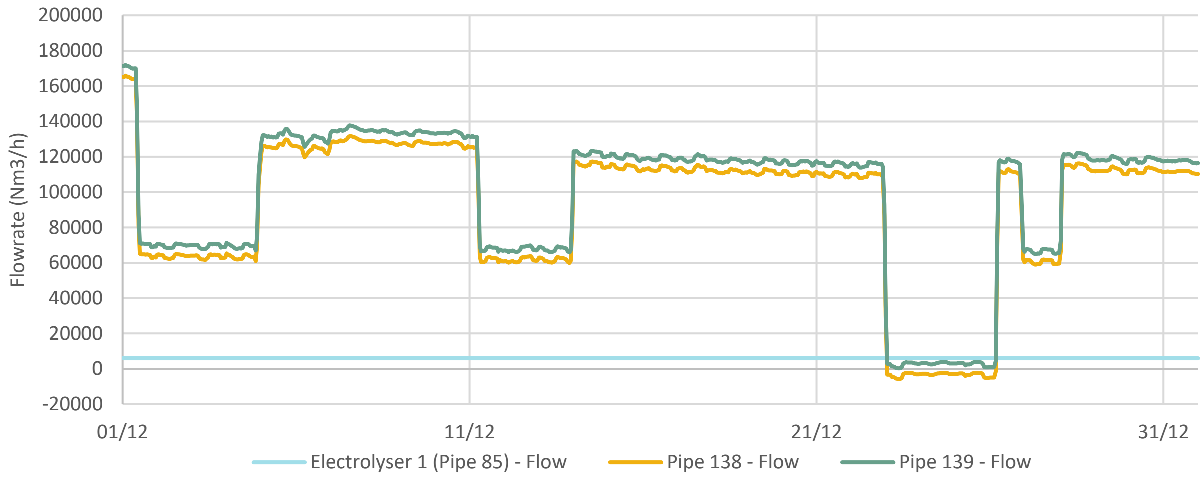


Figure 17 T-junction between Electrolyzer 1 and the main pipeline.

Figure 17 illustrates the location of the electrolyzer in close proximity to the underground gas storage facility. This network configuration introduces operational challenges associated with bidirectional flow conditions during gas injection and extraction cycles. During the extraction phase, the gas flow is directed southward, allowing the application of a 5% hydrogen blending limit. In contrast, during the injection phase, the flow direction reverses, and a stricter hydrogen blending limit of 2% must be enforced to comply with network operational constraints.

Simulation results are shown in Figure 18. The top graph illustrates the gas flow rates in the three pipelines connected to the T-junction, while the bottom graphs show the corresponding hydrogen concentrations in each pipeline. During the analysed period, the gas storage facility predominantly operates in extraction mode. To maintain the hydrogen blending limit at 5%, the required gas flow rate from the storage facility must remain above approximately 120 kNm³/h. As shown in the figure, when the flow rate decreases below this threshold, the hydrogen concentration increases significantly. In particular, when the storage facility is not supplying gas, the hydrogen concentration rises sharply and can reach up to 100 %.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.



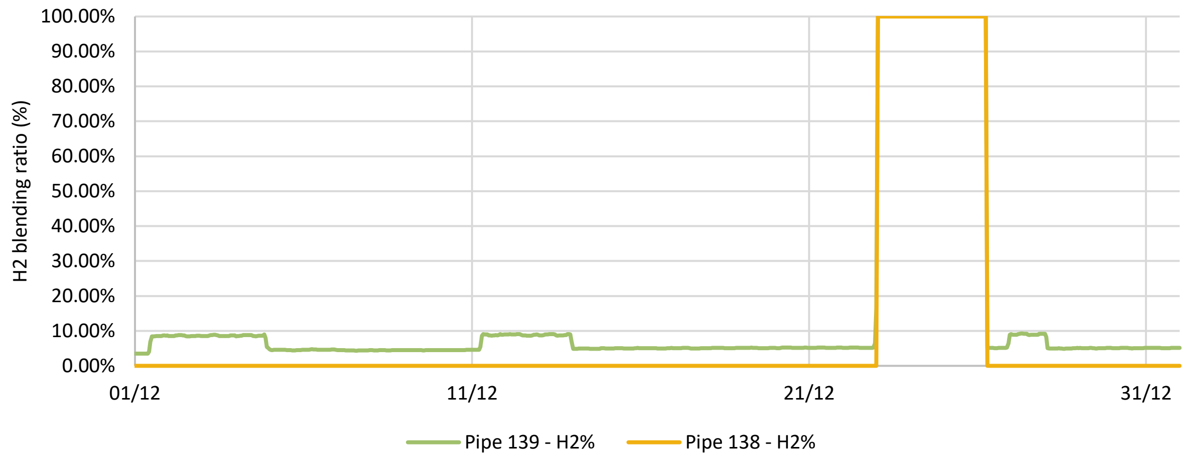


Figure 18 Simulation results for the Electrolyzer 1 configuration: gas flow rate (top graph) and hydrogen blending ratio (bottom graph)

Similar simulations were also performed for Electrolyzers 2 and 3, and the summary of the results is presented in Table 10. The table shows the frequency and duration of hydrogen blending limit exceedances over the one-month simulation period. In addition, it quantifies the percentage reduction in the maximum hydrogen production capacity required to maintain compliance with the prescribed blending limits under varying flow conditions.

Table 10 Percentage of simulation time exceeding the 5% hydrogen blending limit and allowable volume as a percentage of the total volume over the December simulation period

Location	duration exceeding the 5% limit	allowed volume as a percentage of maximum total volume
Electrolyzer 1	69%	78%
Electrolyzer 2	100%	21%
Electrolyzer 3	100%	11%

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

It is concluded that, under the current regulatory constraints of a 5% hydrogen blending limit in the network and a 2% limit at critical assets such as cross-border interconnections and underground gas storage facilities, the planned electrolyzer capacity exceeds the allowable injection capability (curtailment needed). Compliance with these limits significantly restricts the feasible operating range of the electrolyzers. Electrolyzer suppliers should take into account network limitations, particularly the maximum natural gas flow capacity, when designing their facilities.

The system would only be adequately accommodated if the blending limit were increased to approximately 20%, or alternatively, if a dedicated hydrogen pipeline infrastructure were implemented to transport hydrogen separately from the natural gas network.

Hydrogen accumulation may occur during injection into a bidirectional pipeline as a result of flow reversals

Electrolyzers 2 (Figure 19) and 3 are located along a main transmission corridor connecting the eastern and western interconnection points. The gas flow direction in this corridor changes intermittently throughout the year, with reversals occurring at various times in both summer and winter, rather than following a fixed seasonal pattern (Figure 20). These variations are driven by fluctuations in supply and demand as well as market-driven operational mechanisms which does not depend on network operator decisions.

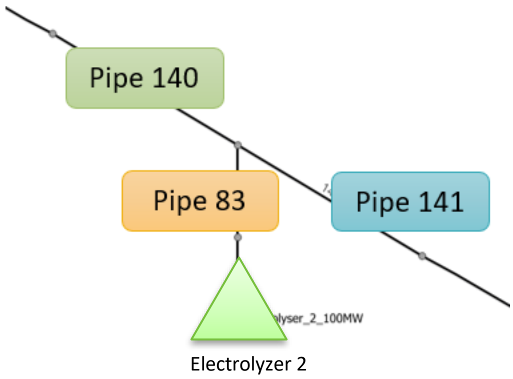


Figure 19 T-junction between Electrolyzer 2 and the main pipeline.

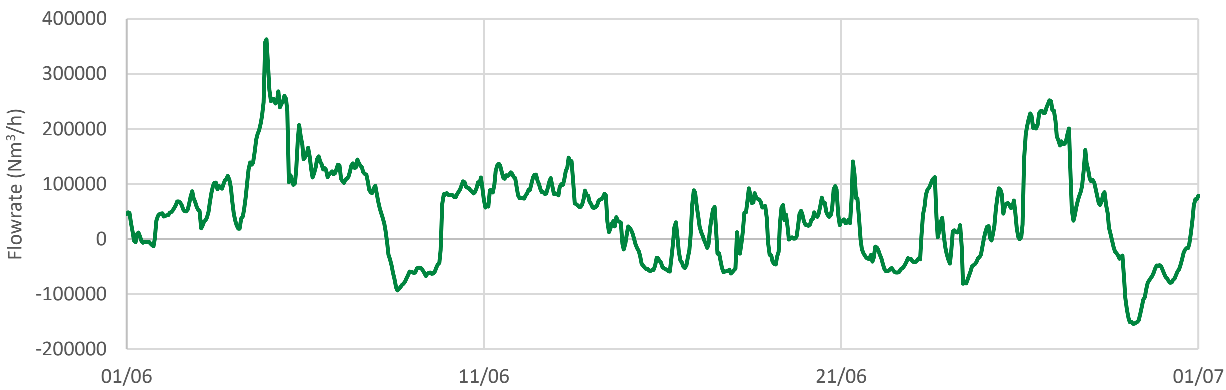


Figure 20 Flow rate during summer in the main transmission pipeline connected to Electrolyzer 2

Such intermittent flow reversals introduce additional complexity to hydrogen injection strategies, as the main pipeline may not consistently contain 100% natural gas, if hydrogen has been injected before. Instead, it may already include residual hydrogen that has not yet been fully purged from the network, leading to varying baseline hydrogen concentrations and more complex blending conditions.

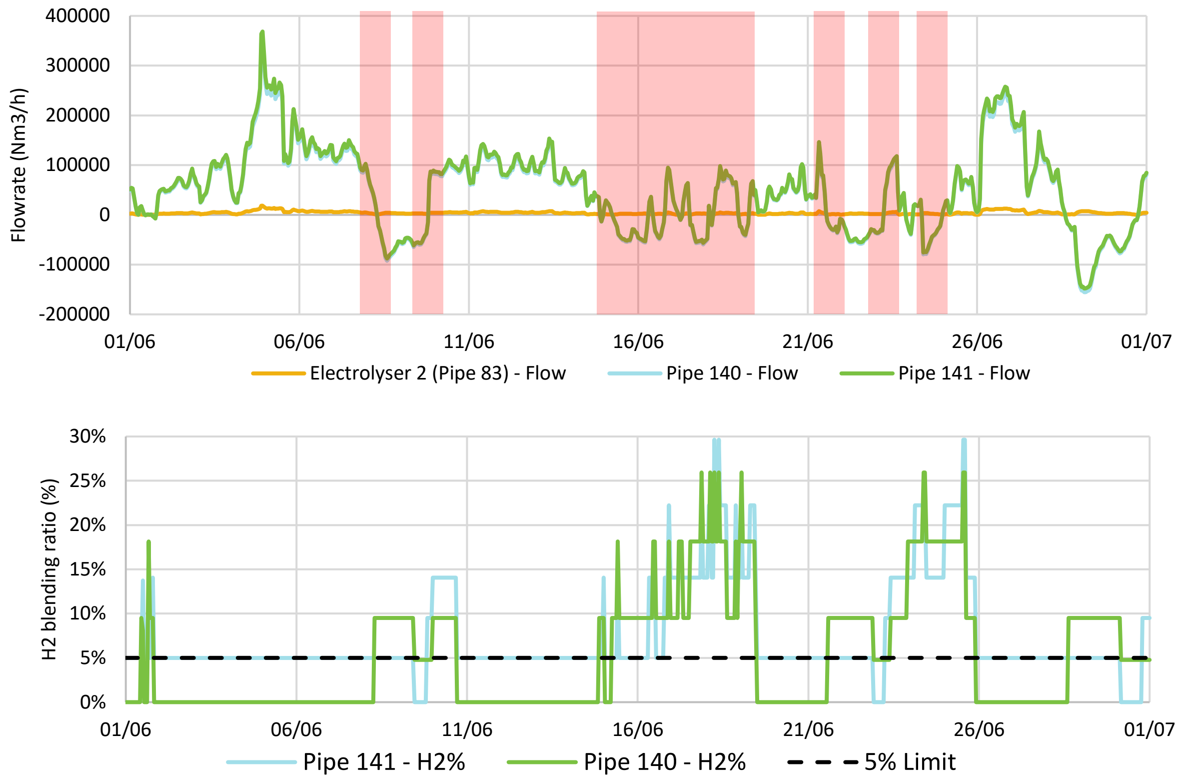


Figure 21 Simulation results for the Electrolyzer 2 configuration: gas flow rate (top graph) and hydrogen blending ratio (bottom graph)

As can be seen in Figure 21, the electrolyzer output has been curtailed to maintain the hydrogen concentration within the 5% blending limit, it is assumed that normal flow is from pipe 140 to pipe 141. However, during periods of flow reversal (highlighted by the red shaded area), curtailment based solely on the instantaneous flow ratio leads to hydrogen accumulation in the main pipeline. To avoid this situation, not only flow measurements but also continuous gas quality measurements within the pipeline are required prior to hydrogen injection into the grid. This enables accurate monitoring of the existing hydrogen concentration in the network and ensures that the maximum allowable hydrogen blending limit is not exceeded.

Underground gas storage can be used to manage and limit hydrogen concentrations

UGS facilities can play an important operational role in managing hydrogen concentrations within the natural gas transmission network, particularly under high hydrogen injection scenarios. When significant quantities of hydrogen are injected into the grid from multiple electrolyzer installations, certain sections of the network may experience elevated hydrogen concentrations due to limited natural gas throughput, bidirectional flow conditions, or flow reversals. Under such circumstances, the network may require flushing or dilution to restore hydrogen concentrations below the allowable blending limits.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

In this context, underground gas storage facilities can be used as controllable sources of natural gas to dilute hydrogen-rich gas mixtures within the transmission system. By increasing natural gas withdrawal from storage, the total gas flow in the affected pipeline sections can be increased, thereby reducing the volumetric hydrogen concentration and helping maintain compliance with regulatory blending limits. This approach is particularly beneficial in transmission corridors where hydrogen accumulation may occur as a result of intermittent flow reversals or reduced natural gas demand.

In addition to network-wide concentration management, UGS facilities can also support the operation of electrolyzers located in close proximity to storage sites. For example, during periods of high hydrogen production, the TSO may coordinate increased gas extraction from the storage facility to provide sufficient natural gas flow for dilution purposes. This operational strategy enables higher electrolyzer utilization while ensuring that the hydrogen concentration remains below the prescribed 5% blending threshold.

The operational integration between hydrogen producers and storage operators requires coordinated scheduling and network management. Such coordination can be implemented through the TSO nomination and balancing framework, particularly via the day-ahead nomination process. By incorporating anticipated hydrogen injection rates and storage withdrawal profiles into daily operational planning, the TSO can proactively manage gas quality, maintain network stability, and minimize the risk of hydrogen concentration exceedances. It should be said that for doing this the legal gas market rules should allow to operators to do that, what it is not the case nowadays. Also, it should be taken into account that normal operation of natural gas storages is on a seasonal basis; injection: April-October, extraction: November – March.

Furthermore, underground gas storage facilities may provide additional flexibility services for future hydrogen-integrated gas systems, including temporary buffering of natural gas supply fluctuations, mitigation of hydrogen accumulation during low-demand periods, and support for dynamic operation of renewable-powered electrolyzers. As hydrogen injection volumes increase in future transmission networks, the interaction between electrolyzer operation, gas flow dynamics, and underground storage utilization is expected to become an increasingly important aspect of TSO operational strategy and gas quality management. Of course, this is limited by the availability of gas storages in the affected area.

3.4 DSO network use case

3.4.1 Riccione, Italy

The Riccione use case concerns a natural gas distribution network at urban level located in Riccione, a seaside town on the Adriatic Sea, Italy. The infrastructure is operated by INRETE Distribuzione Energia S.p.A., an Italian distribution system operator (DSO). The area covered by the network is approximately of 20 km^2 almost entirely occupied by the urban context. This case is representative of the distribution infrastructure of urban context, with multiple gas entry points, regulated in pressure.

The most relevant reasons for selecting this network are:

1. Interaction between pressure setpoints at different entry stations: in networks with multiple pressure-regulated entry stations, changes in the pressure setpoint at one station influence the hydraulic balance and, consequently, the propagation of hydrogen blends injected from a single source.
2. Assessment of end-user gas quality and its variation in function of pressure set points.

On the same pressure level, it is possible to monitor how different fluid-dynamic equilibrium influences the hydrogen blending distribution.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

3.4.1.1 Network geometry and assets

The Riccione gas distribution network has already been described in Deliverable D4.1 [1].

It is composed of two pressure tiers: 5 – 1.5 bar_g (4th species[1]) and <0.04 bar_g (7th species), following the Italian classification of pressure level. Overall, it serves about 23,000 final users and it is fed by two city-gates (Regulation and Metering station – ReMi in the Italian jargon) which are connected to the transmission system.

