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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

D4.1 Report describing the defined simulated test cases, realistic scale testcase(s), and available operational models including required data set and format

VERSION	DATE	TYPE	DISSEMINATION LEVEL
Version 1.0	28-August-2024	Report	Public

ABSTRACT

This report includes case studies, network data, and scenarios that will be utilized in future activities, such as network design and optimization, as well as the analysis of operational strategies for hydrogen injection into the gas grid. There are three high-pressure networks operated by TSOs in Spain, Norway, and Italy, along with two low-pressure networks managed by DSOs in Spain and Italy. In addition to these real-world networks, the report offers simplified test networks for evaluating the functionality, accuracy, performance, and robustness of the software developed in this project. The final section presents an overview of various gas network simulation tools used by TSO and DSO partners.

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Release history

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List of Abbreviations

Table 1: List of abbreviations

Term	Explanation
TSO	Transmission System Operator
DSO	Distribution System Operator
NG	Natural gas
UGS	Underground Gas Storage
CCS	Carbon Capture and Storage
CHE	Clean Hydrogen to Europe
AHH	Aukra Hydrogen Hub
ESDL	Energy System Description Language
GIS	Geographical Information System
EMX	EnergyModelsX
IDE	Integrated Development Environment
MILP	Mixed-Integer Linear Problem
SCADA	Supervisory Control and Data

Executive Summary

This deliverable is reporting the results of Task 4.1 of the SHIMMER project. This task has done several activities to support other tasks in work package 4 by providing Test Cases and Realistic Cases for optimization of network design and operational strategies for injection and flow transport management. The Test Cases will be used for testing and validation of software functionality, correctness, performance, and robustness. While the Realistic Cases will be used for analysis of several relevant hydrogen injection challenges in the gas network.

For the Test Cases, there are two example networks that will be used for simulating the gas network with admixing of hydrogen and gas composition tracking. These two networks represent both TSO (high pressure) and DSO (low pressure) gas infrastructure. Additionally, this report includes three example networks that will subsequently be used to evaluate the performance of the new features of the optimisation model.

For the Realistic Cases, there are three high pressure networks from TSOs operated in Spain, Norway and Italy and two low pressure networks from DSOs operated in Spain and Italy. Since the network currently is still used for natural gas, any hydrogen scenarios (e.g. hydrogen injection, storage, compressor, etc.) will be added based on TSO/DSO's plan or artificially added if it is not in plan.

Several available gas network models from consortium members are also presented and compared. In Task 4.2 and Task 4.3 the research partners' gas network models (from SINTEF, PoliTo and TNO) will be used and developed further. The commercial gas network models used by TSO/DSO partners will be used for verification and validation. Operational data of gas networks (pressure, flow, composition, etc.) gathered from operators also will be used to validate the tool developed in this project.

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

The current chapter is introducing the contents of the report in five parts. The background and motivation of Task 4.1 is explained as well as the added benefit of the readers which may have different professions and knowledge about the topic of gas networks. The reader is also prepared for this report by getting to know about the storyline of this report, the involvement of the study partners and other stakeholders. Finally, a connection is made with the other deliverables and the next steps for this project.

1.1 Purpose of the document

Task 4.1 contains the definition of network models and case studies and is the first task of work package 4 and contains three subtasks. In the current document the work on Task 4.1 and all its subtasks will be reported. There are three subtasks:

- 4.1.1 Test cases
- 4.1.2 Realistic cases
- 4.1.3 Operational gas network models

In the first subtask, the cases that are intended to test the capabilities of the gas network models are discussed and defined. This is preparatory work for ensuring that the available software's functionalities are tested and validated. The test cases are simplified scenarios which employ the minimum capabilities of each model which are required for the realistic cases.

The second subtask contains cases that should simulate a real scenario or a future scenario. These scenarios aim to give us insights about the design of the future gas networks. More specifically, strategies for hydrogen injection and different aspects of the gas network design will be investigated.

A third subtask is responsible for reviewing the gas network models which are available amongst the consortium partners. The available models were introduced, and the minimum requirements are explained based on the defined scenarios and example networks. Finally, the models which are selected for the purposes of the continuation of the work in work package 4, are presented.

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 H_2 blending
3) To map how contractual constrains will affect H_2 admissibility
4) To establish general guidelines on how gas quality parameters will impact H_2 admissibility
5) To establish optimal operational strategies and best practice recommendations for handling and control of H_2 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 and the injection of hydrogen. This study focuses on integrating low-carbon gases and ensuring the safe injection of hydrogen into the transmission and distribution infrastructure of European countries. The intended audience and the respective added benefit for each body includes:

- **Technical standardization bodies:** To fill knowledge gaps and provide guidance for future regulations on the integration of renewable gases.
- **Transmission and distribution gas network operators (TSOs and DSOs):** To address uncertainties about the operation of future gas networks by investigating strategies for asset management and hydrogen injection.

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- **Regulatory bodies:** To offer guidance for regulations that will harmonize gas quality, define incentives, and establish a market framework among European countries.
- **Gas technology providers:** To enhance understanding of current technology levels and provide insights into potential future product requirements and new products.
- **Investors in the renewable gas sector:** To facilitate Europe-wide investments by harmonizing the renewable gas and hydrogen sectors across Europe.

Readers of this document are expected to have existing knowledge about the transmission and distribution gas networks and understand the challenges associated with their operation. Beyond this basic knowledge, reading this report does not require detailed technical expertise. Technical terms that are referenced in the text are explained in the Background and Motivation chapter in a straightforward manner.

1.3 Structure of this document

The current document includes the results of Task 4.1. As it was already explained, the subtasks 4.1.1 Test Cases, 4.1.2 Realistic cases and 4.1.3 Gas Network Models are reported in this order in three separate chapters. The chapters about the subtasks of 4.1 comprise the main part of the report. To give more context and assist in the reading of the document, an Introduction chapter which is the current chapter and a Background and Motivation chapter precede the main part of the report. In the end of the report the work of Task 4.1 is concluded in a separate chapter. The chapters come in the following order:

1. Introduction
2. Background and Motivation
3. Test Cases
4. Realistic Cases
5. Gas Network Model
6. Conclusions
7. References

1.4 Stakeholder involvement

Stakeholders of this work package are organizations with a mutual interest in the outcome of the SHIMMER project, working collaboratively to complete its tasks. Specifically, these stakeholders include research partners and transmission and distribution (T&D) gas network operators from various European countries. A comprehensive list of these 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 Organisation 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 defined roles within the work package. The network operators contribute by providing network examples for simulations and offering their expertise to define realistic scenarios, aiming to derive valuable conclusions. The research partners are responsible for preparing case studies, simulating scenarios, analysing results, drawing conclusions, and documenting all work associated with this package. Regular meetings are held among all stakeholders to monitor project progress and ensure alignment with the project's scope and goals. Involving all stakeholders is crucial for maintaining the quality and reliability of the study's results.

The involvement of these organizations is evident throughout the project. Specifically, the research partners have prepared the current report, which includes background knowledge, methodology, scenario definitions, and research questions. The operators have supplied the necessary example networks and measurement data for simulations. The partners have worked closely together during the scenario definition and data collection processes. Additionally, for this work package, TNO from the research partners is leading the tasks.

This collaborative approach ensures that the SHIMMER project benefits from diverse expertise, ultimately contributing to a higher integration and safer hydrogen injection management in multi-gas networks.

1.5 Relationship with other deliverables

The test cases presented in this document will be used to validate the tools developed by SINTEF and PoliTO in Task 4.2 and are reported in the following deliverables:

- D4.2 Tool for infrastructure optimization (investments and capacity)
- D4.4 Open-source fluid-dynamic model with gas quality tracking released with handbook and tutorials

The realistic cases presented in this document will be used to run simulations and optimizations in Task 4.2 and Task 4.3 and will be reported in following deliverables:

- D4.3 Report documenting recommendations of mixing strategies and infrastructure needs
- 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
- D4.6 Report on parametric analysis and out-of-domain generalization of results; analysis and guidelines for smart network operation

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2 Background and Motivation

2.1 Introduction

Task 4.1 will define the general model structure (data model) of a gas network infrastructure such that all the network components (pipelines, equipment, storage facilities, processing equipment) are included. The gas network infrastructures are divided into two categories: Test Cases and Realistic Cases. Test Cases are a collection of simplified gas networks infrastructures to be used for validation of gas network model developed in Task 4.2. While Realistic Cases are gas networks infrastructures provided by TSOs and DSOs from real network as part of their infrastructure. This data model is used for both network design and detailed network simulation.