In this study, we focused on the higher-pressure tier only. The topology of the addressed infrastructure is given in Figure 22 higher-pressure level of the natural gas distribution infrastructure of Riccione (INRETE) considered in this deliverable.. The red squares in the map represents the 24 final gas pressure reduction stations (FRS – final reduction station in the Italian jargon), which are the interconnecting plants between the higher and the lower pressure grid. These are the main gas exit points from the piece of infrastructure considered. However, individual final users are also connected at this level of the network, though they are not represented here (to ease the readability of the figure). From a topological point of view, the network database consists of 249 pipelines and 241 nodes. Out of these 241 nodes, 110 are the additional consumption points directly connected to the 4th species pipeline system.

Figure 22 higher-pressure level of the natural gas distribution infrastructure of Riccione (INRETE) considered in this deliverable.

The lower level of the infrastructure (p ≤ 0.04 bar_g) is composed of a highly meshed lower pressure network which feeds the majority of the final users (mainly residential and commercial). The topology of this level follows the urban road network. It has been neglected in this use case but has been considered in Chapter 4 addressing the optimal positioning of monitoring points.

3.4.1.2 Boundary Conditions

The nominal values of the main operational settings are as follows according to the data provided by the DSO: entry pressure at the Primary ReMi station (node 240): 4.5 bar; entry pressure at the Secondary ReMi station

[1] "species" is the technical Italian nomenclature for "pressure tier" or "pressure level".

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(node 240): 4.1 bar; exit flow to Riccione users. In this use case, a steady state maximum consumption case has been considered, with network's overall consumption of about 10600 Sm^3/h

To perform the scenario simulation, the ReMi stations have been assigned with a pressure set point profile each while all the other nodes of the network are treated as junctions (i.e. the exit flow is zero) or consumption points with assigned outflowing gas flow rate.

3.4.1.3 Scenarios description

Hydrogen is supplied premixed at the Primary ReMi station (node 240), with 20% hydrogen blend. The pressure set point of the Primary and Secondary ReMi station is modulated as displayed in Figure 23.

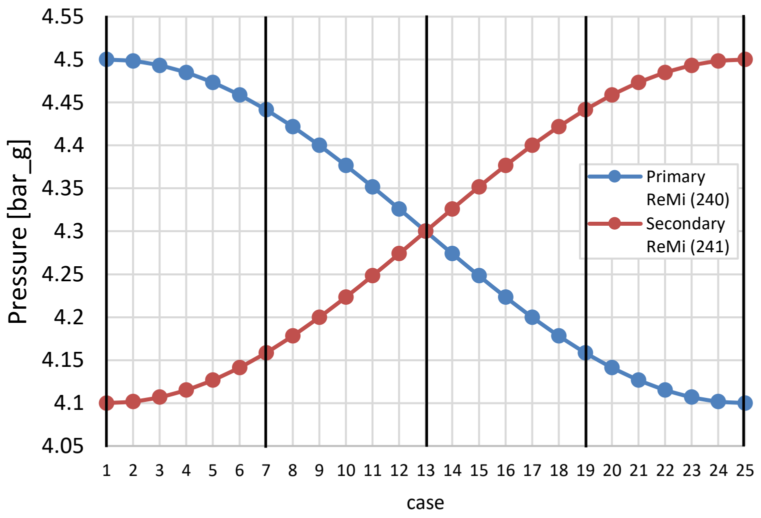

Figure 23 Investigated pressure set points at the two gas-entry stations of Riccione network.

By keeping the spatial distribution of the gas consumption constant, the goal is to assess the impact of modulating the pressure set point at the two gas entry points on the overall steady-state distribution of hydrogen blends throughout the network.

In particular, the five highlighted cases will be compared in the next section.

3.4.1.4 Findings

In multi-entry DSO networks, pressure set points act as gas-quality control variables, because they determine how hydrogen blends spread across the distribution grid

The Riccione use case shows that hydrogen distribution in urban DSO networks with multiple entry points is strongly affected by pressure set-point management. When a 20 vol% hydrogen blend is supplied from one ReMi station and natural gas from another, the hydrogen-affected area is determined by the hydraulic balance between the two inlets and the hydrogen concentration can be different than the nominal hydrogen concentration at the blended entry point because of mixing phenomena depending on the network topology.

In the analysed cases, the pressure set point of the hydrogen-blended inlet (node 240) is reduced from 4.5 to 4.1 bar-g, while the natural-gas inlet (node 241) is increased from 4.1 to 4.5 bar-g. This shifts the supply contribution of the hydrogen-blended inlet from about 46% to about 21% of total network supply (see Figure 26). As a result, the part of the network reached by hydrogen progressively contracts, and the distribution of

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

hydrogen concentration among nodes changes, as depicted in Figure 24. In the most hydrogen-favourable case, a significant share of nodes receives the 20 vol% blend, while other nodes receive intermediate concentrations around 8% because of in-network mixing between the blended and natural-gas streams, as displayed in Figure 25. Moving across the cases, Figure 25 gives a quantitative indication of the reduction of the hydrogen influenced area as well as the occurrence of in-network mixing.

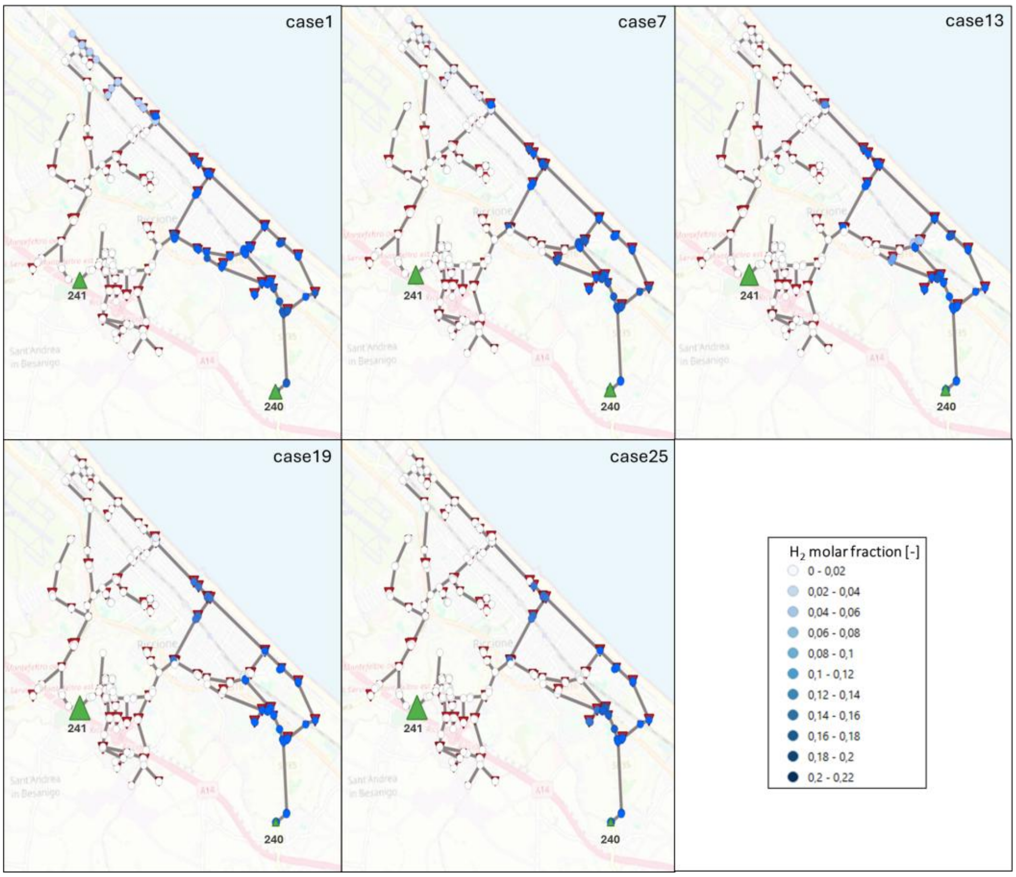

Figure 24 Steady state distribution map of hydrogen blends at different pressure set points of the inlet gas stations.

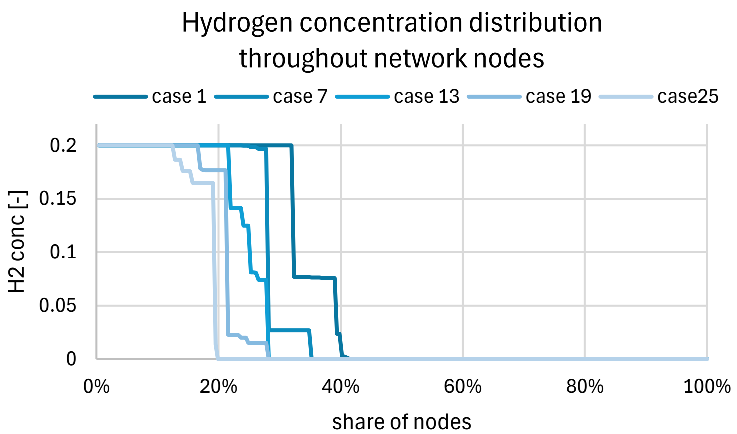

Figure 25 Ordered distribution of the hydrogen blend concentration over the network's nodes.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

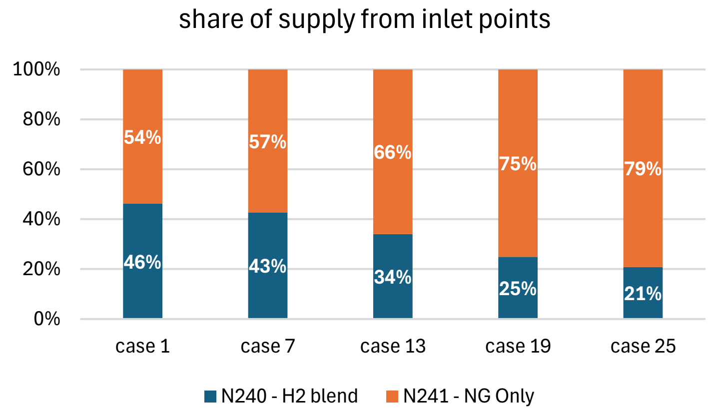

Figure 26 Relative contribution variation of the two inlet nodes to the overall gas supply to the network.

This finding shows that, in distribution networks, pressure regulation can reshape gas-quality zones. Final reduction stations and directly connected users may experience different hydrogen concentrations depending on entry-station pressure settings, even if the injected blend remains unchanged. Therefore, distribution-level blending should be assessed through combined hydraulic and gas-quality analysis, rather than by checking only the hydrogen concentration at the injection point. These simulations, together with the ones carried out in the generalization and parametric studies presented in Deliverable D4.6, highlights the occurrence of the so-called "zero flow point" (as discussed in EN 16726:2025 – annex F) which may be critical with respect to gas quality management, particularly considering the rate of variation of quality parameters.

For policy makers, regulators and standardization bodies, hydrogen blending rules for DSO networks should account for multi-entry operation, pressure-regulated gas-quality zones and downstream monitoring. Entry-point compliance is necessary but not sufficient where different gas sources interact within the same distribution grid.

For DSOs and the gas industry, pressure set-point management should be treated as an operational lever for hydrogen blending. Especially in cases where hydrogen blend is created at ReMi stations or in any case when gas with different quality enters the distribution network from different entry points, distribution operators can use pressure regulation to expand, to limit or to redirect the area exposed to hydrogen, as well as to keep the areas as steady as possible. This requires gas-quality tracking, monitoring at strategic final reduction stations and/or other specific monitoring points to be integrated with pressure-quality control procedures.

3.4.2 Palma de Mallorca, Spain

The Palma use case concerns a natural gas network located on the island of Palma de Mallorca, Spain. The system is operated by REDEXIS, a Spanish distribution system operator (DSO), and supplies natural gas to the city of Palma and its surrounding areas. The analysed network comprises high-pressure transmission pipelines connected to lower-pressure distribution networks, thereby enabling the representation of interactions between transmission- and distribution-level infrastructure.

The Palma case was selected as it provides a realistic and representative test environment for evaluating hydrogen injection across coupled transmission and distribution systems. In this configuration, hydrogen is supplied premixed with natural gas at one of the upstream entry points, ensuring that hydrogen concentration limits at the injection boundary are already satisfied by design. As a result, the analysis does not focus on enforcing injection constraints at the supply point, but rather on investigating the downstream transport, dispersion, and mixing behaviour of hydrogen within the network.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

The network structure and operational characteristics enable a detailed assessment of hydrogen propagation across pressure levels and throughout the DSO system. The main reasons for selecting this test network are outlined below:

- **Interaction between transmission and distribution systems**

  The network includes four connection points between high-pressure transmission pipelines and low-pressure distribution pipelines. These multiple interface boundaries allow hydrogen to enter the distribution system through different entry locations, providing a robust framework for assessing how injection location and boundary conditions influence hydrogen dispersion at the TSO–DSO interface.

- **Direct assessment of end-user gas quality**
  The topology of the network enables hydrogen to be injected upstream while simultaneously tracking its impact on gas quality at downstream DSO exit points. This facilitates a direct evaluation of hydrogen concentrations delivered to end consumers under realistic operating conditions.

- **Geometric complexity of the DSO network**
  The distribution system contains looped low-pressure pipeline structures, which introduce recirculation effects and enhanced mixing behaviour that are not present in purely radial networks. This structural complexity makes the Palma network particularly suitable for analysing hydrogen transport phenomena in realistic DSO configurations..

3.4.2.1 Network geometry and assets

In Figure 27, the network geometry and assets are illustrated. The network consists of the TSO pipelines illustrated with black, which are operated at 80 bar. The TSO network is supplied at a single injection point located in the south-eastern part of the system, indicated by a red flame icon. For the purpose of this study, two additional supply locations are assumed and are represented by orange flame icons. These additional supply points are introduced to increase the operational complexity of the DSO network. The mixing behaviour of natural gas and pure hydrogen is investigated through simulations in which the gases are supplied from different combinations of the available supply locations. Simulations with 1 and 2 supply locations are performed.

The low-pressure distribution system (DSO) is connected to the high-pressure TSO network via four interface locations, referred to as city gates, which are indicated by black valve icons. The low-pressure pipelines are shown in green and operate at a nominal pressure of 5 bar.

The DSO network includes 24 district stations that serve as exit points to downstream, lower-pressure (0.4 bar and 50 mbar) distribution networks. These district stations represent boundary connections to secondary distribution systems. In addition, two locations provide connectivity to adjacent network areas with further district stations. For modelling simplicity, these two connections are represented as exit points, since historical measurements indicate that flow direction at these locations is consistently oriented towards the connected downstream systems.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

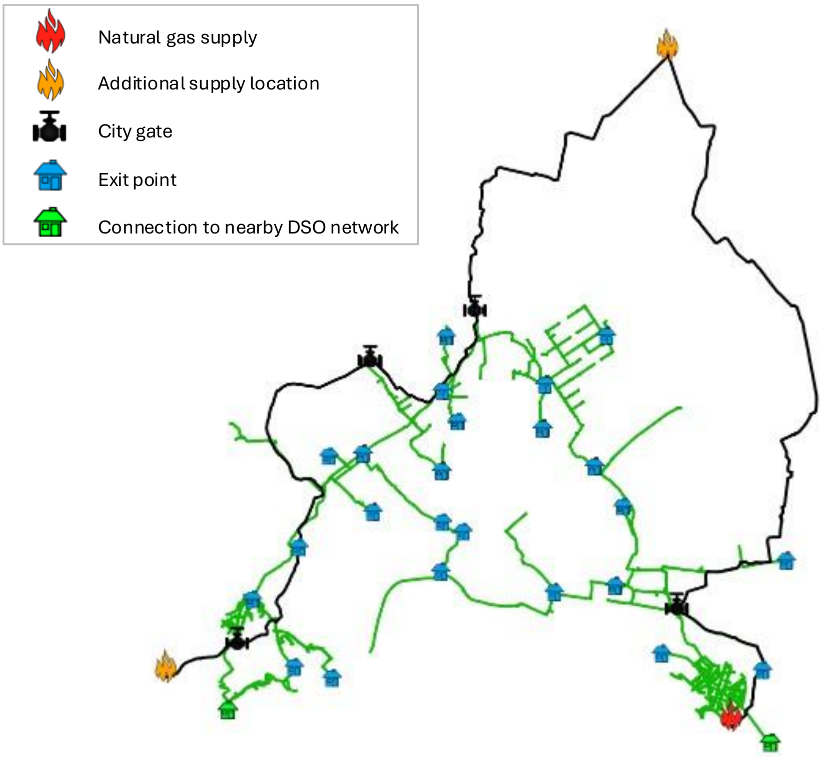

Figure 27 Palma DSO use case network

Table 11 Palma DSO use case network assets

Asset	Properties
80 bar pipelines	37 km
5 bar pipelines	98 km
Gas supply	1 existing location 2 additional locations for this study
City gates	4 locations
Exit points	24 district stations 2 Connections to nearby area

3.4.2.2 Boundary conditions

Flowrate measurements at the exit points of the DSO network are available for both winter and summer periods. These measurements are provided at an hourly resolution and are expressed in Nm^3/h.

The flow data recorded at the 24 district stations are interpreted as gas consumption within the DSO network, as these points represent deliveries to downstream distribution systems and end users. The flow measurements at the two interconnection points are also treated as consumption, even though these locations are not classified as district stations.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

Winter measurements are available for the months of January and February. The total consumption flow across the 24 district stations is presented in Figure 28 for the winter period and in Figure 29 for the summer period. During winter, the total consumption ranges between 3 and 22 kNm³/h. In contrast, summer consumption is significantly lower, amounting to less than half of the winter values, with variations between near-zero and 9 kNm³/h.

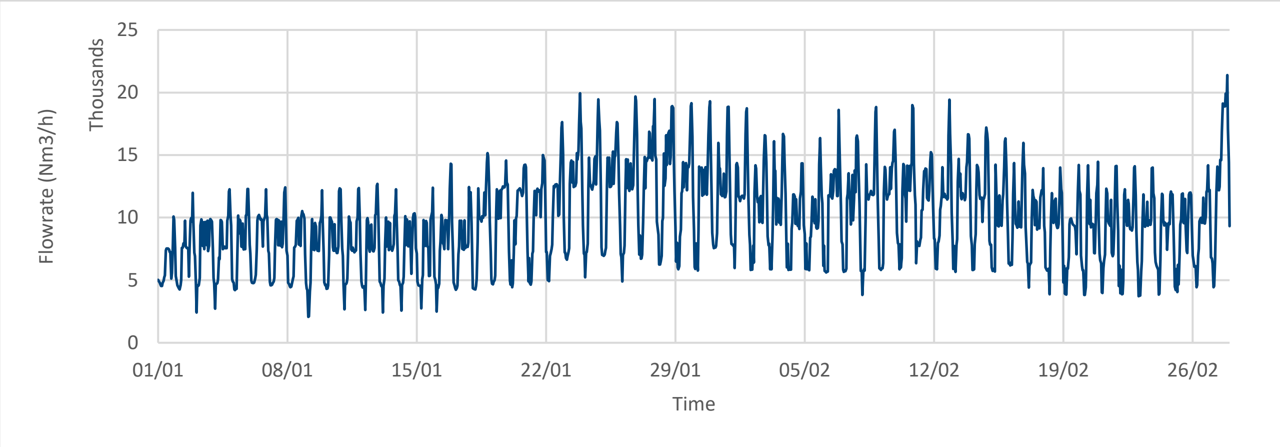

Figure 28 Total measured consumption during winter

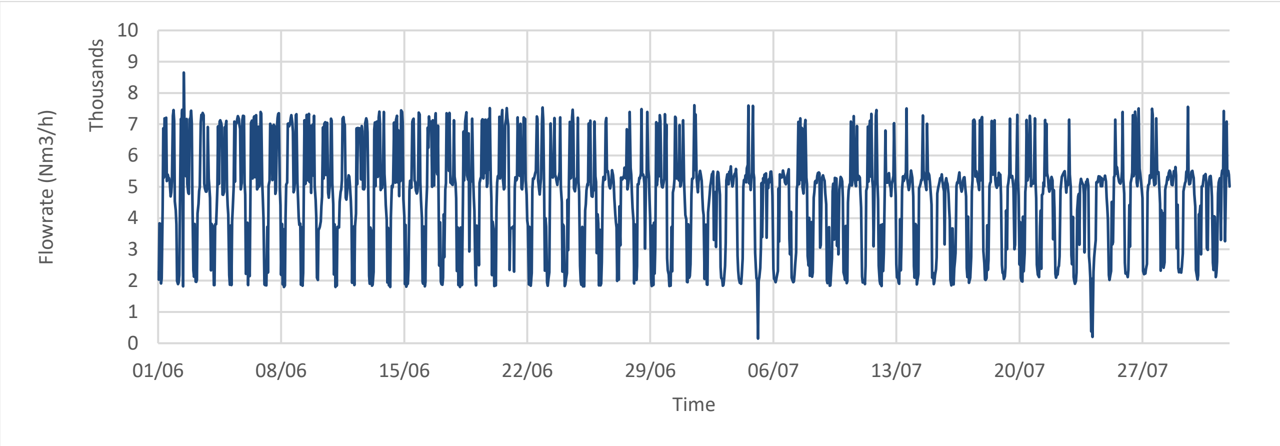

Figure 29 Total measured consumption during summer

Injection of hydrogen

In Figure 30 the supply points of the high-pressure pipeline are illustrated in the network of Palma for the current study. Supply location 1 is the existing location in the network that continuously supplies all the Palma area. For research purposes Supply location 2 and 3 are selected as additional hypothetical injection points of Hydrogen.

At each supply location, the incoming gas mixture is prescribed as a boundary condition. In the simulations, it is assumed that a fixed hydrogen-to-natural gas ratio enters the network at these entry points. This representation implies that pure hydrogen injection occurs upstream of the supply locations, where it is blended with natural gas prior to entering the transmission system. The hydrogen flow is assumed to be actively controlled such that the prescribed hydrogen concentration in the injected mixture is maintained at the target level throughout the simulation period.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

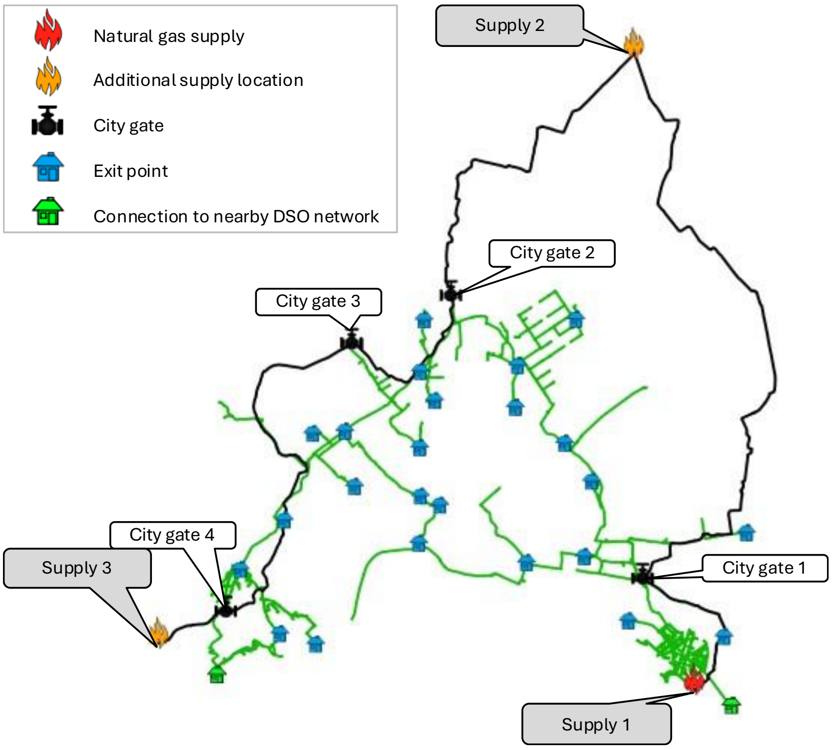

Figure 30 Supply locations in the Palma use case. The supply locations are the locations were the hydrogen flow is simulated.

3.4.2.3 Scenarios description

This section presents the set of simulated scenarios developed for the DSO network to assess the impact of hydrogen injection under varying operating conditions. Following the description of the network topology, assets, and boundary conditions, a series of time-domain simulations was performed using the AURORA gas network simulation tool. AURORA models transient gas flow and pressure dynamics while explicitly tracking gas composition, enabling detailed analysis of hydrogen concentration evolution throughout the network.

The defined scenarios focus on variations in supply configurations and seasonal demand profiles. They are designed to investigate both transient hydrogen transport behaviour and the resulting quasi-steady-state operating conditions within the DSO network

A. Single-supply Scenarios

In the first group of scenarios, the network is supplied from one of the three available supply locations at the 80 bar pressure level. To capture seasonal variations in demand and flow patterns, simulations are conducted for two representative operating conditions: winter and summer. The initial condition of the network is assumed to be 100% natural gas, while the active supply location injects a gas mixture consisting of 95% natural gas and 5% hydrogen.

These simulations therefore enable the analysis of hydrogen propagation throughout the network, as well as the associated transient and time-dependent system response, under simplified supply configurations.

B. Dual-supply scenarios with hydrogen admixture

The second group of scenarios investigates more complex operating conditions involving simultaneous operation of two supply locations. Only the combinations of Supply Locations 1–2 and 1–3 are considered.

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Supply Location 1 represents the existing operational supply point of the network, while Locations 2 and 3 are introduced to enable the assessment of alternative and more stressed operating configurations.

The initial condition of the network is assumed to be 100% natural gas. For each supply combination, one supply location injects pure natural gas, while the other supplies a gas mixture composed of 95% natural gas and 5% hydrogen by volume. Simulations are performed for both winter and summer demand profiles.

Consequently, the initial phase of each simulation captures the transient behaviour of the system as hydrogen propagates through an initially hydrogen-free network. In the later stages, the system evolves towards a quasi-steady operating state, which becomes largely independent of the initial conditions. This final phase is therefore used to evaluate steady-state hydrogen distribution under multi-supply operation.

Additionally, the distribution of the supplied flow between the two active Supply Locations is highly dynamic for both the 1-2 and 1-3 combinations. It is observed that Supply location 1 is the dominant one in terms of flow rate, with 50%-90% of the total flow rate passing through it. The remaining 50%-10% flows through the second Supply Location, either 2 or 3. The reasons are:

- Supply location 1 is connected to the city gate via a shorter pipeline compared to Locations 2
- Supply Location 1 is located near exit points with higher flow demand

3.4.2.4 Findings

In this section, the results obtained from the simulation of the Palma network under winter and summer conditions are presented and discussed.

Hydrogen blending delay from supply to end consumers due to network topology and low flow rates.

A gas network model with a composition-tracking algorithm can be used to determine the transport time of gas species throughout the network. In the case of a single injection of a 5% hydrogen mixture at Location 1, a time delay is observed between the change in gas quality at the supply point and its arrival at downstream district stations.

This delay is caused by a combination of low flow velocities, long transport distances, and the meshed topology of the DSO network, which introduces multiple flow paths and mixing effects. During winter conditions, when the maximum total demand flowrate reaches approximately 20 kNm³/h, the gas mixture containing 5% hydrogen requires around 8 hours to reach City Gate 1. In contrast, the transport time to City Gates 2, 3, and 4 is significantly longer, ranging from approximately 8 to 14 days, respectively (Figure 31). During summer conditions, when network demand and gas velocities are substantially lower, these transport delays increase further and can exceed more than one month.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

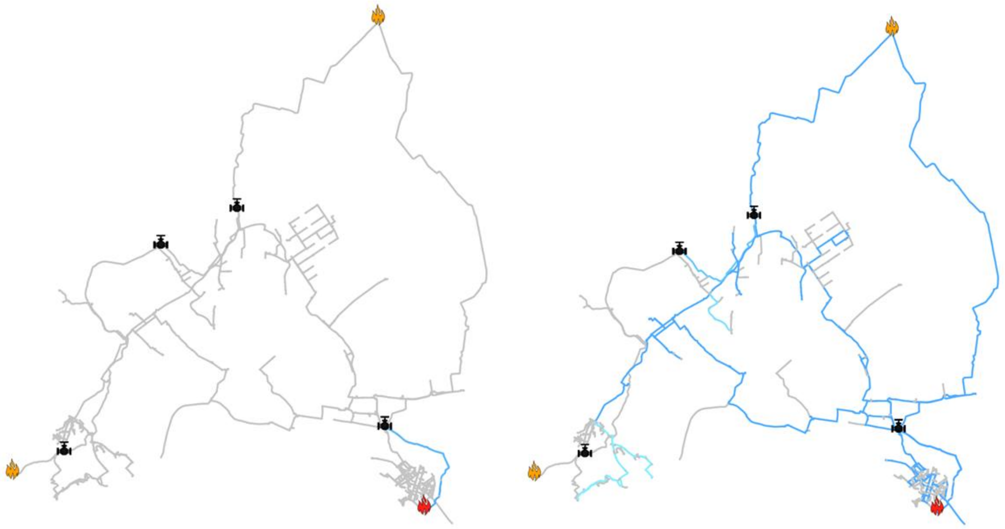

Figure 31 Results of winter consumption simulation in Palma network. Results are shown with a colour gradient from grey to blue which indicates hydrogen % from 0% to 5%. <u>Left figure</u>: the results at 8 hours after the start of the simulation. <u>Right figure</u>: the results from 8 days after the start of the simulation.

When analysing the gas composition at each district station (Figure 32), it can be observed that not all end consumers receive the same gas quality during the first weeks following hydrogen injection. The hydrogen concentration at each city gate depends on the existing gas composition within the 80-bar transmission pipeline prior to the introduction of the hydrogen-natural gas mixture. As a result, significant temporal and spatial differences in gas quality may occur across the network.

This discrepancy may lead to inequality among consumers, since each customer may receive gas with a different hydrogen concentration and therefore a different calorific value. In the case of a 5% hydrogen admixture, a larger gas volume is required to deliver the same amount of energy compared to pure natural gas. If gas billing and metering remain volume-based rather than energy-based, consumers receiving gas with higher hydrogen content may incur higher costs to obtain the same usable energy, resulting in non-uniform consumer impacts across the network.

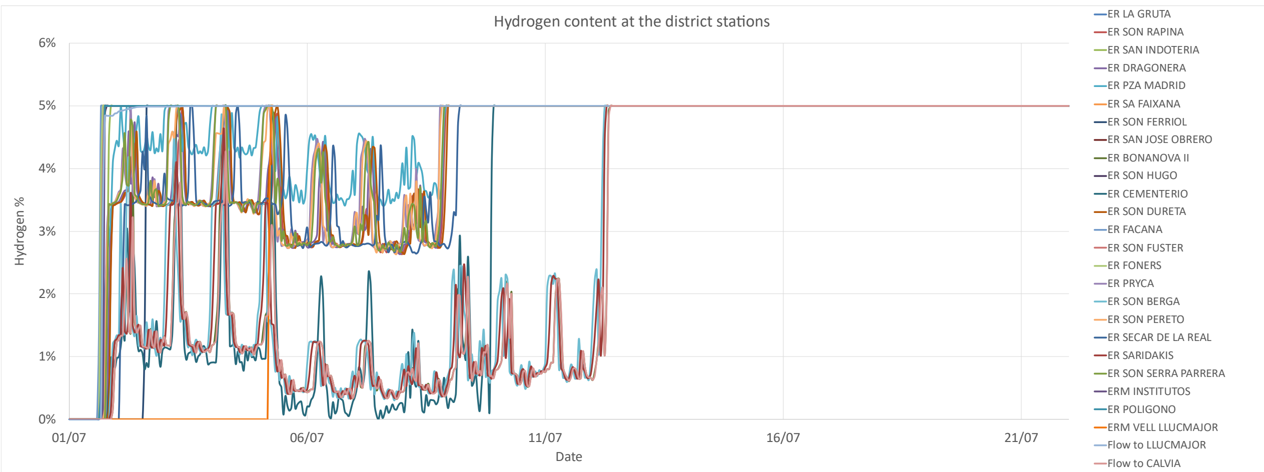

Figure 32 Hydrogen concentration at each district station over time for a single 5% hydrogen injection during the summer period.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

Gas quality behaviour under dual-supply operation

When two supply locations operate at the same time, one injecting pure natural gas and the other injecting a hydrogen-enriched gas mixture, the network does not converge to a single uniform gas composition. Instead, gas quality remains spatially non-uniform due to the continuous mixing of the two different supply streams.

After dual-supply operation begins, the network goes through a transition period during which the gas composition at the exit points gradually changes and moves toward intermediate values in between 0-5%. Although the system never becomes fully uniform, it gradually reaches a quasi-steady condition, where changes in gas quality become relatively small and remain within a stable range rather than continuing to vary significantly over time.

Two simulation cases were considered:

- Case 1: A gas mixture containing 5% hydrogen is injected upstream of Supplier 1, while Supplier 3 injects 100% natural gas (Figure 33).
- Case 2: A gas mixture containing 5% hydrogen is injected upstream of Supplier 3, while Supplier 1 injects 100% natural gas (Figure 34).