Available operational models of gas networks within the consortium will be selected and used for simulation of selected test and realistic cases with the capability of quality tracking and management of multi-gas networks. These gas network models are also used as comparison and validation of gas network models developed in Task 4.2.

2.2 Task description

Task 4.1 is divided into three subtasks as following:

Subtask 4.1.1 Test Cases: The development of the software for optimization of network design, dynamic network simulation, operational strategy testing and parametric analysis requires a set of (small) testbed models for testing and validation of software functionality, correctness, performance, and robustness. These test cases (both for TSO and DSO archetypes) are defined in this subtask and serve as a testbed throughout the project.

Subtask 4.1.2 Realistic Cases: Relevant TSO and DSO test cases include networks with the inclusion of compression stations, storage facilities and other non-pipe elements, multiple-city gates for natural gas and blends injection. Realistic cases from TSOs and DSOs will be defined to investigate strategies for H_2 injection. The selected cases consider networks that in size and realizability fits the time scales described in the challenges and will be representatives of EU relevant gas infrastructure assets. The final selection of realistic cases is defined in collaboration with stakeholders (gas network operators) in the consortium that provide gas network technical data to perform simulations to test the computational capability of the code and the correctness of the fluid-dynamic results.

At least one realistic case at transmission network level will be investigated to analyze relevant hydrogen injection challenges such as

1) sector coupling of power and gas networks with line-pack management challenge in variable supply/demand profiles;
2) hydrogen blending and transport from EU neighborhood areas (e.g., North Africa) analyzing compression behavior challenge;
3) multiple industrial users with deblending technologies at final facilities as quality assurance challenge;
4) EU-interconnection with deblending towards gas quality harmonization challenge;
5) storage system as dispatch/asset management challenge;
6) multiple gas injection in the network as smart flow/pressure control challenge.

At the distribution network level, at least one realistic scale regional network case will be considered to investigate specific challenges that involve detailed quality tracking and quality control for safety of users. The next design and control strategy challenges are investigated:

1) multiple pressure levels and multiple city-gates;
2) a complex meshed grid with multiple injections points, injection levels and supply profiles;
3) a wide range of end-users (industrial, domestic) with very specific quality demands and time varying demand profiles;

4) limited local storage facilities and limited linepack;
5) quality sensor positioning.

Subtask 4.1.3 Operational gas network models: The consortium has developed over time a series of operational models of gas networks specifically tailored to handle complexity of hydrogen injection scenarios. These models feature the transient and multicomponent fluid-dynamic description of any kind of gas network, equipped also with quality tracking features. These models will be used in Task 4.2 for infrastructure optimization and Task 4.3 to determine operational strategies of gas networks with hydrogen blending. In the framework of this task, operational gas network models will be reviewed within the consortium with the aim to identify required data set and format in supporting subtasks 4.1.1 and 4.1.2.

2.3 Methodology

The execution of Task 4.1 is in collaboration between SHIMMER work package 4 research partners and TSO/DSO partners. Since Task 4.1 is related to other tasks and in order to get overall picture of work package 4, each research partner presented their task responsibilities and capabilities within the project and each TSO/DSO partner presented gas network simulation models that are used in the company.

Research partners prepared a list of requirements for gas network infrastructure based on objectives of this work package as guidance for TSO/DSO partner in selecting the network. The networks are selected based on scenarios discussed between research partners and TSO/DSO partners.

The list of network and data requirements for TSO/DSO are presented in Appendix A.

As mentioned in the chapter 1.5, the selected networks will be simulated and optimized in Task 4.2 and Task 4.3. Simulation is defined by solving the equations that describe the flow in the pipelines and getting the results. The results of simulations consist of:

- **Pressure**. Pressure values is obtained at the nodes of the network.
- **Flow**. Flow values can be in the form of volumetric flow rate or flow velocity, and they are obtained at the pipelines of the network.
- **Gas composition**. The simulation model tracks the gas quality or gas composition from the supply and injection points until the off takers in the network. The gas composition values are obtained at the pipelines.

Optimization of the selected gas networks will also take place in the same tasks. An optimization model, dedicated for gas networks will be employed to optimize:

- **Infrastructure**. For the current study, we focus on optimizing the infrastructure by adjusting the storage capacity and hydrogen injection points. This optimization is also called investment optimization.
- **Operation**. The operation in the selected networks will be optimized by deciding the pressure setpoints and the hydrogen injection flow to maintain the %H2 setpoint.

2.4 Term definition

The “cases” in this work package are defined by the selection of a gas network infrastructure and a scenario, in particular:

- The term “test case” refers to a simple natural gas network infrastructure that highlights the essential features representative of typical and recurring real-world systems. The definition of test cases is a fundamental part of the software testing process and ensures that different aspects of the software are functioning as expected.
- The term “realistic case” refers to natural gas network infrastructures that closely mimic real-world systems. To define them, real-world data, provided by TSOs and DSOs are employed.

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- The term "scenario" refers to a set of operational conditions that can illustrate possible future states (e.g., hydrogen blending) or to model the impact of various factors on the infrastructure (e.g., pressure and/or flow control).

Each infrastructure is characterized by specific features. In view of a taxonomy of the possible gas network infrastructures and scenarios, the main technical and topological features have been divided into four classes (see Figure 1). Each class qualify a specific type of feature concurring to define the infrastructure itself.

1. The class "topology" defines the main shape of the network in terms of connections between the pipes: the simplest is the "tree-shaped" one, where the pipe connections between one point to another are such that only one path is possible. When instead the topology presents one loop, there is at least a couple of junctions between pipes that are connected by two possible paths. The more loops are present, the more complex is the network topology (until the highly meshed one).
2. Another qualifier of a gas network infrastructure is the presence of non-pipe elements (such as compressor, valves, etc.)
3. The number of gas entry points has also been considered as a separate class for the definition of a gas network infrastructure. This qualifier could also be considered as a sub-class of the topology. Anyway, the choice to consider it as separate class lies on the fact that this project is focussing on the distributed injection of hydrogen, thus entry points (and their position) will be relevant features.
4. To complete the definition of a gas network infrastructure, the number of pressure levels and the nominal pressure level at which they are operated finalize the set of information for the definition of the infrastructure.

This taxonomy helps the definition of network archetypes useful to define test cases. These archetypes will also be a reference to the qualification of the realistic cases: the real network infrastructure provided by the TSOs-DSOs can thus be framed using this taxonomy.

A diagram representation is given in Figure 1, where for each class the main possible features are listed. On the right-hand side of the scheme, each feature is allocated between DSOs and/or TSOs to mark a general preliminary distinction between the two levels of the overall gas infrastructure.

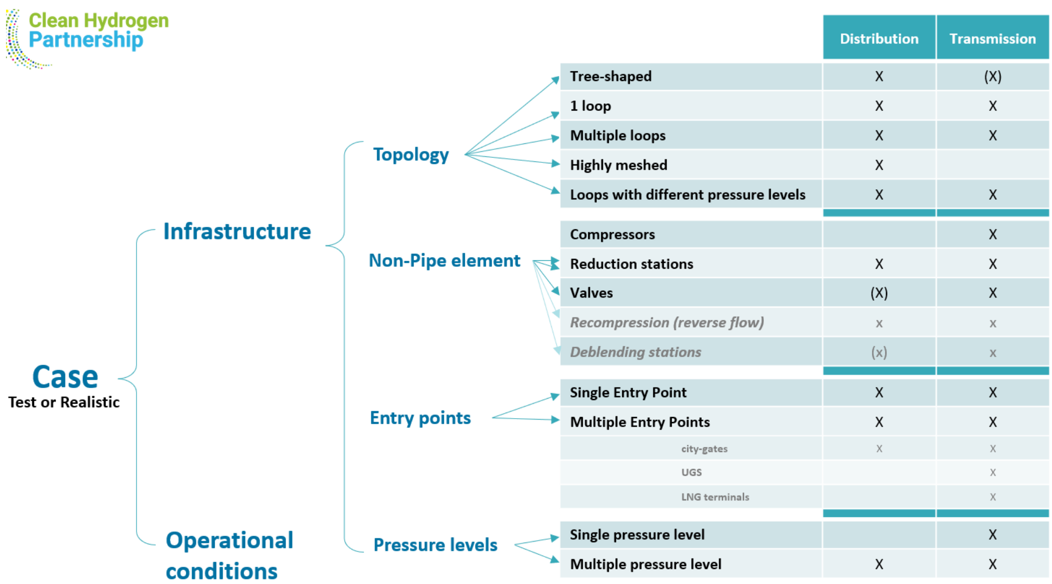

Figure 1: Diagram representation of the infrastructure features of a Test or Realistic case.

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The operational conditions (see Figure 2) are defined by the way gas fluxes are managed inside the infrastructure i.e., the behaviour of the consumptions and of the injections. For the sake of the taxonomy, it has been distinguished between "exit points" and "entry points".

For the "exit points" two sub-classes have been considered: the consumption pattern and the nodal share and distributions. The first class is qualified by the typical temporal evolution of the gas consumption (that is often related to the type of final user(s)). The second class aims at describing how the different types of users (and thus of possible consumption patterns) are distributed throughout the network.

For the "entry points", the subclasses are defined by the possible types of facilities acting as entry points and their related control mode (i.e., pressure or flow control), defining the way the gas is fed within the network. In this classification there is no consideration of the position of the entry points on the network because this has already been considered at the level of the infrastructure description as gas entry points are typically facilities and/or little plants so pieces of the hardware composing the infrastructure.

A diagram representation is given below.

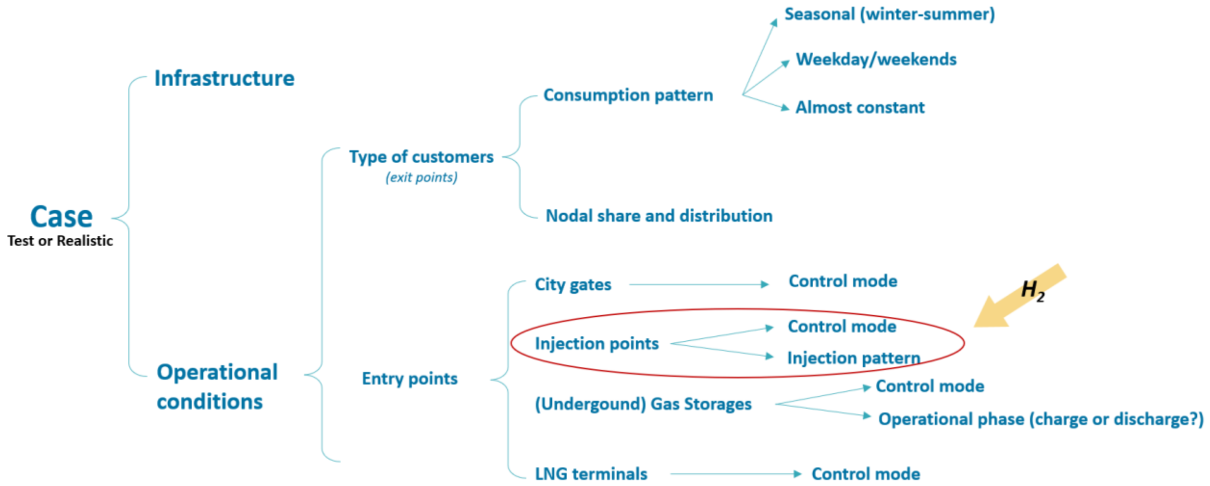

Figure 2: Diagram representation of operational conditions of a Test or Realistic case.

Considering the interest of this project on the hydrogen injection within the gas network, the "injection points" class will be the most relevant one for the variation of cases with hydrogen injection.

2.5 Scenario storylines

Several scenarios for TSOs and DSOs networks are developed to simulate strategies for hydrogen injection and blending, studying optimal configuration and infrastructural adaptation, and finding optimal operational management of the network with the aim of a safe integration of hydrogen within the gas network. Each scenario aims at the investigation of a particular challenge among the ones described in Section 2.2**.**

2.5.1 TSO network challenges

For the transmission scope, the challenges are:

1) **Multiple** and **distributed injection** of hydrogen **with discontinuous production**:
this scenario exemplifies the coupling of the power and the gas sector by means of power-to-hydrogen technologies and hydrogen blending. The overgeneration from renewable energy plants (assumed to be distributed over a certain territory where a gas network is also present) is used to power distributed hydrogen facilities that inject it into the nearest gas network point.

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This situation would generate over the gas infrastructure a scenario of multiple and geographically distributed sources of hydrogen that may inject following several different profiles. Consequently, the gas network will be subjected to quality perturbances even exceeding the acceptable limits. This in turn would cause "shadowing" effect for blending by the upstream injection point on to the downstream ones, limiting the network access and implying curtailments of hydrogen.

All these cited criticalities are the scope of the investigation of a realistic case that is representative of this scenario. The simulation model may first highlight the criticalities. The optimization model can instead solve part of those considering different objectives: optimal coordination among hydrogen injection to keep the hydrogen share within a certain band, optimal siting of the injection points to avoid or limit "shadowing", optimal sizing of distributed hydrogen storages. The optimal solution can then be tested through a further run of simulation to verify the optimal configurations.

2) **Multiple** and **distributed injection** of hydrogen to be **driven** by means of **pressure-flow controls**: this scenario still lies on the cases of distributed injections of hydrogen but focussing on the flow and quality control strategies. Different hydrogen sources connected to different locations of a gas network have a direct influence over certain areas (i.e., set of nodes that are contiguous or sufficiently near to the injection point). Depending on the distances among the sources, the injection/consumption balance and the injection pressure levels, these areas change and can interfere with each other causing further mixing of gas blends within the network.

   By controlling the pressure levels of the injections, it is possible to modify the area of influence of each injection source and thus performing a control over the hydrogen diffusion throughout the infrastructure. The main scope of investigation of this scenario is studying effective strategies to perform an active gas quality control and management to reduce unacceptable sources interferences and possible injection curtailments. Besides the simulation activities, the optimization model might be applied with the objective to find the optimal correlation between gas consumption pattern and distribution with pressure level set-point at the gas entry facilities with the objective to keep the share of hydrogen in specific nodes within a certain band.

3) **Long distance transport** of NG+H_2 mixture with different % of H_2 and variable gas flow rate: this scenario is connected to cases in which the topology of the infrastructure is representative of long pipeline backbones, with few branches (inwards or outwards) and potentially no loops (but rather parallel lines). This can be modelled with an already blended gas instead of considering hydrogen injection and admixing within the infrastructure (both in pure and in blended form). Simulating the realistic behaviour of the gas request to the final end of the infrastructure (representing a set of final consumer demand or the export flow rate) and pressure variation at the starting point (representing the pressure set-point at the outlet of a compression station), the effects of hydrogen presence on the pressure drops along the system can be evaluated, also in case of varying composition of hydrogen blend at the input node.
   The scope of investigation of this scenario is the evaluation of how different shares of hydrogen in the natural gas blend affect the transport in terms of increase of inlet pressure requirements w.r.t Maximum Allowable Operating Pressure (MAOP). Thus, modification in the upstream gas compressors set points or the reduction of the capacity of transport.
   Possible extensions of this scenario may include the presence of further hydrogen injection along the main trunkline. From an optimization point of view, this scenario leads to the evaluation of optimal pressure set point/optimal operational strategy of an upstream compression station and or the cost-optimal refurbishment of a hydrogen compliant compression station based on some operational constraints such as minimum pressure set point at the final end of the pipeline, minimum granted flow rate capacity under different assumptions about hydrogen shares (constant or variable). Also, this

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scenario can highlight the optimal mix between imported blended hydrogen and distributed injection of hydrogen along the pipeline length (e.g. the case of imports vs. local distributed production).

4) **Integration of deblending technologies** at network significant nodes where %H_2 should be capped: this scenario considers deblending technologies for the quality management and control of specific areas of the infrastructure. Even though the deblending technologies relies on different technological solutions, they act as filters from the perspective of the gas infrastructure, separating hydrogen and natural gas with different yields and efficiency. The reason for including deblending in the framework of hydrogen transport and distribution can be related to stringent quality constraint reasons at the locations where specific natural gas customer are located (i.e., natural gas refuelling stations, gas turbine power plants, etc…) or the extraction of hydrogen for its final use in pure form. The need for deblending can be potentially relevant also at cross-border points because of gas quality harmonization needs.

   The scope of the investigation is to integrate these technologies within the gas network modelling and evaluate the impact on gas quality distribution of sub-scenarios in which the hydrogen is separated to protect sensible cluster of customers downstream and then potentially re-injected for quality management reasons, for increasing the overall hydrogen share or simply used in pure form outside the infrastructure. The use of the optimization model on this scenario may help to optimally locate the de-blending facilities according to sensible users' locations and it could also be used for deciding whether is more cost-effective to install deblending facilities or taking different countermeasures (e.g. disconnection of the final customer, adaptation of the final customer, etc.)