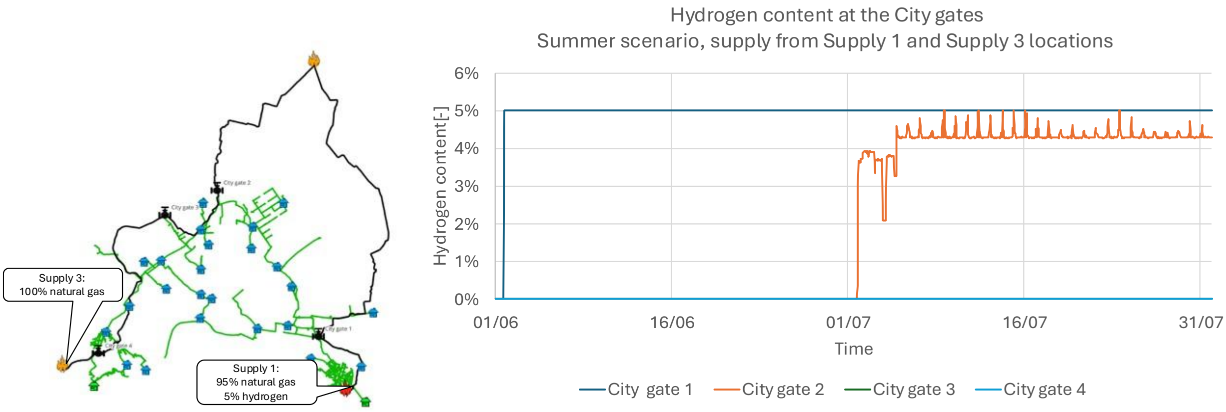

Figure 33 Summer scenario for Case 1. Gas mixture at City gate 2 stabilizes at approximately 4.2% hydrogen.

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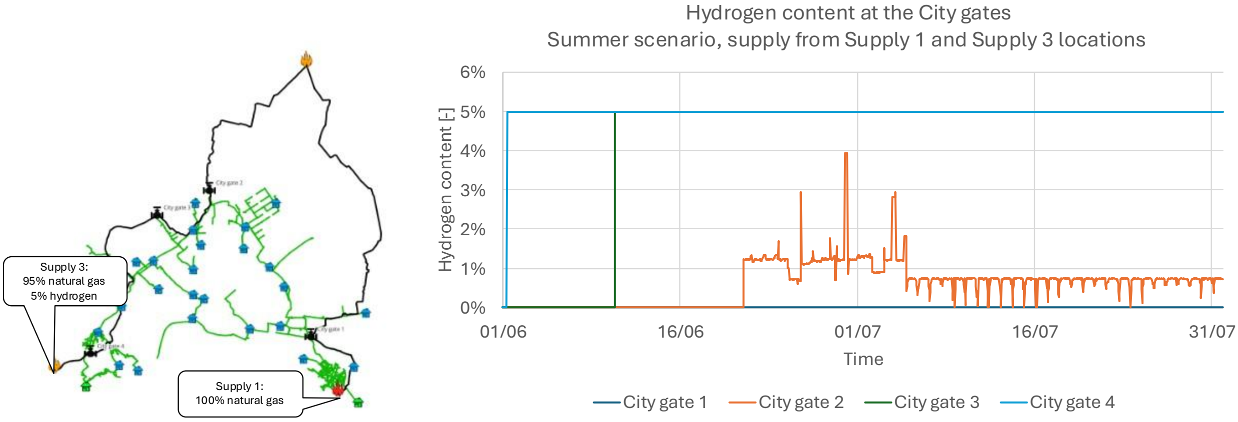
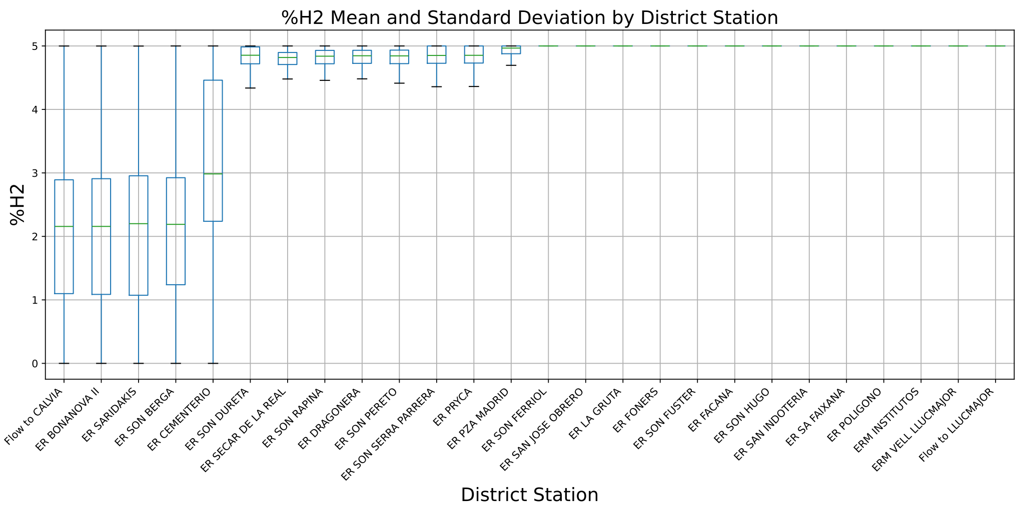


Figure 34 Summer scenario for Case 2. Gas mixture at City gate 2 stabilizes at approximately 0.4% hydrogen.

The simulation results provide further insight into this behaviour. A transition period of approximately 21- 34 days was observed before the network reached an almost stable intermediate condition. Consistent with previous findings for the summer period, stabilization takes longer than one month in certain parts of the network, particularly at City Gate 2, which is located between two supply sources and is therefore influenced by competing flow paths and prolonged mixing effects.

The range of gas composition at each district station for Case 1 and Case 2 during the summer period is shown in Figure 35. The figure presents the average gas composition at each district station over the entire simulation period. This information can be used as an additional input for billing calculations in cases where energy-based metering is not installed.



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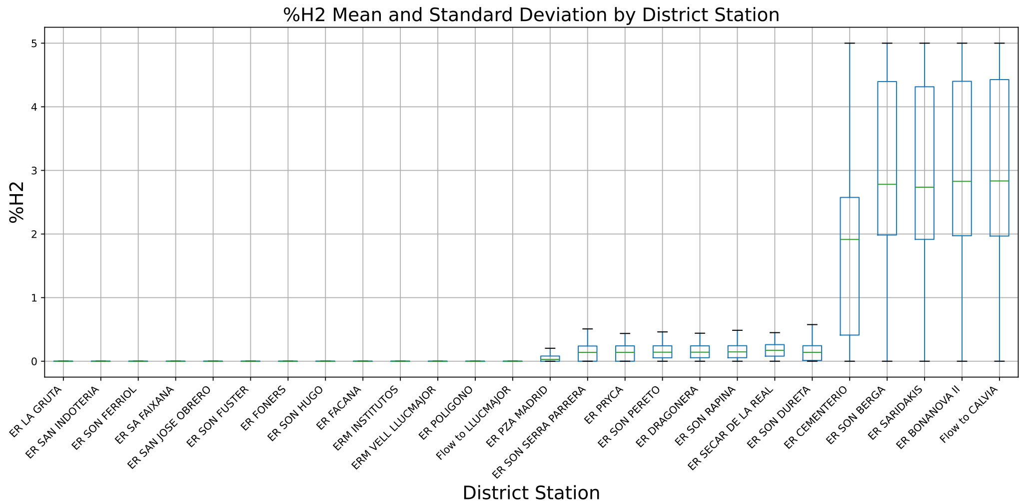

Figure 35 Average hydrogen concentration and standard deviation at district stations for Case 1 (top) and Case 2 (bottom), summer period.

Dynamic adjustment of city gate pressure setpoints to regulate flow distribution and avoid hydrogen exposure in critical areas.

Another important insight from the simulation with gas composition tracking is that the spatial distribution of hydrogen is strongly governed by the relative flow contributions from each city gate. Since each city gate acts as a boundary between the transmission system and the distribution network, its operating conditions directly influence both the direction and magnitude of gas flows entering the DSO system.

A key controllable parameter in this context is the setpoint pressure at each city gate. By adjusting the pressure setpoint, the operator can effectively redistribute flow shares between different entry points in the network. A higher setpoint pressure at a given city gate typically increases its hydraulic driving force relative to other entry points, thereby attracting a larger share of the incoming flow. Conversely, lowering the setpoint reduces its contribution and shifts the flow toward alternative supply locations.

This hydraulic coupling can be used as an operational control mechanism to manage hydrogen propagation. In situations where certain parts of the network are sensitive to hydrogen admixture, such as industrial consumers, the flow paths can be actively influenced to minimize hydrogen exposure. By increasing the setpoint pressure at specific city gates, flow can be preferentially rerouted through alternative entry points, effectively steering hydrogen-enriched streams away from critical areas.

However, this type of control is not purely local. Changes in one city gate setpoint can propagate through the network and affect flow distribution at other entry points due to the meshed structure and interdependence of pressure levels. Therefore, any such operational strategy requires a system-level assessment to ensure that flow redistribution does not unintentionally increase hydrogen concentrations elsewhere in the network or violate blending constraints at other locations.

Overall, the results indicate that city gate pressure management can serve as a practical operational lever for hydrogen blending control, complementing supply-side regulation and enabling more targeted management of hydrogen distribution within complex gas networks.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

4 Positioning of optimal monitoring points in the network

4.1 Introduction

With the introduction of renewable gases such as green hydrogen and biogases into conventional natural gas systems, being able to accurately know the gas quality throughout a grid is becoming increasingly important for aspects relating to regulations, safety, and billing practices. To achieve this increased level of knowledge of gas quality, most existing grids need to be expanded with additional sensing capacity. However, these sensors, especially those measuring gas quality, are often expensive, and thus DSO or TSO's are limited in the number of them they can realistically install. An investigation of the available sensor technologies for quality monitoring has been published in deliverable D4.7 Gas Quality Measurement Technologies for Hydrogen Injection [3].

Thus, there is an inherent trade-off to the placement of new sensors in gas networks: more sensors are desired from an informational perspective as more sensors provide more insights into the behavior and status of the grid, but at the same time, installing fewer sensors is more economically attractive. Optimal sensor placement is the process of finding the balance between these two opposing incentives. It aims to find the smallest number of sensors (and their locations within the grid) needed to be placed in a grid in order to achieve a specified measuring accuracy/limit throughout it.

When hydrogen is admixed into gas streams and injected into a gas grid at a variety of (decentralized) sources, each containing different fractions of hydrogen in their mixes, tracking hydrogen through the network becomes non-trivial. While hydrogen contents may be known at each point of injection, they change and evolve over time throughout the grid as streams of different gas qualities mix with each other. Due to uncertainties in network characteristics (reported versus actual pipe roughness, diameter, etc.) and consumer behavior, the points at which this mixing occurs are challenging to estimate. As a result, accurately keeping track of how the hydrogen contents of the gas in a grid evolves in real-time becomes highly challenging without directly sensing (parts of) the streams within the network.

When adding sensors to a grid for measuring gas quality, there are typically two goals one may want to achieve:

- Knowing the exact (or as close to exact as possible) value of gas quality at all points or key points in a network.
- Ensuring the gas quality is within legal or technical limits throughout the network.

Where the first goal is relevant for fair billing purposes[2], while the second is related to safety or legal concerns; not all equipment connected to a grid may be able to handle the same amount of hydrogen as others, or a (local) government may pose restrictions on the amount of hydrogen that may be mixed into a natural gas grid. While the difference between these two goals is subtle, they can have a big impact on the optimal sensor placement approach taken. Most notably, the first goal sets more strict requirements on knowing exact values, whilst the other simply requires being able to know values are within allowed margins.

Due to the scope of the SHIMMER project, the work presented in this document focuses on the latter of the two goals. This goal aims to employ sensors throughout a network to be able to monitor that no point of interest in the grid (consumer, compressor, turbine, etc.) is fed with gas that contains a fraction of hydrogen above a set limit. While this problem can be trivially solved by limiting the amount of hydrogen directly at each gas

[2] When admixing less dense hydrogen volumetric billing can be unfair in cases where hydrogen is not evenly distributed throughout the grid (which happens often). In those cases, consumers receiving gas with higher percentages of hydrogen will have to consume more gas by volume as hydrogen has a lower energy density by volume. Thus, if this volume is not corrected based on the actual gas quality but is billed the same as pure natural gas, this consumer will end up paying more compared to those receiving gas with lesser amounts of hydrogen in it.

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injection point, this work covers the scenario in which such constraints cannot be put in place. In addition, this scenario also covers any situation in which this injection limitation has been accidentally exceeded.

In this work, a recurrent clustering-based approach to sensor placement has been developed that ensures that a minimal set of sensors can estimate the hydrogen contents of a cluster of similar consumers within a specified bandwidth limit. The next section goes into the details of the problem statement and the developed algorithm to solve the sensor optimization problem in question. The results of the application of the developed methods to a case study of a real-world gas grid are presented in the subsequent section. The final section of this chapter provides findings on the reported work on the sensor placement process.

4.2 Methodology

The aim of the sensor placement algorithm developed in this work is to find a minimal set of sensors in a given gas grid that ensures that at all times the measurements coming from this set of sensors can guarantee that the gas quality within the entire network is known to be within a provided error bandwidth. This comes down to finding a number of sensors spaced out through the network that, when their measured values are known, allow a grid operator to estimate the values of all non-measured points-of-interest to within a given range around the measured value. For example, given a maximum hydrogen content error bandwidth of 1%, if a sensor measures 3% of hydrogen to be present, all other nodes that this sensor stands in for should have a hydrogen content between 2% and 4% (e.g. deviating from the measured value by less than 1%). This concept is schematically depicted in Figure 36.

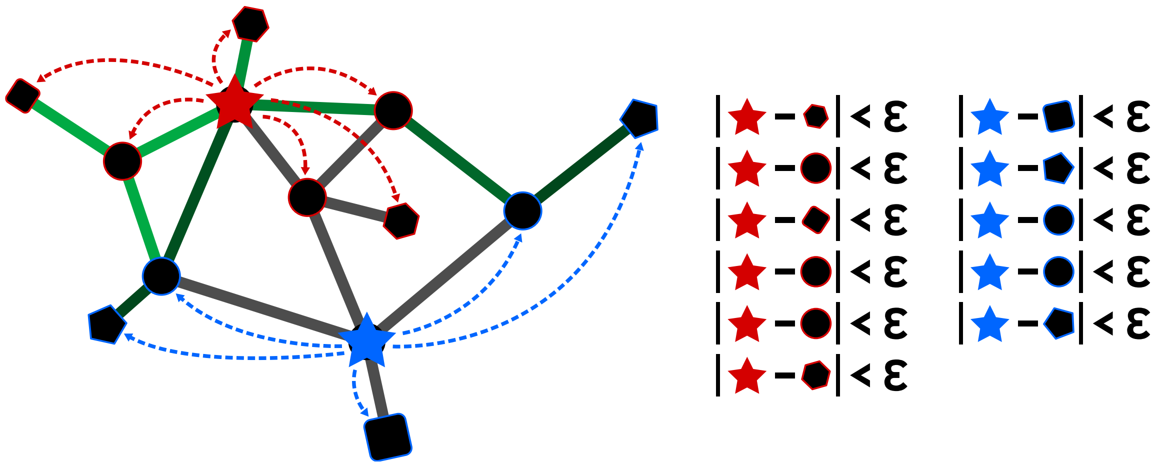

Figure 36 Schematic depiction of the sensor placement goal: finding the best sensor locations (red and blue stars) such that the difference between their measured values and that of all other nodes in the network (black shapes) is within a specified absolute error bandwidth (e.g. 1%).

In this work, optimal sensor locations are determined in combination with simulations of the gas network in which the sensors need to be placed. A period of admixed hydrogen-natural gas flow throughout the grid is simulated, and its results are used to find the optimal sensor locations for the grid in question during the simulated period. Figure 37 shows a simplified depiction of a typical outcome of such a simulation, showing the hydrogen content per node in the network over the simulated period. As can be seen, such simulations often show distinct patterns shared between sets of nodes. For instance, some might always receive a constant amount of hydrogen, others have gradually varying patterns, while others show considerable fluctuations that follow along with typical daily consumer profiles. The type of profile that a node shows is directly related to its location within the network; those close to a point where gas is fed into the network will show very few fluctuations, while those located near parts of the network where streams of different gas quality mix will show much more significant fluctuations. The sensor placement method developed in this work is based on this fact.

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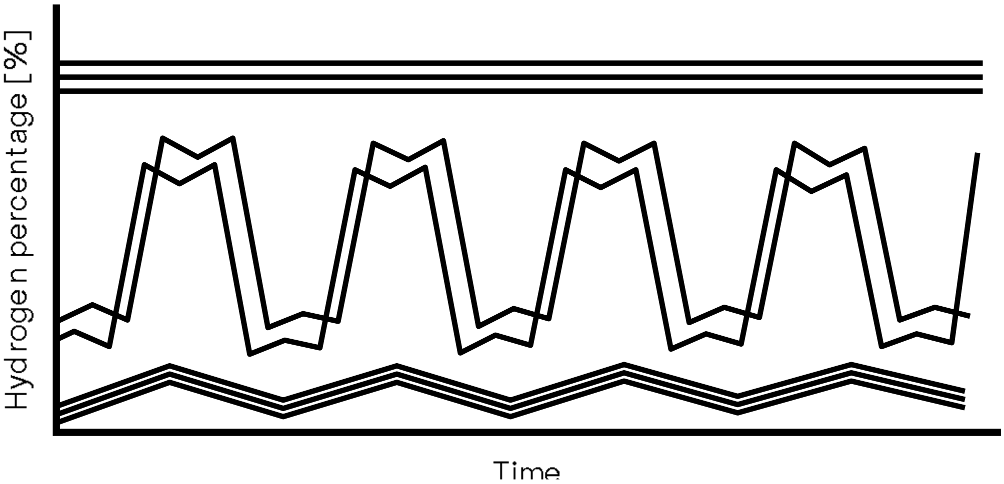

Figure 37 Simplified depiction of a typical simulation result for admixed hydrogen-natural gas flow in a gas grid. Here, each line corresponds to an individual node/asset/consumer/etc. in the network.

By dividing the simulated gas quality profiles into groups of nodes with similar behaviour (called clusters), one can use the measured value of one node in a cluster of multiple nodes to act as the representative node for the entire cluster, thereby drastically reducing the number of required sensors.

In this work, clustering is done by comparing all simulated node profiles to each other by computing their Euclidean distances. This provides an array of values that indicate how similar each profile is to each other profile. Using these similarities, the hierarchical clustering method of scikit-learn[3] is used to divide the entire collection of profiles into groups that show similar behaviour during the simulated period. Once the clusters are found, the representative "stand-in" node within each cluster has to be identified. As discussed, the value of this node will eventually be used as the value for all nodes within the cluster. To find it, the computed similarities are used to identify the node within the cluster that on average is most similar to all other nodes in the cluster. The results of this process are shown for the simplified node profiles in Figure 38.

[3] https://scikit-learn.org/stable/modules/clustering.html#hierarchical-clustering

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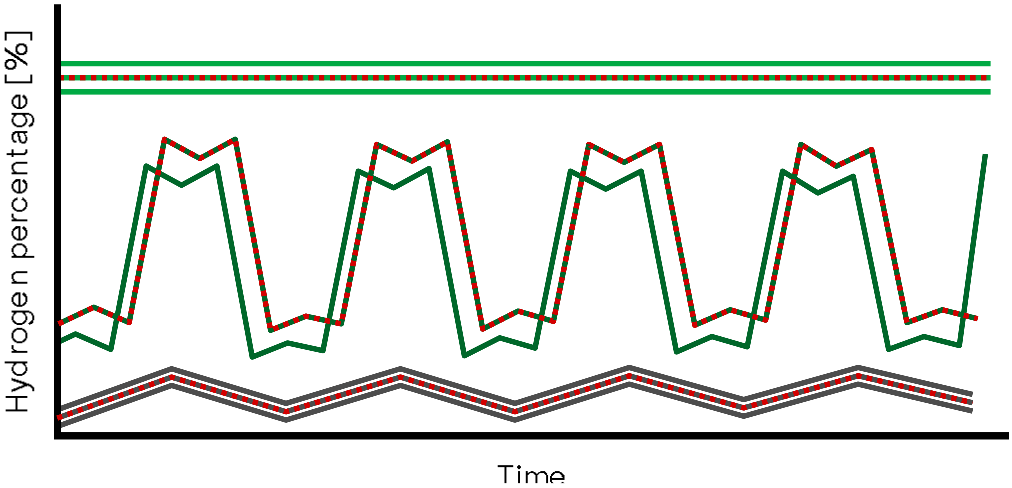

Figure 38 Simplified example results of the clustering method and representative node finding method. Each cluster is depicted with a different colour, while the representative sensor nodes are indicated using a red dashed line.

One complicating factor in the above-described workflow is the maximum allowed error between the measured sensor node value used to represent all node values in a cluster, and the actual values of the nodes in a cluster. For instance, one might identify the optimal sensor node within a cluster that can estimate the values of all other nodes in the cluster to within an absolute value of 1.5% hydrogen contents. However, if the goal of the sensor placement is to never be off by more than 1% hydrogen contents, this outcome does not satisfy the constraints of the problem.

This issue can be solved by adding additional sensors within this cluster, or by dividing the cluster into additional sub-clusters. To make the method more consistent, the latter option was implemented in a recursive manner. In this approach (Figure 39), the entire collection of nodes is first divided into two clusters. For these two clusters, the in-cluster similarity is used to find the most representative node, and the maximum estimation error of this node is calculated. If this error is within the error limits defined, the node is selected to be a sensor location. If the error is not within the limit, the cluster it was in is divided into two subcluster, for which the most representative nodes are again computed and checked for their maximum error limit. The process is repeated until the entire network is divided into clusters with a representative node that can estimate the value of all other nodes in the cluster to within the error limit. If a cluster cannot be further subdivided (because there is only one node in it), the algorithm simply places a sensor in the single node of said cluster. This means that extreme outlier nodes will often end up requiring a sensor to be placed in them to stay within the error bounds.

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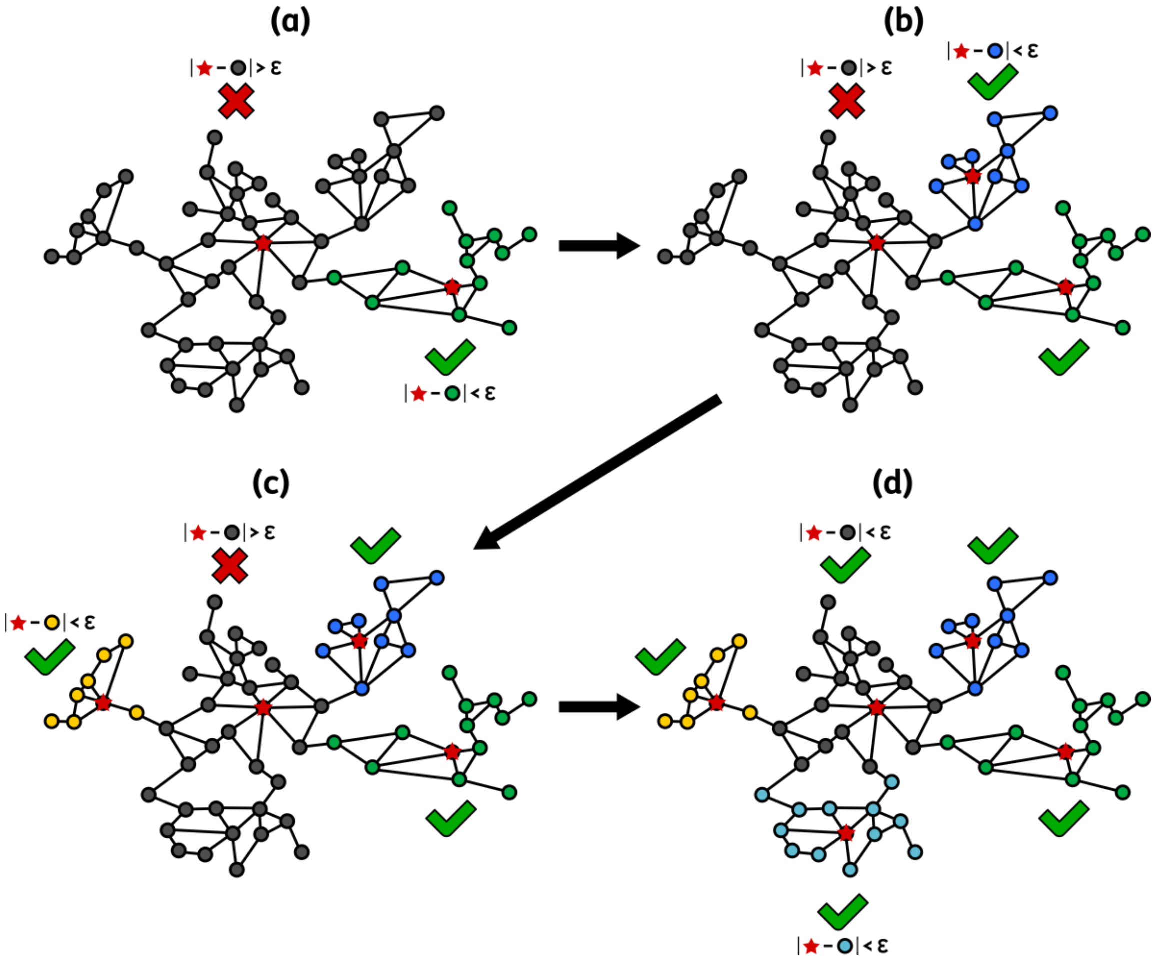

Figure 39 Schematic depiction of the recurrent clustering and sensor placement method.

A given grid is first divided into two clusters, and the simulated hydrogen content profiles are used to find the optimal sensor location within that cluster (red stars). The sensor location is used to estimate the hydrogen contents in all other nodes in the cluster, and this estimate is compared against the known simulated values. If the error in this comparison exceeds the define error limit, the cluster is further subdivided into two more clusters, and the error comparison is performed again. This process is repeated until every cluster contains a sensor that can estimate hydrogen contents for all other nodes to within the pre-defined error.

To summarize, the developed sensor placement workflow consists of the following steps, which assumes the relevant simulation results have already been generated:

1. The maximum estimation error for the gas quality (i.e. hydrogen percentage) is defined.
2. Using the Euclidean distance, the similarities between all simulated node profiles (as schematically depicted in Figure 36 are calculated.
3. Based on the similarities of the previous step, the nodes are divided into two clusters.
4. Per cluster, the following steps are performed:
    a. The node which is on average the most similar to all other nodes in the cluster is identified as a potential sensor location.

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   b. The profile of the sensor candidate is compared to all other nodes in the cluster for each individual timestep.
   c. Based on the above comparison, the worst-case single-timestep estimation error is determined.
   d. This maximum error is compared against the error limit set in Step 1. If it is within the allowed limit, the sensor candidate is added to the final list of sensors. If it is not within the limit, Steps 3-4 are repeated for the cluster in question.
5. Once the recurrent process of Steps 3-4 has been completed and all nodes within the network can be estimate to within the limit from Step 1, the process is ended, and the found sensor locations are returned.

4.3 Results and discussion

The sensor placement method described in the previous section was tested and demonstrated on a case study of a real-world gas network of the Riccione area in Italy; previously described in Section 3.4.1. Currently, no hydrogen is injected in the Riccione grid. For the purpose of this study, hydrogen injection is artificially introduced in the simulations. Using TNO’s internal gas network simulation software AURORA, a week of gas flow through the Riccione network (Figure 22) was simulated. To emulate hydrogen admixing into the network, one of the gas injection points of the network (at Secondary Entry or node 241) had its composition changed such that 2% of its total gas composition was hydrogen. The other injection point (at Primary Entry or node 240) had a composition that was fully natural gas. To create the gas flow profiles as schematically shown in Figure 37, the Riccione grid was simulated for a total of 8 days, with the first day being included to allow the transients in the network to settle. The simulation was performed for a period corresponding to winter demands in early January (more specifically from 2-10 January). Standard consumption profiles for the period of the year were used to simulate the gas demand at regular and small gas consumers in the network. For privacy and regulation concerns, consumers were combined into consumer groups of around 20 households per group. As such, 463 of such 'consumers' were simulated in the current work. In the remainder of this text, the word 'consumer' is used to refer to such consumer groups. Figure 40 shows the simulated hydrogen fraction at all these consumers in the Riccione network. When performing the clustering on these profiles, the first 24 hours are ignored to remove the effect of the start-up behaviour during which the flows have not yet stabilised throughout the network.

Sensors were allowed to be placed in all consumer nodes of the network. In theory, optimal placement of sensors should allow for all points (nodes) in a network to be considered during the placement process. However, in reality it will be practically and economically infeasible to place a sensor at any point in the network. Moreover, operators typically prefer to place sensors only within pressure reduction stations, where they are more easily reachable. However, since gas stream mixing primarily occurs in the low-pressure 40 mbarg grid, this latter restriction severely limits the gas quality sensing capability. Therefore, the option of only allowing sensors to be placed in consumer nodes was chosen as a middle-ground between practicality of placement and accuracy of the sensing capacity.

In total, two different sensor placement scenarios were evaluated: one in which the total allowed maximum error between sensor node and (simulated) true values in the network in absolute terms was 1% hydrogen content, and one scenario in which this limit was 0.5%.

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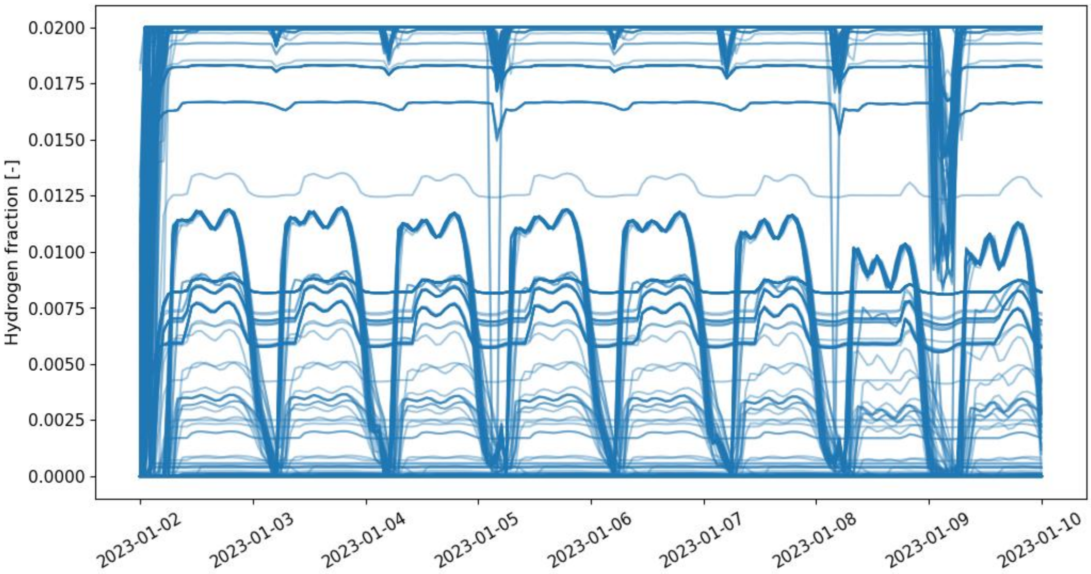

Figure 40 Simulated hydrogen gas fraction at the consumers in the Riccione network used to demonstrate the sensor placement method.

4.3.1 1% error bandwidth scenario

Figure 41 shows the simulated time-series profiles from Figure 40 separated into the clusters created by the recurrent clustering-based sensor placement method described in the previous section for the 1% error bandwidth scenario. In addition, Figure 42 shows a bar chart plotting the number of consumers in each cluster. As can be seen, the algorithm finds that with only 8 sensors (and thus 8 clusters) the hydrogen contents in all 463 consumers can be known to within an absolute value of 1% based on what is measured at each sensor. Of course, this is significantly less than the alternative in which a sensor needs to be placed at each individual consumer.

Looking at the detailed clusters shown in Figure 40, it can be seen that in general the algorithm places the sensor in a consumer whose time-series profile lies somewhere in the middle of all other profiles in the cluster (especially for "cluster_5"). However, when the majority of the profiles in a cluster show the same profile with only a few profiles showing deviating behaviour, as is the case for "cluster_4" (the cluster contains 125 consumers, but only ~20-30 show hydrogen contents that are non-zero), the algorithm places the sensor in one of the consumers that show the more dominant type of profile within the cluster. As the sensor is placed in the consumer that is on average the most similar to all others, this is in line with the expected behaviour of the algorithm.

Figure 42 shows clearly that not every cluster contains the same number of consumers. From the fourth cluster onwards, the number of consumers in a cluster decreases rapidly. As such, not every sensor contributes equally to improving the robustness of gas quality sensing in the system. While one sensor can stand in for nearly 200 consumers, another only covers 2 consumers. This has to do with the error restriction chosen, as well as the lay-out of the network, location of the consumers and gas injection points, and many other factors. In the end, outliers in hydrogen content profiles such as those seen for "cluster_2" will always show up, so it will be impossible to prevent the type of trends seen in Figure 42 from happening. At the same time, these results do provide insights into how "important" each sensor is, which an operator can use to decide whether it is worth it to put in an additional sensor to cover two additional consumers, or whether they are willing to take a risk if it means saving on investments needed for this extra sensor.