5) **Injection** and **extraction** of $NG+H_2$ blends in Underground Gas Storages (UGS):
   from the perspective of the gas infrastructure modelling, Underground Gas Storages can be considered as point on the networks acting as a sink of $NG+H_2$ during the charging phase (gas storages) and as a source of $NG+H_2$ during the discharging phase. The integration of these technologies interfacing with the gas infrastructure is relevant in the framework of hydrogen blending because they bring complex interactions: charging and discharging rates, as well as storage capacity may be affected by the presence of hydrogen (and its varying share). What is more, the $NG+H_2$ blend that is stored in large quantities in UGS may undergo changing in the composition because of bio-chemical reactions happening underground or because of stratification phenomena. The scope of the investigation of this scenario is not to model the phenomena happening inside the UGS but rather simulate the behaviour interaction between storage(s) and the infrastructure, considering peculiar behaviour in terms of possible hydrogen share losses as determined by a literature review. From an optimization perspective, the optimization model can be used in this specific scenario to optimally design separate pure hydrogen storages for the adjustment of hydrogen share of the gas flux exiting the underground storage facility and re-entering the gas infrastructure.

2.5.2 DSO network challenges

For distribution, the challenges are similar to most of the ones described for TSOs but with some peculiarities related to the generally smaller extension of the infrastructure but its higher degree of complexity in terms of topologies. Because of this increased topological complexity, the optimization model would not be systematically employed on this level of the infrastructure.

At distribution level, the main challenges are:

1) **Multiple** and **distributed injection** of hydrogen **at different pressure levels**:
   As distribution infrastructures are often structured with at least two pressure levels and anyways they are interconnected to the higher-pressure transmission level of the gas infrastructure through one or

more pressure reduction plants, this scenario exemplifies the cases of distribution infrastructures receiving hydrogen blends from the upper hierarchical level (TSO) while also integrating distributed hydrogen injection directly at distribution level (at both the pressure levels, if relevant). The scope of the investigation is to simulate the hydrogen distribution at the different levels of the infrastructure, controlling possible sources interferences and testing some modulation strategy to better integrate the hydrogen within the infrastructure.

2) **Multiple** and **distributed injection** of hydrogen **with different hydrogen share** and **time varying injection/consumption:**
   referring to type of infrastructures like the ones described at the previous point, with this scenario the aim is focussing specifically on how the hydrogen concentration distributes through a complex infrastructure (e.g., highly meshed) under different working conditions (namely: injection/consumption patterns, consumption localization, hydrogen share at the different injection points). The scope of the investigation is to evaluate the possibility of defining areas with homogeneous gas quality and detecting remarkable points on the infrastructure that are representative for gas quality monitoring of an entire area.

3) **Integration of deblending technologies:**
   Similarly, to the challenge description above, this scenario considers deblending technologies for the quality management and control of specific areas of the infrastructure or at specific final user level. The scope of the investigation is to simulate the behaviour of a distribution infrastructure in case of employment of deblending technologies at a few specific points either for “filtering” the presence of hydrogen for some users (end eventually performing a reinjection) or in case of extraction of hydrogen for uses in pure form. The focus would be on the impact on the variation of the share of hydrogen throughout the network.

4) **Integration of storages for quality stability:**
   In the context of injection of hydrogen at distribution level, the limited extension of the infrastructure often come along with the limited consumption of natural gas, especially during warm season. If hydrogen is instead produced locally from renewable sources with the aim of injecting it into the distribution grid, the seasonal production pattern may be the opposite thus being detrimental for an effective integration of hydrogen within the network. The scope of the investigation is the evaluation of the gas storage needs (both natural gas and hydrogen) to help stabilizing the gas quality of the network and also identify the best location where to connect the storages with the rest of the infrastructure.

2.6 Objectives

Task 4.1 has the objective to provide gas network infrastructure models, operational data, scenarios and the selection of gas network simulation/optimization models for Task 4.2 and 4.3 in work package 4.

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

3 Test Cases

Test cases are meant to represent network archetypes: simple gas network infrastructures that showcase the minimum features to be representative of common and recurrent real infrastructures. Along with the infrastructure, also the operating conditions need to be defined. These will be simplified representation of consumptions and injections flow rates and pattern (e.g. referred to standard consumption profiles for classified types of final users).

Before proceeding with analysing the realistic cases in SHIMMER, several test cases are proposed for the simulation and the optimisation models. The aim is to use simplified network topologies that allow a comprehensive validation and check on the performance of the models used during the project.

3.1 Test cases for simulation

In the peculiar case of simulating gas networks in which gases with different quality (or literally different gases – e.g., hydrogen) are flowing, the features that needs to be validated, besides the capability of right prediction of pressures and pipeline flow rates are:

- Admixing: the capability of calculating the correct composition of the gas outflowing a node in which streams of gases with different composition converges and admix.
- Quality tracking: the capability of following the gas quality variation in time along a pipeline or through a series (or a set) of nodes.

Two test networks were designed to evaluate the performance of the features in the simulation model:

Test network 1:

This network is composed of two inlet points feeding a single pressure tier infrastructure. The outlet points are usually located at the ending points of the pipelines. From a topological point of view, the network has multiple interconnected loops but anyways in a limited number. This characteristic, together with the presence of at least two inlet points, makes it non-obvious the distribution of the gas fluxes throughout the pipelines and by consequence the admixing of the gas fluxes in case of differences in gas composition. It is worth noting that the location of the gas admixing (within the grid) may change according to the injection/consumption pattern and magnitude of the neighbouring nodes.

The topology is representative of a portion of a national (or regional) gas network infrastructure (usually transmission level. Together with the admixing problem, this case can also be used to test quality tracking along the pipe capability of the simulation model(s).

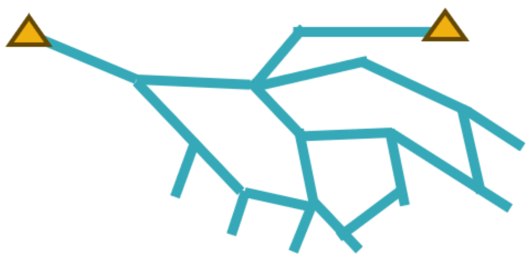

Figure 3: Example of a test network archetype for simulation with 2 inlet points with different compositions and a single pressure level with some loops.

Test network 2:

This network is composed of two inlet points feeding a multiple (two) pressure tier infrastructure. The outlet points can be located both at the ending points of the high-pressure level network or distributed over the low-pressure infrastructure. From a topological point of view, the network showcases a meshed grid in the lower

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pressure tier, quite complex from a fluid-dynamic point of view. What is more, also the lower pressure tier is characterized by two different inlet points. To be noted that the two level of the infrastructure are physically connected by specific non-pipe elements (regulation stations) that should also be simulated by the model, considering that they can perform some control strategies over the infrastructure.

The problem of admixing is even more complex in this test case where also control strategies of non-pipeline elements can be tested. The quality tracking aspect can either be addressed at a pipeline level or, especially for the highly meshed are, as the tracking of quality perturbation at node level.

The topology is representative of a portion of a local distribution network, with the lower pressure tier being the urban area. It may also be representative of an interconnection between the transmission and the distribution level. national (or regional) gas network infrastructure (usually transmission level. This case can be used to test quality tracking capability of the simulation model(s) in a highly meshed networks, as well as the gas admixing and internal blending.

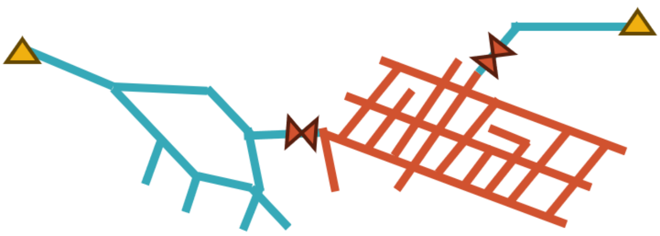

Figure 4: Example of a test network archetype for simulation with 2 inlets, 2 pressure levels and a meshed grid (representative of an urban distribution system)

3.2 Test cases for optimisation

As described in Section 2, SHIMMER will deploy mathematical optimisation for examining the optimal long-term decision-making process. This modelling approach aims to find the best possible solution (e.g., cost minimisation) to a problem defined by sets of constraints (e.g., demand-supply balance, technical constraints). Five different features need to be considered in the optimisation model developed in SHIMMER to ensure the appropriate representation of the network physics and long-term decision-making:

- **Pooling/Mixing problem**: It involves optimising the blending of gases (blending strategies) from multiple sources to meet specific requirements at various delivery points.
- **Pipeline investments**: This refers to the capability of evaluating investing in new pipelines to improve network capacity and reliability. One potential analysis is to compare the alternatives of pure hydrogen pipelines, repurposing existing pipelines for pure hydrogen or blended transport.
- **Bidirectional flows:** Models the ability of pipelines to support gas flows in both directions. In networks where isolated storage facilities (no production or demand in the same node) are connected to the rest of the network via a single pipeline, bidirectional flow is crucial. Basically, gas needs to flow towards the storage facility and back into the network depending on the conditions of demand/supply.
- **Storage investments and management:** It assesses the role of gas storage facilities in providing more flexibility to the network, especially under production fluctuations. The optimisation model will account for the operational capabilities but also the strategic decisions involving their capacity and location.
- **Compression problem:** Required to maintain adequate gas pressure and flow throughout the network. The model can also consider the possibility of investing in new assets (compressors/decompressors).

Three test networks were designed to evaluate the performance of the features in the optimisation model.

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Test network 1: The first network is composed of three inlet points, two pooling nodes and two outlets. This basic configuration will check the model behaviour regarding the pooling problem and storage investments and operations. This test network topology was selected as it has been used in multiple optimisation publications and it is referred as the generalized pooling problem where connections between pool nodes are allowed [1]. Different types of injection (natural gas, hydrogen, or already blended gas) and demand will be considered.

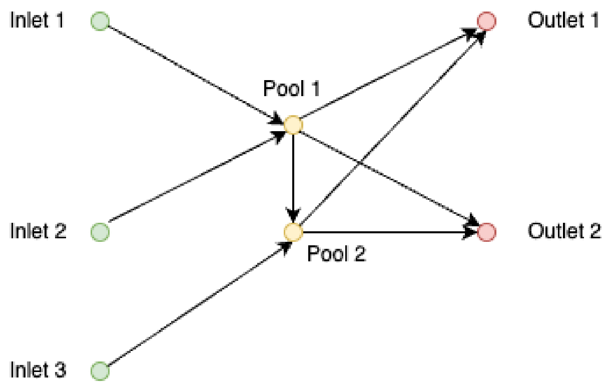

Figure 5: The test network for optimization where there are connections between nodes.

Test network 2: This network is proposed for investigating the different pipeline strategy investments. For each inlet-outlet connection, the model will evaluate investing in one or two pipelines, each of which can be used for blended gas, pure hydrogen, or pure natural gas. The network, with fixed types of pipelines, will be used to examine compression strategies.

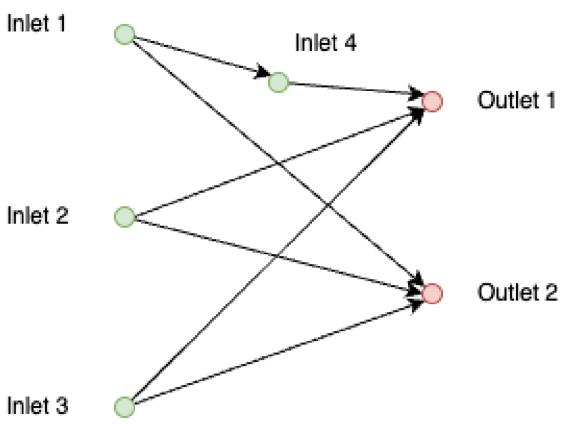

Figure 6: The test network for optimization of investment strategies.

Test network 3: The last test network considered for the optimisation model is used for evaluating bidirectional flows. In this case, the network has a loop topology with one inlet, one outlet and a storage device connected via a pipeline with bidirectional capabilities. The same or a similar network can be used to evaluate the modelling of the compression operations in the model, as optimising cyclic networks are harder to solve than linear or tree topologies.

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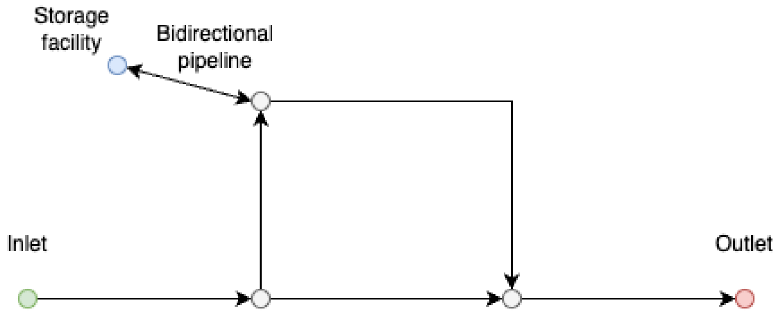

Figure 7: The test network for optimization of bidirectional flow and loop

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4 Realistic Cases

4.1 Norwegian high-pressure network

Gassco AS, a state-owned company, operates the gas transport system that extends from the Norwegian continental shelf to various European destinations. As the primary operator, Gassco manages a large network of processing plants, pipelines, platforms, and gas terminals. Thus, the company plays a critical role in capacity management and infrastructure development. The network, spanning over 8,800 kilometres of steel pipelines, supplies approximately 25% of the natural gas consumed by the European Union.

In the context of Task 4.1, Gassco has provided comprehensive details on a specific segment of its network, which is currently under consideration for pure hydrogen transportation from the Norwegian continental shelf to Germany (see Figure 8). The plan includes:

- The new pure hydrogen pipelines Nyhamna Hydrogen, Kollsnes Hydrogen and Kårstø Hydrogen connecting the onshore blue hydrogen production at Nyhamna, Kollsnes and Kårstø to Draupner (sub-sea tie-in point).
- Two options for connecting Draupner with Germany: either the new pure hydrogen pipeline Export Hydrogen Pipeline, or repurposing the existing Europipe I.

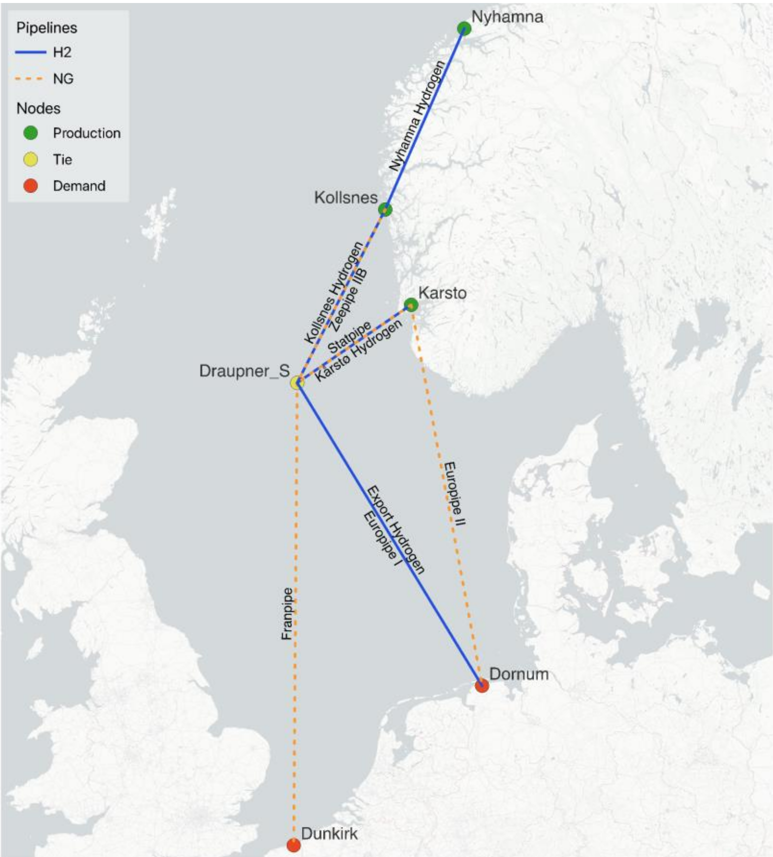

Figure 8: The current pure H2 transport plan considered by Gassco.

The Norwegian realistic case considered in SHIMMER aims to investigate the option of blended hydrogen pipelines. Figure 9 shows the different nodes and pipelines considered for this case, where:

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- There are three natural gas and hydrogen inlets (Nyhamna, Kårstø and Kollsnes), a receiving terminal (Dornum), and a subsea tie-in point (Draupner). The outlet in France (Dunkirk) is shown in the figure for model validation.
- The existing pipelines, Zeepipe IIA, Statpipe, Europipe II and Europipe, will be considered pipelines for transporting blended gas.
- The potential of investing in the pure hydrogen pipelines Kollsnes Hydrogen, Kårstø Hydrogen and Export Hydrogen Pipeline will also be considered to compare the realistic case with the initial Gassco plans.
- The network connecting Nyhamna with Kollsnes and Kårstø will be considered options for transporting blended gas.