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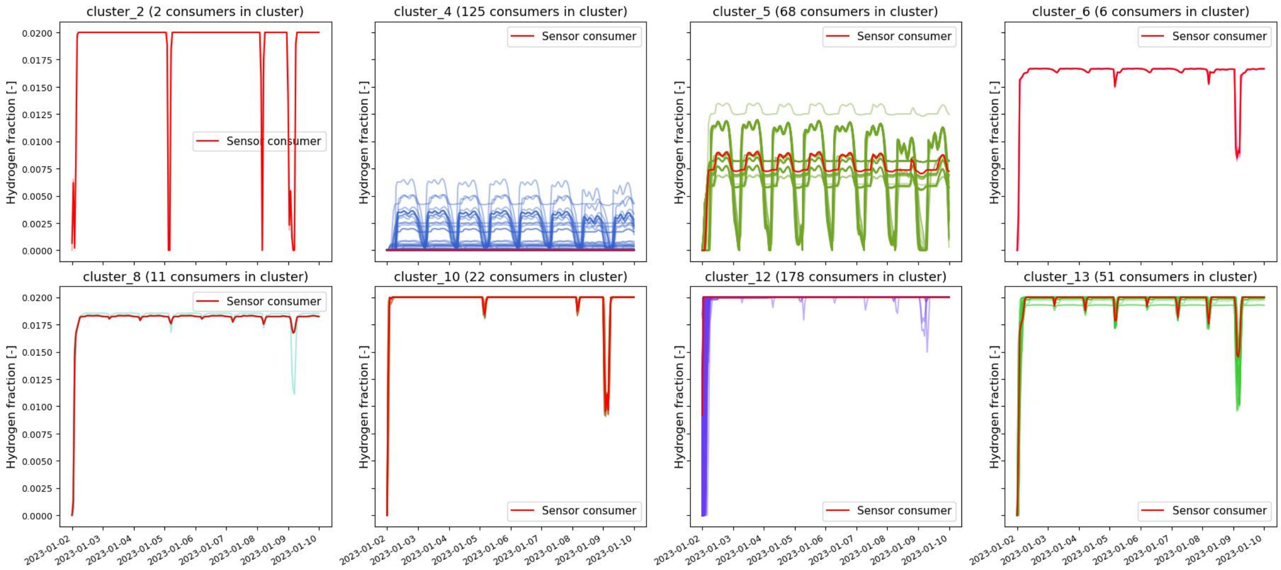

Figure 41 Simulated hydrogen content profiles as clustered using the recurrent clustering algorithm to ensure the sensor node in each cluster can estimate the hydrogen contents in all other consumers in the cluster to within an absolute value bandwidth of 1%. The profile in which the algorithm places the sensor is indicated in red. The first 24 hours of the profiles is disregarded in the comparisons to remove the effect of transient start up behaviour. Cluster names are generated automatically by the algorithm and have no specific meaning.

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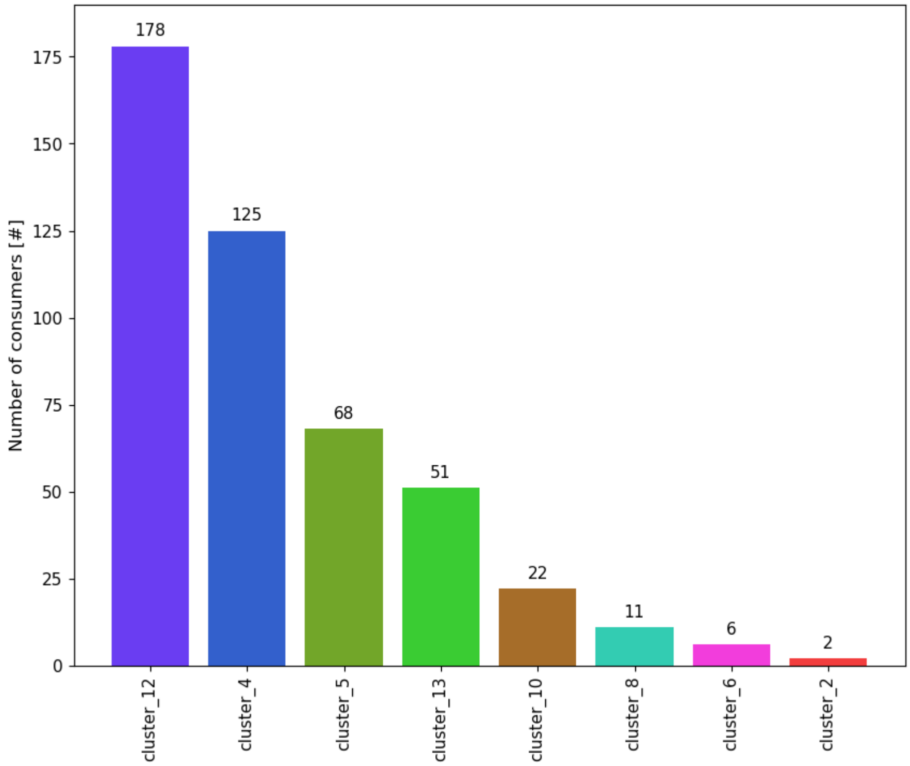

Figure 42 Bar chart showing the number of consumers in each cluster found by the recurrent clustering algorithm to ensure the sensor node in each cluster can estimate the hydrogen contents in all other consumers in the cluster to within an absolute value bandwidth of 1%. Cluster names are generated automatically by the algorithm and have no specific meaning.

Figure 43 shows a plot of the Riccione grid with the consumer nodes in the network coloured based on the clusters found by the sensor placement algorithm. In addition, the sensor for each cluster is indicated by a star. Looking at the clusters (as well as Figure 41) and taking into account the locations of the two injection suppliers (gas injection points), the grid can be divided into three high-level regions:

- A region of consumers receiving mostly 2% hydrogen. This corresponds to the purple nodes on bottom-left side of the grid.
- A region of consumers receiving mostly pure natural gas. This corresponds to the blue nodes on the right of the grid.
- A transition region in which consumers get varying levels of hydrogen content based on the time of day and day of the week (due to temporal consumption behaviour). This includes all other clusters, but is most clearly seen in the dark green nodes.

These regions are also in line with what has previously been seen qualitatively in simulations of the Riccione grid (Section 3.4.1.4). Together with the information presented in Figure 42, these high-level geographic regions identified can be used as insights by an operator to decide on potentially merging some of the smaller clusters to further reduce the number of sensors required at the cost of lessening the certainty of their sensing capabilities.

Another interesting fact that can be seen from Figure 43 is that the dark and light green clusters are both geographically separated, having part of their cluster in one location of the grid, while another part is in a different location. This is due to the fact that at the moment the clustering algorithm works purely by comparing

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the simulated time-series as plotted in Figure 40 and does not take the spatial location of a consumer into account. As a result, it is possible for geographically separated consumers that show similar hydrogen contents over time to be assigned to the same cluster. While these consumers are mathematically similar, in a practical setting it might not be ideal to consider them as such as potential geographical changes (e.g. temporary flow diversion for maintenance) could affect the translation of sensor measurements to other cluster nodes. Therefore, future iterations of the sensor placement method should look into incorporating not only the time-series similarity, but also spatial similarity into the clustering method.

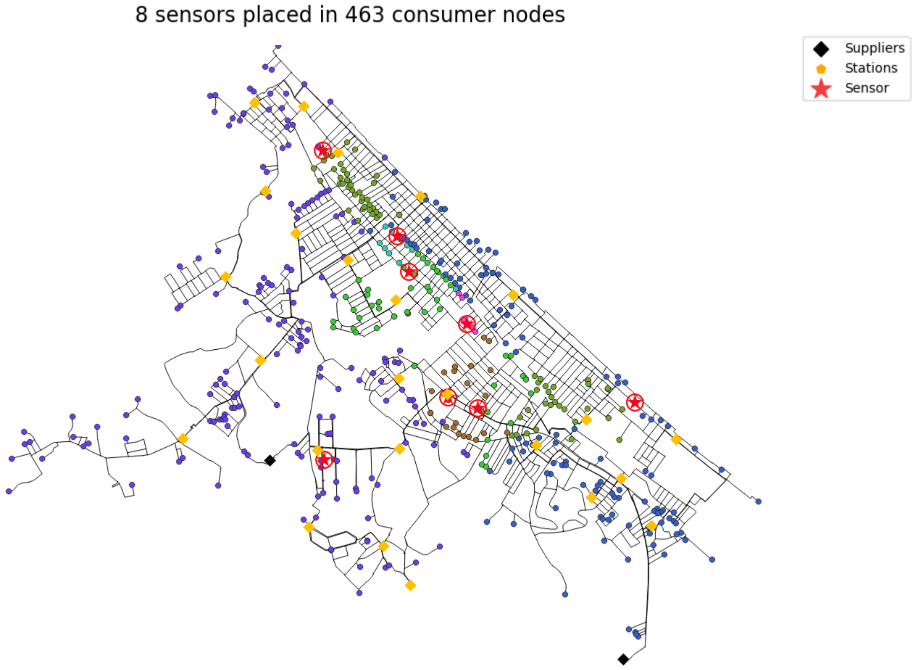

Figure 43 The Riccione network including the sensor locations and consumer clusters determined by the recurrent clustering algorithm to ensure the sensor node in each cluster can estimate the hydrogen contents in all other consumers in the cluster to within an absolute value bandwidth of 1%.

4.3.2 0.5% error bandwidth scenario

Figure 44 shows the simulated time-series profiles from Figure 40 separated into the clusters created by the recurrent clustering-based sensor placement method described in the previous section for the 0.5% error bandwidth scenario. Due to the higher number of clusters (20), profiles were plotted all in the same plot to prevent it from getting too cluttered. For the same reason the sensor profiles were also not highlighted in red anymore. Figure 45 shows a bar chart plotting the number of consumers in each cluster. As can be seen, the algorithm now finds that with 20 sensors the hydrogen contents in all 463 consumers can be known to within an absolute value of 0.5% based on what is measured at each sensor. Compared to the 1% error bandwidth, this is an increase of more than twice the number of sensors needed. As can be seen from the bar chart, this is mostly due to more edge cases appearing where the only way through which the error limit can be satisfied for certain consumers is to measure them directly. As in the previous scenario, this information can be used by an operator to decide whether or not it is worth it to place an additional sensor in the grid just to keep track of the hydrogen contents of a single consumer.

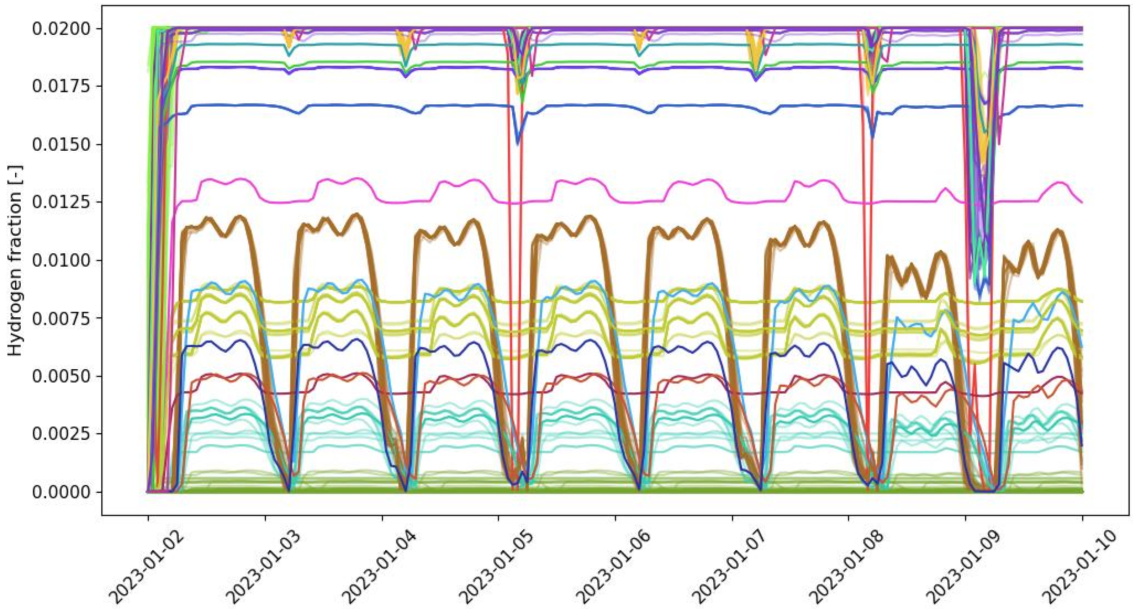

Figure 44 Simulated hydrogen content profiles as clustered using the recurrent clustering algorithm to ensure the sensor node in each cluster can estimate the hydrogen contents in all other consumers in the cluster to within an absolute value bandwidth of 0.5%. The first 24 hours of the profiles is disregarded in the comparisons to remove the effect of transient start up behavior. Due to the high number of clusters, clusters had to be plotted together in one plot and the sensor profiles were left out to prevent the plot from becoming cluttered.

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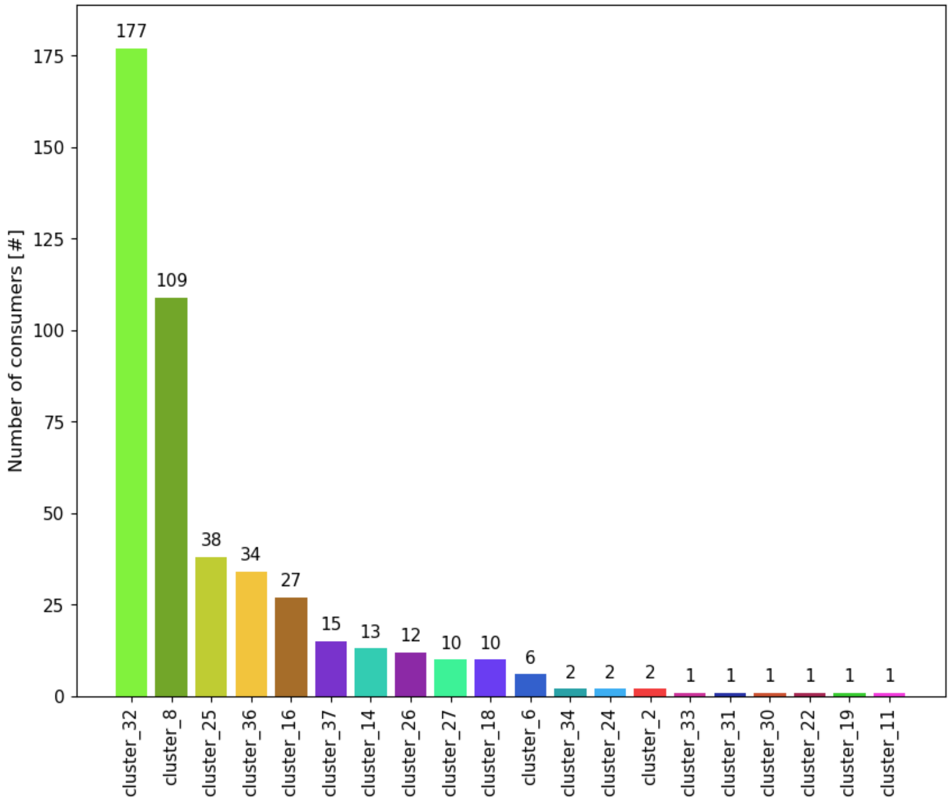

Figure 45 Bar chart showing the number of consumers in each cluster found by the recurrent clustering algorithm to ensure the sensor node in each cluster can estimate the hydrogen contents in all other consumers in the cluster to within an absolute value bandwidth of 0.5%. Cluster names are generated automatically by the algorithm and have no specific meaning.

The geographic clustering of the consumers is shown in Figure 46. When comparing these results to the 1% scenario results in Figure 43, it can be seen that the three previously identified regimes still persist. All additional sensors the method places due to the stricter error constraint come from further subdivisions of the latter transition region. This indicates that the other two regions are fairly stable, and are unlikely to need additional sensors placed within them even if the error constraint is made even stricter.

As seen in the previous scenario, there are still certain consumers that are geographically separated from the other members of their cluster.