Non-existent pipelines depicted for blended gas in the Figure 9 will be examined to either transport blended gas or pure hydrogen. For repurposed pipelines there will be an upper limit for the hydrogen fraction This means that a pipeline repurposed for blends cannot transport pure hydrogen. In contrast, pipelines specifically for pure hydrogen and natural gas are limited to transporting only their respective gases.

Figure 9 Realistic case study considered in the Norwegian Case for the analysis of blending opportunities.

The three inlet points under consideration for the Norwegian case were selected in alignment with the main large-scale hydrogen production initiatives: the Clean Hydrogen to Europe (CHE) project and the Aukra Hydrogen Hub (AHH). The CHE project is centred on hydrogen production in Kollsnes and Kårstø, while the AHH explores opportunities in Nyhamna. Both projects target a production capacity of around 0.45 Mtpa of blue hydrogen by 2030, using natural gas plants combined with Carbon Capture and Storage (CCS) [2].

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The Norwegian government has ambitious goals for developing offshore wind on the Norwegian continental shelf. In 2020, the areas of Sørlige Nordsjø and Utsira Nord were open to license applications, and in 2024, the call for project proposals was open for interested production firms to apply. Following these plans, wind offshore power generated in Sørlige Nordsjø and Utsira Nord is considered in the Norwegian realistic case (see Figure 10). Small-scale green hydrogen projects are currently in the early stages of development, so limited information is available to be considered in SHIMMER.

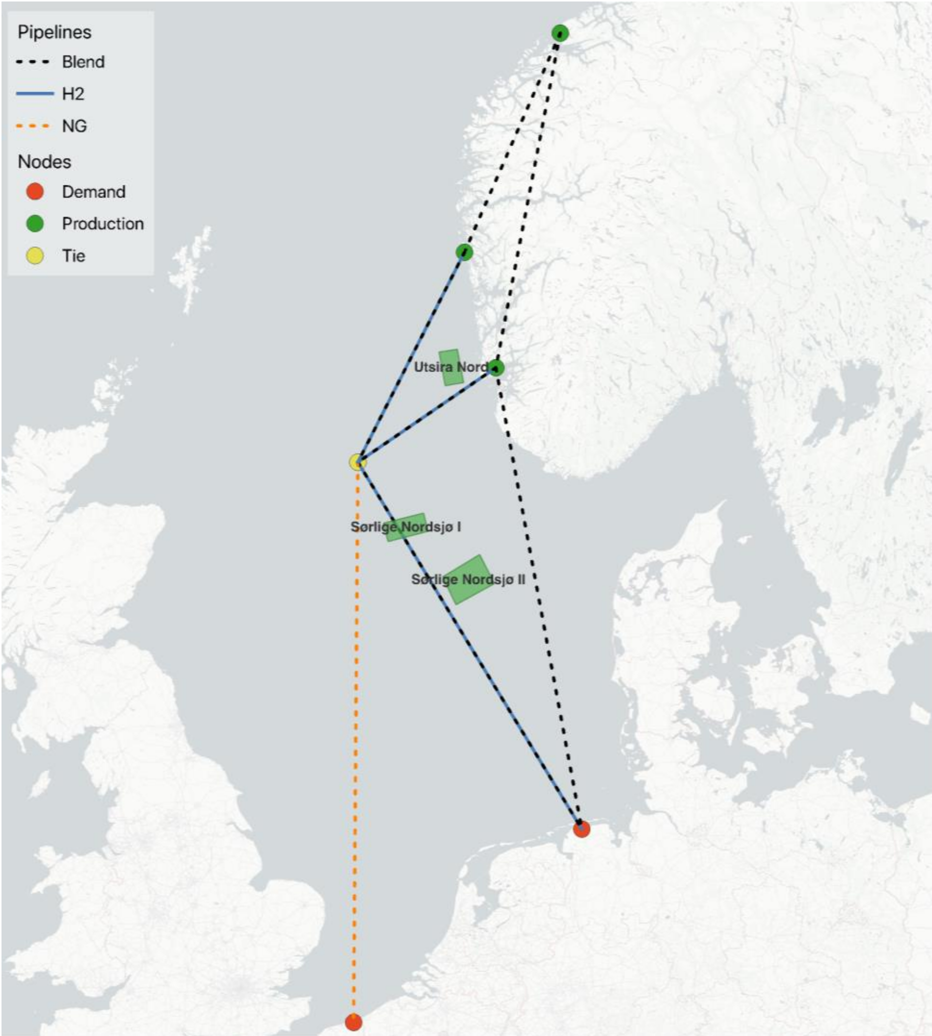

Figure 10. Wind offshore areas considered in the Norwegian realistic case.

Concerning the challenges in WP4, the selected Norwegian network offers a pertinent case study for exploring the dynamics between green hydrogen production and the gas network, shedding light on operational and strategic challenges.

At the operational level, the study will focus on maintaining and achieving hydrogen quality standards. Efforts include exploring solutions to harmonise gas quality across European borders and defining effective pressure control strategies to manage the flow and correct integration of hydrogen within the network. Furthermore, the variable nature of renewable energy sources implies fluctuating hydrogen production. This variability necessitates the development of strategies such as line-packing and storage management (under-ground storage systems) to buffer against these fluctuations and ensure a consistent gas supply.

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At a strategic level, the use case study will include the analysis of investment decision plans related to the transmission infrastructure (pure hydrogen and blended pipelines), blending and deblending technologies, and compressors that ensure a feasible network.

4.2 Italian high-pressure network

The infrastructure provided by Snam S. p. A. serves as the primary Italian entity responsible for the transportation and storage of natural gas throughout the country for gas delivery to Italian users. It maintains nearly all of Italy's gas transportation infrastructure, boasting 32,727 kilometres of operational pipelines under high and medium pressure, which represent roughly 94% of the total transportation network.

For the purpose of this project, the transport infrastructure of the island of Sicily has been chosen.

The overall extent of the Sicilian grid spans approximately 150 kilometres. It comprises a high-pressure backbone operated between 60 and 70 bar_g, and two middle-pressure loops operated between 24 and 60 bar_g. The high-pressure core is composed of two or three parallel pipelines with diameters ranging from 0.8 to 1.1 metres, while the middle-pressure circuits are composed of single pipelines with diameters from 0.1 to 0.7 metres, as shown in Figure 11.

Natural gas arrives from Algeria through Tunisia and Libya at the import points of Mazara del Vallo and Gela, respectively via the Transmed and Greenstream pipelines. These imports, as well as natural gas from national production, are then transported towards Enna where they are mixed and compressed up to 70 bar. From Enna, natural gas is transported towards Messina, where another compression up to 70 bar occurs. Here, the natural gas joins the rest of the Italian peninsula's infrastructure. Table 3 below summarises the network characteristics:

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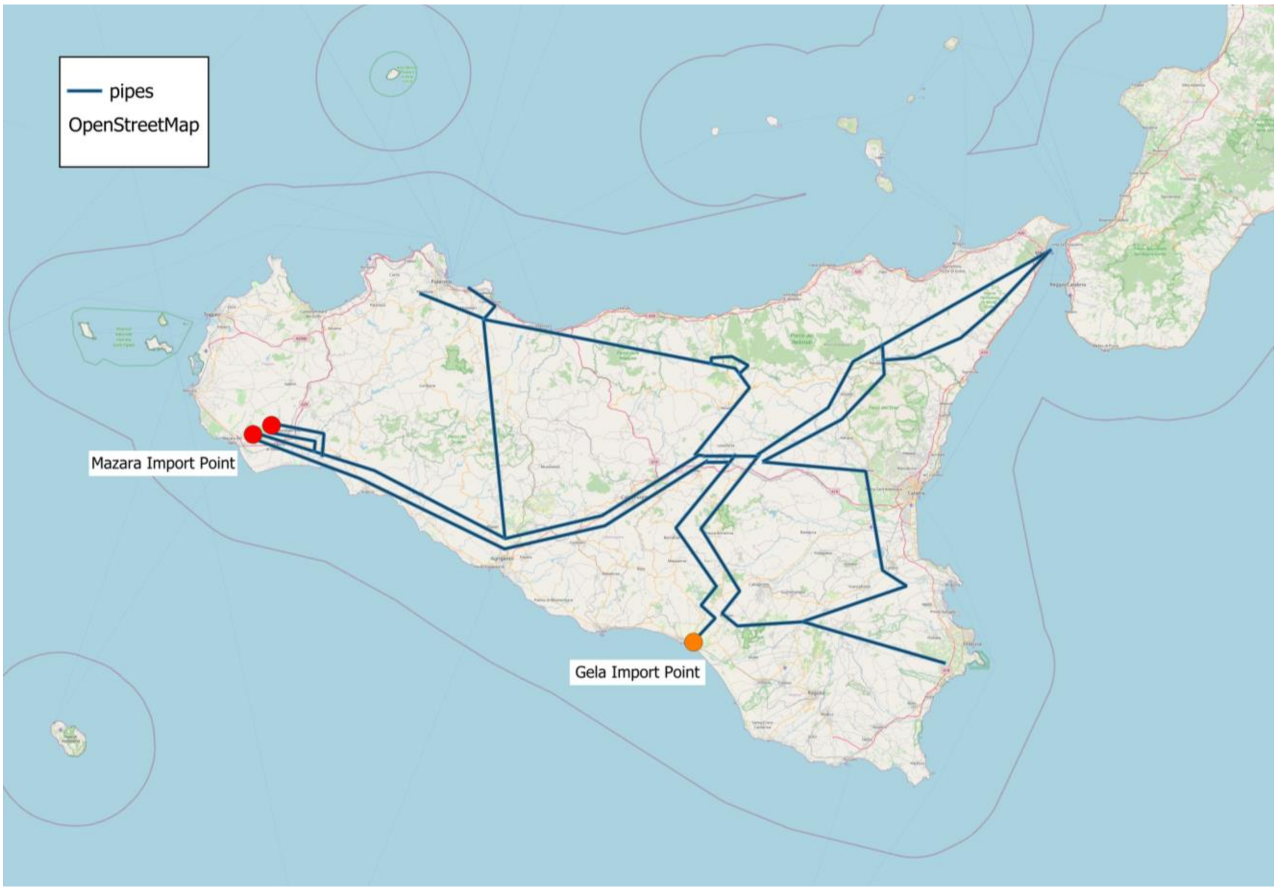

Figure 11: Current natural gas transmission infrastructure of Sicily considered by Snam.

Table 3: List of assets in SNAM case-study.

Pipelines	Total length = 150 km High-pressure backbone = 60-70 bar Middle-pressure loops = 24-60 bar
Compressor stations	2 stations
Control valves	2 valves

From the energy perspective, Sicily holds a high renewable energy potential: it is the second region in Italy for installed wind power capacity and the seventh for installed photovoltaic power capacity. The island's infrastructure is a valuable asset for Italy and Europe, thanks to its strategic location at the centre of the Mediterranean and its abundance of conventional and renewable energy sources. However, in order to bear the renewable production, the electricity grid needs to be updated. In the meantime, the excess renewable power could be fed to an electrolyser for hydrogen production [3].

Therefore, this case study is relevant to explore power and gas sector coupling, with multiple and distributed injections of green hydrogen in the grid. The criticality of this scenario is the management of the hydrogen blending with variable supply profiles, that come from the discontinuous renewable electricity production.

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Here, importance is given to quality perturbances and hydrogen sources interferences, possible curtailments, and re-injections of hydrogen and linepack management.

Since the infrastructure has several natural gas inlets, another interesting scenario to study is how to manage these multiple and distributed natural gas and hydrogen sources. A way to ensure uniform gas quality could be, in fact, to use smart flow and/or pressure control strategies. In this scenario, importance is given to gas quality distribution active control.

At the end, the aims of these investigations are to determine the system and engineering constraints that can reduce hydrogen acceptability into the network as well as provide general guidelines and optimal operational strategies for hydrogen blending.

4.3 Italian low-pressure network

INRETE Distribuzione Energia S. p. A. is responsible for the distribution of electricity and natural gas in the Emilia-Romagna and Tuscany regions. They facilitate connections to their managed networks, ensuring the uninterrupted delivery and safety of services. Moreover, they manage service requests, oversee meter installation and upkeep, and maintain records of gas and electricity usage.

For this project, the gas distribution grid of the city of Riccione, displayed below, has been supplied.

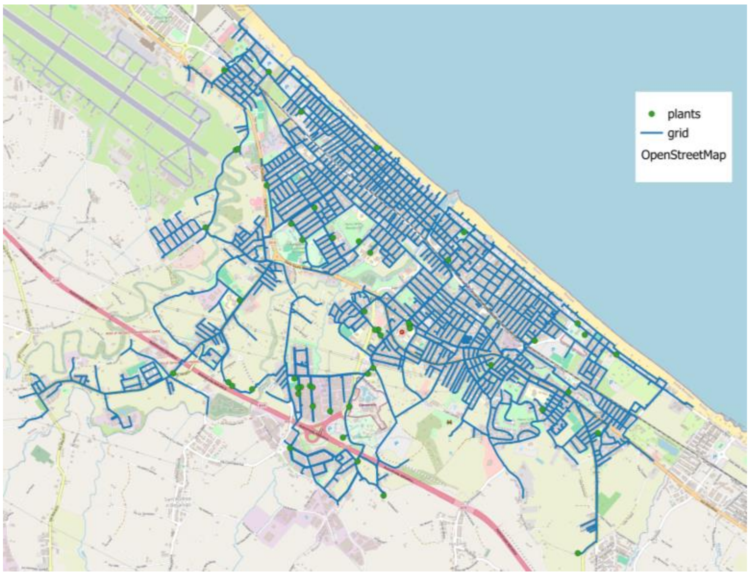

Figure 12: Current natural gas distribution infrastructure of Riccione considered by INRETE.

This network is composed of more than three thousand pipelines, of which, about four hundred are operated between 5 and 1.5 bar, and the remaining part consists of pipelines directly connected to the final user, therefore their maximum operating pressure cannot be higher than 0.04 bar, as shown in Figure 12.

The gas distribution grid in Riccione is supplied by two entry points connected to the transportation network (city gates). Apart from this, there are eighteen final gas pressure reduction stations and more than twenty-three thousand final users, that are both residential and industrial. Therefore, natural gas is employed for several purposes: heating, cooking, domestic hot water production as well as technological uses. Table 4 summarizes the network characteristics.

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Table 4: Summary of assets in the INRETE gas network case study.

Pipelines	Pressure levels • 1.5 - 5 bar • 0.04 bar
TSO-DSO connection points	2 points
Final pressure reduction station	18 points
Final users	23 000

This case study is particularly relevant because it allows us to explore the consequences of hydrogen blending for an interconnected distribution network that supplies a variety of users with different gas quality requirements. For example, residential users could accept larger shares of hydrogen in their mixtures, while industrial users (in this specific case foundry and food industry) cannot accept hydrogen content higher than 5% vol without plant modifications.

This assessment aims at the simulation of an infrastructure that comprises both blending and deblending technologies at the network's significant nodes (near to sensitive consumers), where the hydrogen percentage in the mixture should be capped. In a further development of this scenario, the hydrogen that is curtailed due to quality requirements could be re-injected in different parts of the grid, where no sensitive consumer is connected.

The main aims of this evaluation are the mapping of how contractual constraints affect hydrogen admissibility into the grid and the establishment of general guidelines for safe hydrogen blending.

4.4 Spanish high-pressure network

ENAGAS is a Spanish company specialized in the transmission, regasification, and storage of natural gas. The company is the main natural gas TSO in Spain as it is the owner and operator of more than 12000 km of high-pressure gas pipelines. The company's gas network in Spain comprises of the high-pressure pipelines, 6 connections to neighbouring countries, 19 compressor stations, 45 transmission maintenance centres, network connection points and regulation, and metering stations.

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Figure 13: The high-pressure transmission network case from ENAGAS. The network is located in the area of Zaragoza in Spain. Red line illustrates the pipelines, blue circles illustrate the compressor stations (EC) and the black circle illustrates the underground storage facility (AS).

For the tasks of the current work package, ENAGAS provided a part of the transmission network, which is illustrated above with Figure 13. The high-pressure pipelines are in the area of Zaragoza, in the North-East part of Spain close by the border with France. The selected network consists of 17 pipe sections with a total length of 738 km, and it is operated with a nominal pressure of 72 bar. The maximum allowable pressure of this network is 80 bar. In the network there are also 4 compressor stations which are given with blue circles and one underground storage facility which is given with a black circle. The assets are also listed below in Table 5.

Table 5: List of assets in the ENAGAS high-pressure transmission network case study.