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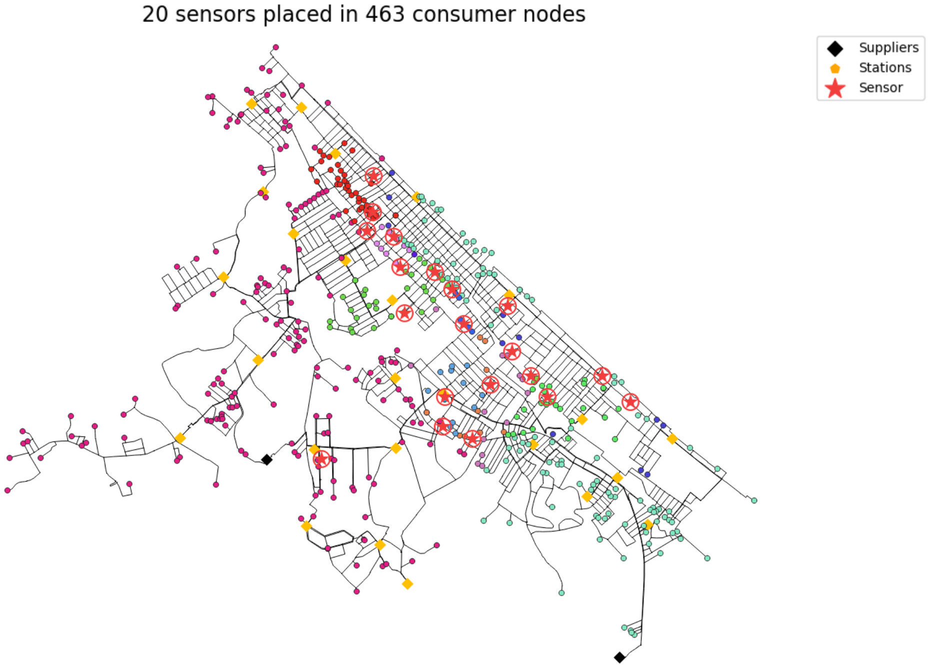

Figure 46 The Riccione network including the sensor locations and consumer clusters determined by the recurrent clustering algorithm to ensure the sensor node in each cluster can estimate the hydrogen contents in all other consumers in the cluster to within an absolute value bandwidth of 0.5%.

4.4 Findings

Based on the results presented in the previous section, it is clear that there is a major trade-off between the maximum allowed error bandwidth within which the hydrogen contents throughout the network should be known, and the number of sensors that need to be placed within it. When the error limit was made to be twice as strict, the number of sensors needed increased by more than double. While not reported in this document, when running the sensor placement algorithm for a scenario with an error limit of 0.25%, the number of sensors required increased to 35, showing that the trend roughly holds. In addition, the same trends are expected to occur when the error limit is kept constant but the percentage of admixed hydrogen is increased, as in the current problem formulation these are (inversely) equivalent.

At the same time, results also indicate that there are a large number of edge cases in which, to satisfy the strict limits, dedicated sensors are needed to keep track of the gas quality in only one consumer or clusters of only a few consumers. This hints at the fact that in some cases the provided constraint that the error limit cannot be exceeded at any point in time might be too strict, and simultaneously provides inputs to operators to make more informed decisions on the trade-off between investments needed to add additional sensors to a grid and the value of information provided back by these sensors.

To further substantiate such decision-making, future versions of the sensor placement algorithm should incorporate additional risk metrics in their results that provide insights into how often the error limit will be exceeded in case a specific sensor is removed from the network. Furthermore, the optimization goal could be updated to focus on this performance indicator instead, or to allow a certain leniency in exceeding the error limit to a pre-defined extend or duration. This will help operators make even better informed decisions on what the impact is off reducing the suggested number of sensors in the system.

From the presented results, three regions with general trends in hydrogen contents could be identified: one with stable maximum hydrogen contents, one with stable pure natural gas contents, and a transition region in

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between. When the error bandwidth was made stricter, additional sensors were primarily placed within this latter transition region. This shows that the two more stable regions see a higher effectiveness of the sensor placement, as a single sensor placed in these regions can stand in for a large number of consumers, and stricter error limits do not require placing additional sensors in these regions. At the same time, it shows that more targeted analysis of the transition region is needed to find out to what extend certain lone sensors (sensor that cover a single outlier consumer) could be removed, and what impact that would have on the total cost and robustness of the grids sensing capabilities.

It should be noted that the results presented considered a single week period in winter. As hydrogen contents typically vary more in the summer period due to the overall lower flowrates (in which daily consumption patterns dominate more), it is expected that overall more sensors would be needed. Additional research would be needed into these cases, as well as into methods for finding optimal sensor locations that are applicable to both winter and summer periods. In addition, the simulated period included a window of time at the start in which transient changes occurred whilst the admixed hydrogen got injected into the grid. For the purpose of the sensor placement, this period (of roughly 24 hours) was not included in the comparison between consumer profiles. This was done to ensure the found set of optimal sensors was most relevant to regular operation of the network. As this sort of transient behavior is expected to rarely take place, it was considered best to disregard it during the analysis and not have the placement of the sensors be impacted by such atypical trends.

In addition, the current method estimates the values of all nodes within a cluster through the value of the sensor node within that cluster. I.e. it aims to find one consumer in each cluster that serves as the optimal “representation” for all other consumers of the cluster. Currently, this estimate is done by simply assuming the hydrogen contents of all consumers in a cluster are the same as those measured at the sensor node. While the results shown in this report show that this works decently well, it remains a rather simplified approach that likely leads to an overall higher number of sensors needed per grid than a more sophisticated method might. By employing a more complex estimation method (based on grid-geometry-based interpolation, physical modelling, or data-driven approaches), it might be possible to more accurately estimate the hydrogen content in a node using the measured values at the sensor. By improving these estimates, it might be possible to satisfy the error constraint in larger clusters, requiring fewer additional subdivisions and therefore fewer sensors in total.

Finally, the results showed that some of the clusters identified using the hydrogen content profile clustering approach contained members that were geographically separated from each other. While this may be mathematically valid, in practice this might lead to unreasonable clusters. Thus, in the future the clustering method should be updated to take both the profile similarity as well a spatial similarity into account for more geographically consistent clustering results.

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5 Conclusions

This chapter presents general recommendations and conclusions on operational control strategies for hydrogen injection and optimal sensor placement.

5.1 General recommendation on operational control strategies for hydrogen integration in TSO networks

This section provides a set of technical and operational guidelines for the integration of hydrogen into high-pressure gas transmission systems (TSO level), based on the analysis of representative use cases in Sicily (Italy) and the Ebro Valley (Spain). The guidelines are derived from detailed fluid-dynamics simulations under both steady-state and transient conditions, incorporating hydrogen blending, infrastructure repurposing, and distributed injection from renewable energy sources.

The objective is to support policymakers, regulators, standardization bodies and transmission system operators (TSOs) in defining robust strategies for hydrogen deployment, while ensuring network integrity, operational reliability, and compliance with gas-quality standards.

5.1.1 Hydrogen transport pathways and strategic positioning

Hydrogen integration in existing transmission systems can follow two main pathways: (i) blending into the natural gas stream and (ii) the development of dedicated hydrogen transport infrastructure through pipeline repurposing.

The analysis confirms that hydrogen blending can be considered a technically feasible and effective transitional solution, particularly in early deployment phases. However, its scalability is inherently limited due to hydraulic penalties, non-selective downstream delivery, and increasing operational constraints at higher blending ratios. As hydrogen concentration increases, volumetric flow requirements rise accordingly, leading to elevated gas velocities, pressure losses, and compressor energy demand. Nevertheless, this does not necessarily mean a constrain in the network operation for any transmission network section. It will rather depend on specific operational conditions of each part of the gas infrastructure.

In contrast, infrastructure repurposing enables the establishment of dedicated hydrogen corridors, supporting significantly higher transport capacities. This solution is more suitable for long-term, large-scale hydrogen deployment but may requires the reallocation of existing natural gas pipelines capacity if natural gas consumption will not be sufficiently reduced as a consequence of the energy transition. As the network operators' priority is the security of supply, this option may be limited by the necessity of assuring enough natural gas capacity to final customers. Only if spare capacity is available (i.e. parallel pipelines) or capacity reallocation/natural gas re-routing is feasible this option will be considered.

Consequently, hydrogen transport strategies should be framed within a system-level perspective, where blending is positioned as a short-term enabler and pipeline repurposing or new infrastructure as the long-term solution. What is more, scenarios on natural gas consumption, on its supply and on its expected routing should be considered alongside hydrogen take-up scenarios, to jointly manage infrastructural planning on both energy vectors: natural gas and hydrogen.

5.1.2 Hydraulic constraints and operational limits

Hydrogen integration has a direct impact on network hydraulics and operational performance. The introduction of hydrogen into natural gas systems leads to an increase in volumetric flow for the same energy delivery, due to its lower calorific value.

This effect results in:

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- Increased gas velocity, potentially exceeding conventional thresholds for transmission systems;
- Higher frictional pressure losses along pipelines;
- Increased compressor duty and power consumption.

Simulation results indicate that hydrogen blending at moderate levels (e.g. 20% by volume) may push flow velocities beyond typical operational ranges and significantly increase recompression requirements if natural gas system is running at full/near design capacity. These effects can impose constraints on the allowable blending ratio, independent of downstream gas-quality compliance.

Therefore, hydrogen blending limits should not be defined solely based on end-user tolerances, but must also consider network operability, including pressure margins, velocity constraints, and compressor capacity. This requires the integration of hydraulic analysis into gas-quality governance frameworks.

5.1.3 Pipeline repurposing and asset qualification

The feasibility and efficiency of pipeline repurposing for hydrogen transport depend primarily on the ability to maintain acceptable operating pressure without compromising material integrity.

Two alternative approaches are typically considered:

- Conservative pressure derating, based on standard reduction factors;
- Performance-based qualification, allowing full operating pressure if material integrity is demonstrated.

The analysis shows that conservative derating significantly reduces transport performance, while performance-based qualification preserves hydraulic efficiency and minimizes the need for additional compression.

Accordingly, pipeline repurposing strategies should prioritize asset-specific qualification procedures, including verification of:

- Material compatibility with hydrogen,
- Weld integrity and fracture resistance,
- Fatigue behaviour under cyclic loading.

These procedures should be aligned with established technical standards (e.g. ASME B31.12) and emerging European frameworks (e.g. EN 1594, EN 17649), ensuring a harmonized approach to hydrogen readiness across transmission systems. It is worth to say that these have been and is being investigated by EU HORIZON projects like HIGGS, CANDHY or PilgrHYm or National ones (i.e., SyWestH2 in Germany).

5.1.4 System adequacy and capacity reallocation

Repurposing existing gas infrastructure introduces a fundamental trade-off between hydrogen transport capacity and natural gas transmission capability. The conversion of pipeline sections to hydrogen service reduces the throughput and flexibility of the remaining gas network.

Simulation results indicate that partial repurposing can lead to a substantial reduction in natural gas transfer capacity, while the overall energy transport capability of the system may remain approximately balanced due to the additional hydrogen transport capacity.

However, the resulting configuration of the residual natural gas network requires careful assessment of operational conditions, including pressure management, compression requirements and available supply flexibility.

For this reason, hydrogen infrastructure planning should include a dual adequacy assessment, simultaneously evaluating: Hydrogen transport requirements, and Residual natural gas network performance and capacity adequacy.

Such assessments should consider the interaction between hydrogen infrastructure development and the evolution of the remaining natural gas system, ensuring that infrastructure choices are evaluated within an integrated energy-system planning framework.

5.1.5 Dynamic gas quality behaviour and network topology effects

A key insight from the simulations is that hydrogen propagation in transmission networks is inherently dynamic and topology-dependent. Hydrogen concentration does not propagate as a uniform front but is strongly influenced by network configuration, including:

- Parallel pipelines,
- Mixing nodes,
- Compression stations,
- Variable flow ratios and directions.

These features cause delays, dilution, and reshaping of hydrogen concentration profiles along the network. As a result, different locations may experience different hydrogen concentrations over time, especially at the start-up of constant blending injection (when the infrastructure needs to filled up with the new composition thus gas with different quality coexists) or when the upstream blending ratio undergoes small variations.

This finding implies that compliance with a fixed hydrogen concentration at the injection point is not sufficient to ensure the same gas-quality throughout the network. Instead, operators should rely on time- and location-dependent gas-quality assessment.

This includes monitoring not only hydrogen concentration but also derived parameters such as the Wobbe Index and its rate of change, which are critical for downstream end-use compatibility, and calorific value, for billing purposes.

5.1.6 Distributed hydrogen injection from renewable sources

The integration of hydrogen produced from renewable energy sources introduces additional complexity, particularly when injection occurs at multiple, geographically distributed locations.

The analysis demonstrates that the resulting hydrogen concentration depends primarily on the ratio between injected hydrogen flow and local natural gas throughput. Consequently, identical injection rates can produce significantly different outcomes depending on the location within the network.

Injection into high-flow transmission corridors typically results in low hydrogen concentrations due to effective dilution, making this configuration suitable for sector coupling and renewable energy integration. In contrast, injection into low-flow or peripheral network sections can lead to high and rapidly varying hydrogen concentrations, potentially exceeding acceptable limits.

Therefore, hydrogen injection should be treated as a location-specific service, requiring local assessment of injection capacity, gas flow conditions, and downstream constraints. In many cases, direct injection must be complemented by additional measures such as buffer storage on the production site, controlled blending, or coordinated production schedules.

5.1.7 Coordination of multiple injection points

When multiple hydrogen injection points are present, their operation becomes interdependent due to network propagation effects. Hydrogen injected upstream influences the gas composition at downstream locations, reducing the available blending margin over time.

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These interactions are dynamic and influenced by transport delays, flow conditions, and the temporal variability of renewable hydrogen production. As a result, downstream injection capacity cannot be defined independently of upstream activity.

This necessitates the implementation of coordinated injection strategies, including:

- Allocation of blending capacity,
- Priority rules among producers,
- Curtailment mechanisms under constrained conditions.

From an operational perspective, TSOs must rely on integrated tools combining forecasting, real-time monitoring, and dynamic simulation to manage these interactions effectively.

5.1.8 Dynamic gas quality compliance and Wobbe Index variability

The introduction of variable hydrogen injection highlights the limitations of static gas-quality specifications. While the Wobbe Index may remain within acceptable limits under many scenarios, its rate of change can become a critical constraint for downstream users.

Rapid variations in gas quality may affect combustion systems, industrial processes, and sensitive equipment, even when absolute values remain within standard ranges.

The findings indicate that gas-quality regulation should be extended to include dynamic indicators, particularly the rate of change of key parameters such as the Wobbe Index. On the one hand, this requires the adoption of transient simulation tools and continuous monitoring systems to assess compliance under real operating conditions. On the other, constraints on Wobbe Index variability (and, consequently, hydrogen injection rate and its variation) defined either by a common technical standard or by TSO/DSOs depending on the case-specific knowledge of their infrastructure, may entitle TSO/DSO to define hydrogen injection protocols (connection and injection rules and conditions) which would specify how the hydrogen injection should be managed, clarifying possible curtailment strategies if the injection rate is out of specification. This would be relevant for the injection and/or blending station design, as connection/injection rules may infer possible design strategies on the injection or blending unit to be equipped with control systems that helps to maintain the hydrogen injection within the specifications.

5.1.9 Operational role of Underground Gas Storage and flow reversals

The analysis of the Ebro Valley case study highlights the importance of underground gas storage (UGS) facilities in managing hydrogen integration.

UGS can act as a controllable source of natural gas, enabling the dilution of hydrogen-rich mixtures and helping maintain compliance with blending limits, if operationally feasible (i.e. in summer UGS are injecting gas and in winter extracting). In addition, storage facilities provide operational flexibility to accommodate variable hydrogen production from electrolyzers.

However, transmission networks with bidirectional flow conditions introduce additional risks, including hydrogen accumulation during flow reversals. Under such conditions, hydrogen may persist in the network, leading to elevated baseline concentrations and complicating injection control.

To address these challenges, injection strategies must incorporate both flow measurements and gas composition monitoring, ensuring accurate assessment of local conditions prior to hydrogen injection.

5.1.10 Concluding remarks

The guidelines developed in this section emphasize that hydrogen integration in transmission networks is not solely a matter of defining admissible blending limits. Instead, it requires a comprehensive approach that

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integrates hydraulic performance, dynamic gas-quality behaviour, infrastructure capability, and system-level planning.

Key enabling elements include:

- Advanced transient modelling tools,
- Dynamic monitoring of gas composition and flow conditions,
- Coordinated operational frameworks among multiple stakeholders,
- Harmonized technical standards and regulatory approaches.

These elements are essential to ensure that hydrogen can be safely and efficiently integrated into transmission systems while supporting the broader objectives of energy system decarbonisation and sector integration.

5.2 General recommendation on operational control strategies for hydrogen integration in DSO networks

This section provides technical and operational guidelines for hydrogen integration in gas distribution networks (DSO level), based on the analysis of two representative use cases: the urban distribution network of Riccione (Italy) and the coupled transmission–distribution system of Palma de Mallorca (Spain).

The Riccione case represents a typical urban multi-entry distribution network with pressure-regulated supply points, enabling the assessment of the effect of inlet pressure control on hydrogen distribution. The Palma case extends the analysis to a more complex system, where hydrogen is introduced upstream in the transmission grid and propagates through a distribution network characterized by multiple city gates, meshed topology, and seasonal demand variability.

The guidelines aim to support DSOs, regulators, and policymakers in defining hydrogen blending strategies that ensure safe operation, gas-quality compliance, and equitable service delivery to end users.

5.2.1 Role of pressure regulation as a gas-quality control mechanism

The Riccione use case demonstrates that, in multi-entry distribution networks, pressure set points at entry stations act as primary gas-quality control variables. The hydraulic balance between entry points determines the relative contribution of each gas source, and consequently the spatial distribution of hydrogen within the network.

When hydrogen is injected as a premixed stream at one entry point and natural gas is supplied from another, the resulting hydrogen-affected area is not fixed. Instead, it depends on the pressure-driven flow distribution between the inlets. Adjusting the pressure setpoints modifies the contribution of each inlet to the total supply, which in turn reshapes the regions of the network exposed to hydrogen.

As observed in the Riccione simulations, reducing the pressure of the hydrogen-blended inlet while increasing the pressure of the natural-gas inlet leads to a significant reduction of the hydrogen-influenced area and alters the concentration levels across the network. Even when a constant hydrogen blend (e.g. 20 vol%) is injected, downstream nodes may experience a wide range of concentrations due to in-network mixing.

This behaviour establishes that, in DSO networks, gas quality is not directly controlled at the point of injection but emerges as a result of hydraulic equilibrium. Therefore, pressure regulation must be explicitly treated as part of hydrogen blending control strategies.

5.2.2 Gas-quality zoning and implications for end users

The redistribution of flows induced by pressure regulation leads to the formation of gas-quality zones within the distribution network. Different parts of the network may receive:

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- The nominal hydrogen blend,
- Diluted mixtures due to mixing,
- Or pure natural gas in regions dominated by non-hydrogen supply.

As a result, final pressure reduction stations and directly connected users may experience different hydrogen concentrations under the same injection conditions. This phenomenon is particularly relevant in urban networks where multiple entry points interact within a confined topology.

The Riccione case further highlights the presence of intermediate concentration zones, arising from in-network mixing between hydrogen-enriched and natural-gas streams. These zones may exhibit spatially heterogeneous gas compositions even under steady-state conditions.

Additionally, the occurrence of specific hydraulic features such as zero flow points, where flow stagnation or reversal occurs, may lead to increased sensitivity in gas-quality variation. These locations are potentially critical with respect to the rate of change of gas-quality parameters and require particular attention in operational planning.

Consequently, hydrogen blending at the distribution level cannot be assessed solely through compliance at the injection point. It requires a network-wide evaluation of gas quality, considering both spatial distribution and local hydraulic conditions.

5.2.3 Interaction between transmission and distribution systems

The Palma use case highlights the importance of the TSO–DSO interface in hydrogen integration scenarios. Hydrogen is introduced upstream in the transmission system and enters the distribution network through multiple city gates.

In this configuration, hydrogen propagation within the DSO network depends on:

- The location and composition of upstream supply,
- The boundary conditions at each city gate,
- The interaction between multiple entry points.

The presence of several interface points enables hydrogen to enter the distribution system at different locations simultaneously, creating complex mixing behaviour and non-uniform concentration fields across the network.

This demonstrates that hydrogen management in distribution systems must consider not only internal DSO operation, but also the upstream transmission conditions and the coordination between TSO and DSO operators.

5.2.4 Time-dependent hydrogen propagation and system response

The Palma simulations show that hydrogen blending in DSO networks is inherently time-dependent, especially under transient conditions. When hydrogen is introduced into the network, a delay occurs between the change in gas composition at the supply point and its arrival at downstream consumers.

This delay is influenced by:

- Low gas velocities, particularly in distribution systems,
- Long transport distances,
- Meshed network topology, which introduces multiple flow paths and mixing effects.

Under winter conditions with higher demand and higher flow rates, hydrogen propagation occurs relatively faster. However, under summer conditions, characterized by significantly lower demand, transport delays increase substantially and may extend over several weeks.

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As a result, different parts of the network may experience different gas compositions during extended transition periods. This leads to temporal and spatial variability in gas quality, even when the injected mixture is constant.

Therefore, hydrogen blending assessment in DSO networks must include transient analysis, rather than relying solely on steady-state evaluations.

5.2.5 Gas-quality behaviour under multi-supply operation

When multiple supply locations operate simultaneously, each delivering gas with different compositions, the distribution network does not converge to a uniform gas quality. Instead, it evolves towards a quasi-steady state characterized by spatially non-uniform hydrogen concentrations.

The Palma case shows that:

- Gas composition at exit points gradually transitions toward intermediate values,
- The system stabilizes over a prolonged period (several weeks in low-demand conditions),
- Different locations within the network may stabilize at different hydrogen concentration levels.

This behaviour is driven by the continuous mixing of multiple supply streams and by the competition between different flow paths within the network.

Therefore, under multi-supply conditions, hydrogen blending must be treated as a distributed mixing process, where local gas quality depends on both supply configuration and network topology. Uniformity of gas composition cannot be assumed, even after the system reaches a steady operational state.

5.2.6 Implications for consumer impact and gas-quality equity

The non-uniform distribution of hydrogen within the DSO network has direct implications for end users. In particular, different consumers may receive gas with varying hydrogen concentrations, leading to differences in energy content.

Since hydrogen blending reduces the volumetric energy content of the gas, consumers receiving gas with higher hydrogen fractions require a larger volume to obtain the same energy. If billing is based on volume rather than energy, this may lead to inequitable costs among consumers.

The Palma simulations indicate that such disparities can persist during extended transition periods and under steady multi-supply operation. This highlights the need for distribution-level hydrogen integration strategies to consider not only technical feasibility but also fairness in energy delivery.

5.2.7 Operational control through city gate pressure management

Both use cases highlight that pressure regulation at entry points and city gates provides an effective operational lever for controlling hydrogen distribution within DSO networks.

By adjusting the pressure setpoint at a given entry point or city gate:

- The flow contribution of that entry point can be increased or decreased,
- The spatial distribution of hydrogen can be redirected,
- Hydrogen exposure in specific areas can be limited or expanded.

This control mechanism enables DSOs to manage hydrogen propagation dynamically, for example by:

- Limiting hydrogen penetration into sensitive areas (e.g. industrial users),
- Stabilizing gas-quality zones within acceptable limits,
- Balancing competing supply sources.

However, due to the hydraulic coupling of the network, changes in one location affect the entire system. Pressure adjustments may propagate through the network and alter flow distribution at other entry points. As a consequence, pressure-based control strategies must be evaluated at the system level to avoid unintended effects, such as increased hydrogen concentration in other areas.

5.2.8 Monitoring and analysis requirements

The findings from both use cases demonstrate that reliable hydrogen integration at the distribution level requires combined hydraulic and gas-quality assessment supported by monitoring and modelling tools.

In particular, DSOs should implement:

- Gas-quality tracking at strategic locations, including entry points and final reduction stations,
- Monitoring of flow and pressure conditions to capture hydraulic behaviour,
- Modelling tools capable of simulating gas composition evolution under transient and multi-supply conditions.

Such capabilities are necessary to assess the real distribution of hydrogen within the network and to ensure compliance with gas-quality requirements throughout all network zones.

5.2.9 Concluding remarks

Hydrogen blending in DSO networks is governed by a combination of hydraulic control, network topology, and time-dependent behaviour. The Riccione and Palma use cases jointly demonstrate that hydrogen distribution cannot be described by a simple input concentration at entry points, but emerges from complex interactions within the network.

Effective hydrogen integration in distribution systems therefore requires:

- The explicit use of pressure regulation as a gas-quality control mechanism,
- Consideration of spatial and temporal variability in gas composition,
- Coordination between transmission and distribution system operation,
- Monitoring and modelling frameworks to support dynamic gas-quality assessment,
- Attention to consumer-level impacts, including fairness and energy delivery equivalence.

These elements should be incorporated into future regulatory frameworks and operational guidelines for hydrogen deployment in distribution networks.

5.3 General recommendation on gas quality sensor placement

The integration of renewable gases, such as hydrogen and biogases, into natural gas systems introduces significant challenges for monitoring gas quality across transmission and distribution networks. In particular, hydrogen blending leads to spatial and temporal variations in gas composition due to mixing processes, multiple injection points, and dynamic consumption behaviour. As a result, accurately determining gas quality throughout the network becomes essential for regulatory compliance, operational safety, and fair billing practices.

However, the deployment of gas-quality measurement devices is constrained by economic considerations, as such sensors are typically costly. This creates an inherent trade-off between the extent of monitoring coverage and the economic feasibility of sensor installation. Consequently, optimal sensor placement must aim to identify the minimum number of sensors and their locations required to ensure that gas quality throughout the network can be estimated within a predefined accuracy threshold.

Within the scope of this work, the primary objective of sensor placement is to guarantee that hydrogen concentrations at all relevant points in the network remain within specified legal or technical limits. This

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objective differs from full state reconstruction of gas quality, as it prioritizes compliance verification over exact measurement at every point. Exact measurement is only needed for billing purposes.

5.3.1 Challenges of gas-quality monitoring in hydrogen-integrated networks

Hydrogen injection introduces a multi-dimensional monitoring problem, as gas composition evolves dynamically within the network. Even when the hydrogen fraction is known at injection points, downstream concentrations depend on:

- Mixing between different gas streams,
- Network topology and flow paths,
- Temporal variations in demand,
- Uncertainties in network characteristics and consumer behaviour.

These factors make it difficult to predict gas-quality evolution in real time without direct measurement. In particular, nodes located in mixing regions exhibit higher variability and are more difficult to estimate accurately.

As a consequence, a monitoring strategy based solely on injection-point measurements is insufficient. Instead, distributed sensing combined with modelling is required to capture the dynamic behaviour of hydrogen within the network.

5.3.2 Trade-off between accuracy and number of sensors

A fundamental outcome of the methodology is the identification of a strong trade-off between estimation accuracy and the number of required sensors.

Simulation results show that:

- Relaxed error thresholds (e.g. ±1% hydrogen concentration) allow a relatively small number of sensors to cover a large network.
- Stricter error thresholds (e.g. ±0.5% or ±0.25%) significantly increase the number of sensors required, often in a non-linear manner.

This behaviour arises because:

- Tighter accuracy constraints reduce the allowable cluster size (collection of customers),
- More clusters are needed to satisfy the error limits,
- A larger number of nodes cannot be represented by a single sensor.

In practice, achieving very high accuracy may require a disproportionately large number of sensors, particularly due to the presence of outlier nodes with unique gas-quality dynamics.

Therefore, the choice of error bandwidth should be treated as a design parameter, balancing monitoring accuracy against economic feasibility.

5.3.3 Identification of network regions and sensor effectiveness

The application of the methodology reveals that gas networks can often be divided into distinct regions characterized by different gas-quality behaviours. In the Riccione case study, three primary regions were identified:

- A region with relatively stable hydrogen concentration (close to injection levels),
- A region dominated by pure natural gas,
- A transition region with significant temporal variability due to mixing.

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Sensors placed in stable regions are highly effective, as a single sensor can represent a large number of nodes with minimal error. In contrast, the transition region requires a higher density of sensors due to greater variability and sensitivity to operating conditions.

This observation indicates that sensor placement should be adapted to the spatial distribution of gas-quality variability, rather than uniformly distributed across the network.

5.3.4 Practical considerations for sensor placement

While the clustering-based approach provides an optimal solution from a modelling perspective, practical constraints must also be considered.

In real networks:

- Sensors cannot always be placed at arbitrary nodes due to accessibility and installation constraints,
- Operators often prefer locations such as pressure-reduction stations,
- However, restricting sensor placement too strongly may reduce the ability to capture mixing phenomena, particularly in low-pressure networks where gas-quality variability is highest.

Therefore, sensor placement strategies should strike a balance between:

- Practical feasibility of installation,
- Representativeness of selected measurement points,
- Coverage of critical mixing zones.

Additionally, the results show that some clusters may include nodes that are geographically distant but share similar gas-quality profiles. While mathematically valid, such groupings may not be robust in practice, as local operational changes could break these similarities. For this reason, future implementations should consider incorporating spatial proximity constraints alongside profile similarity.

5.3.5 Role of modelling and estimation methods

The current approach estimates gas quality in each cluster by directly assigning the sensor value to all nodes within the cluster. While effective, this represents a simplified estimation method.

More advanced approaches, such as:

- Physics-based interpolation,
- Network-aware estimation,
- Data-driven models,

could improve estimation accuracy within clusters and potentially reduce the number of required sensors.

Furthermore, sensor placement results are dependent on the simulated period used in the analysis. Seasonal variations, particularly lower flow conditions in summer, are expected to increase gas-quality variability and may require additional sensors. Therefore, optimal sensor placement should ideally be validated across multiple operating scenarios.

5.3.6 Concluding remarks

Optimal sensor placement in hydrogen-integrated gas networks requires a systematic approach that combines network simulation, data analysis, and clustering techniques to minimize monitoring costs while ensuring compliance with gas-quality constraints.

The key findings indicate that:

- Hydrogen distribution is highly dynamic and location-dependent, requiring distributed sensing,

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- A clustering-based approach enables significant reduction in the number of sensors,
- There is a strong trade-off between estimation accuracy and sensor deployment cost,
- Sensor placement should focus on regions with high variability, particularly mixing zones,
- Practical constraints and system robustness must be considered alongside purely optimal solutions.

Overall, the methodology provides a robust framework for designing monitoring systems capable of supporting hydrogen integration in gas distribution and transmission networks, while balancing accuracy, cost, and operational feasibility.

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6 References

[1] R. Octaviano, D. Palochis, M. Cavana, L. d. Francesco, L. Hellemo and R. A. Pedrero, "D4.1 – Report describing the defined simulated test cases, realistic-scale test case(s), and available operational models, including required datasets and data formats.," SHIMMER, 2024.

[2] M. Cavana, K. Cascavita, M. Cicuttin, F. Vicini, A. Spadavecchia, L. D. Francesco, S. Berrone and P. Leone, "D4.4 Open-source fluid-dynamic model with gas quality," SHIMMER, 2025.

[3] K. d. Meijere, "D4.7 Gas quality measurement technologies for hydrogen," SHIMMER, 2026.

[4] ASME, "B31.12 - Hydrogen Piping and Pipelines," American Society of Mechanical Engineers, New York, 2023.

[5] R. van der Linden, R. Octaviano, H. Blokland and T. Busking, "Security of Supply in Gas and Hybrid Energy Networks," *Energies,* p. 792, 2021.

[6] MASE - Ministero dell'Ambiente e della Sicurezza Energetica (Italian Ministry of Environment and Energy Security), "Rete Gas," [Online]. Available: https://www.mase.gov.it/portale/web/guest/rete-gas. [Accessed 2026].

[7] ENTSOG, "Transparency Platform," 2026. [Online]. Available: https://transparency.entsog.eu/.

[8] S.p.a., Snam Rete Gas, "Piano Decennale di Sviluppo della Rete di Trasporto del Gas Naturale 2020 - 2029 (Ten Year Gas Network Developement Plan 2020-2029)," San Donato Milanese, 2020.

[9] M. Cavana and P. Leone, "Solar hydrogen from North Africa to Europe through Greenstream: a simulation-based analysis of blending scenarios and production plant sizing," *International Journal of Hydrogen Energy,* vol. 46, no. 43, pp. 22618-22637, 2021.

[10] A. Porter, "Italy's Augusta refinery begins restart operations," Argus, 2025. [Online]. Available: https://www.argusmedia.com/en/news-and-insights/latest-market-news/2676163-italy-s-augusta-refinery-begins-restart-operation. [Accessed 2026].

[11] N.S. Energy, "Lukoil ISAB Refinery," N.S. Energy, 2021. [Online]. Available: https://www.nsenergybusiness.com/projects/lukoil-isab-refinery/?cf-view. [Accessed 2026].

[12] P. C. Lukoil, "Lukoil completes sale of ISAB Refinery in Italy," Lukoil, 2023. [Online]. Available: https://www.lukoil.com/PressCenter/Pressreleases/Pressrelease/lukoil-completes-sale-of-isab-refinery-in-italy. [Accessed 2026].

[13] R. van Rossum, J. Jens, G. La Guardia, A. Wang, L. Kuhnen and M. Overgaag, "European Hydrogen Backbone: A European Hydrogen Infrastructure vision coverin 28 countries," Guidehouse, 2022.

[14] Global Energy Monitor - GEM, "Renewables and other power," GEM, 2026. [Online]. Available: https://globalenergymonitor.org/renewables-and-other-power. [Accessed 2026].

[15] European Commission, *EU Directive 2023/2413 - Renewable Energy Directive Recast (REDIII),* 2023.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.

[16] Ministerio para la Transición Ecológica y el Reto Demográfico, "Orden TED/181/2025, de 13 de febrero, por la que se aprueban las Normas de Gestión Técnica del Sistema Gasista de competencia ministerial.," [Online]. Available: https://www.boe.es/eli/es/o/2025/02/13/ted181.

The research leading to these results has received funding from Horizon Europe, the European Union's Framework Programme for Research and Innovation under grant agreement n° 101111888.