Pipelines	Total length = 738 km Operating pressure = 72 bar Maximum pressure = 80 bar
Compressor stations (EC)	4 stations
Transmission centres (CT)	2 centres
Underground storage facility (AS)	AS Serrablo Capacity = 1,100 million Nm^3 of natural gas

The ENAGAS network has some unique characteristics which will be investigated with several scenarios. The underground storage facility and the high operating pressure of the ENAGAS network make it an interesting case study. Another characteristic of the network is the line pack storage and the underground storage which should be investigated with a transient solver.

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Scenarios with industrial users where hydrogen-natural gas mixture is locally deblended to ensure high-purity gases will be studied. Scenarios with interconnections with European countries will also be simulated, where the gas mixture is deblended with the goal to ensure that pure gases or gas mixtures of a certain quality are transmitted. Additionally, to investigate asset management strategies, a scenario with storage units will be part of this case study.

4.5 Spanish low-pressure network

REDEXIS is the second largest transmitter and fourth largest distributor of natural gas in Spain. The company owns and operates a network of 11700 km of pipelines in 51 provinces of Spain. Its pipeline network consists of steel pipelines for pressures over 10 bar and polyethylene pipes for lower pressures. REDEXIS has been continuously expanding its network. 60% of its transmission network was installed in the last 6 years. The company has also significantly expanded the distribution network between 2015 and 2018 and has plans for more expansions in the coming years.

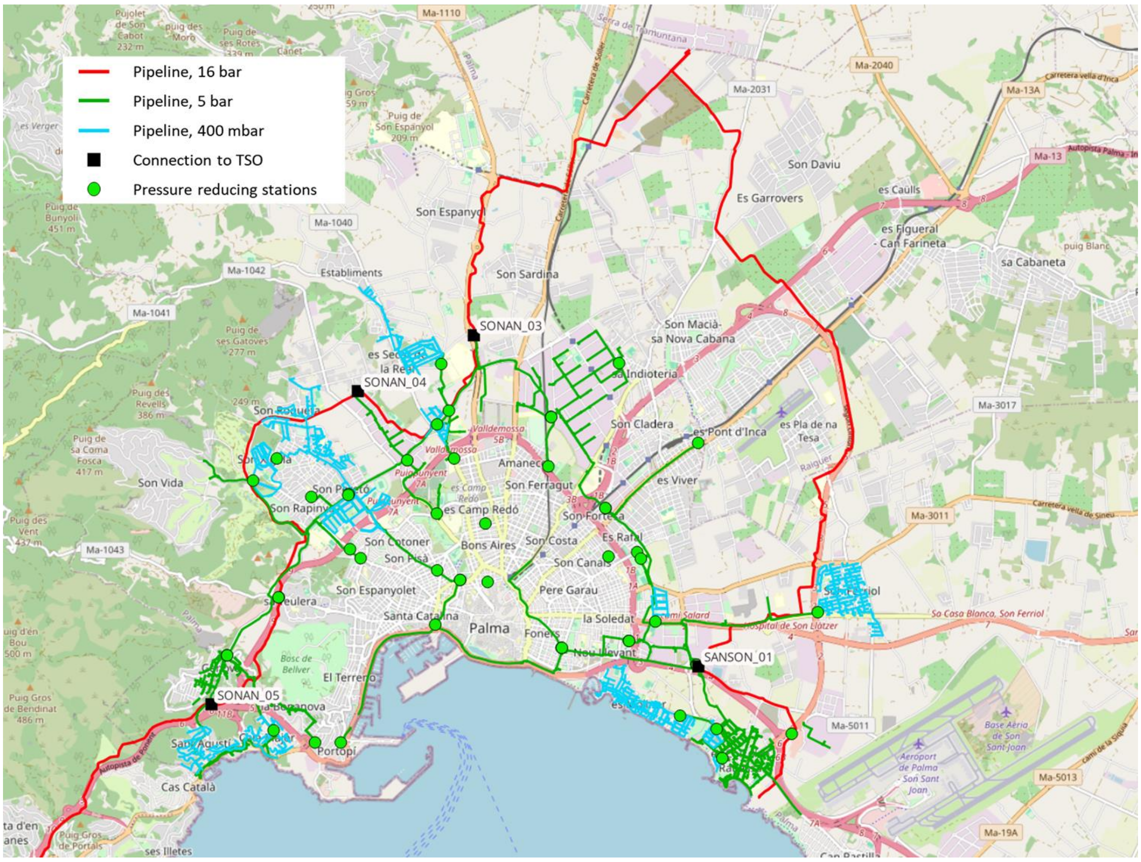

Figure 14: The low-pressure distribution network case from REDEXIS. The network is located on the island of Palma de Mallorca in Spain. The red lines show the 16 bar pipelines (TSO), the green lines show the 5 bar pipelines, and the blue lines show the 400 mbar network. Additionally, the black squares illustrate the connection points to the between 16 bar (TSO) and 5 bar (DSO) pipelines and the green circles illustrate the pressure reducing stations.

REDEXIS has provided a part of the distribution network for performing a case study on a low-pressure distribution network. The selected network is located on the island of Palma de Mallorca and specifically in the city of Palma. It consists of 3 pressure levels the 16 bar transmission pipelines, the 5 bar and 400 mbar distribution pipelines. The selected network is illustrated above with Figure 14. The 16 bar and 5 network are interconnected with 4 stations illustrated with black squares. The 5 bar and 400 mbar networks are

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interconnected with 49 stations. The assets consisting of the REDEXIS case study, are listed below on Table 6.

Table 6: List of assets in the REDEXIS gas network case study.

Pipelines	Total length = 183.34 km Pressure levels • 16 bar • 5 bar • 400 mbar Pipe inner diameters: 26 – 387.36 mm
TSO-DSO connection points	4 points
5 bar – 400 mbar connection points	49 points

The REDEXIS network is interesting as a case study because of the different pressure levels and the combination of the high- and low-pressure pipelines. Moreover, it is a complex network of many pipelines and ring pipes where the distribution and mixing of different gas compositions is not straight forward to predict. As a result, several scenarios with different goals will be performed for this cases study.

The multiple pressure levels of the REDEXIS network will be exploited with scenarios where hydrogen is injected at different pressure levels. Additionally, the complex geometry of the network allows for scenarios where injection points are located on various locations and with an injected gas mixture of different percentages of Hydrogen.

4.6 Scenario description for simulation model

Table 7 links the potential relevant transmission scenarios (provided by TSOs) with the real-case infrastructure, on the basis of topology and network components. Table 8 aims at the same purpose, for distribution-level infrastructures, provided by DSOs. This is done for Simulation only, while for Optimization please refer to the next section (Section 4.7).

Table 7: Potential realistic cases and possible real transmission network application

Realistic Case	**Scenario**	**Real Network possible application**	**Analysis/Scope of Investigation**
Sector coupling of power and gas networks with line-pack management challenge in variable supply/demand profiles	Multiple and distributed injection of hydrogen with discontinuous production	SNAM	Quality perturbances, hydrogen injection sources interference, (re)injection, possible curtailments, linepack management
Hydrogen blending and transport from	Long-distance transport of NG+H2 mixture with	GASSCO	Variation of pressure drops (wrt only NG case), need to change the

EU neighbourhood areas (e.g., North Africa) analysing compression behaviour challenge	different %of H2 and variable gas flow rate No need for a specific injection point - the gas can be already blended Single injection at the start of the pipeline Possible scenario extension: further injections along the way		operation schedule of the compressor to meet the minimum pressure constraints, more compression power needed
Multiple industrial users with deblending technologies at final facilities as quality assurance challenge	Scenarios with reinjection of hydrogen Multiple distributed re-injection sites or storage/extraction of H2 in pure form for pure H2 market/utilization	ENAGAS	Quality perturbances, re-injections, hydrogen re-injection sources interference, possible curtailments
EU-interconnection with deblending towards gas quality harmonization challenge	Deblending technologies at network significant nodes (either near to sensitive users, specific "controlled hydrogen" areas, cross border etc.) where %H2 should be capped	ENAGAS / GASSCO / SNAM	Different gas quality needs
Storage system as dispatch/asset management challenge	Injection and extraction of NG+H2 blends in UGS UGS storage as a sink of NG+H2 and as a source of NG+H2 with different H2 concentration	ENAGAS	Impact of injection/extraction of H2+NG blends from UGS -form the perspective of the gird
Multiple gas injection in the network as smart flow/pressure control challenge	Multiple and distributed injection of hydrogen to be driven by means of pressure-flow controls	SNAM	Quality perturbances, hydrogen re-injection sources interference, possible curtailments, gas quality distribution active control

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Table 8: Potential realistic cases and possible real distribution network

Realistic case	Scenario	Real Network possible application	Analysis/Scope of Investigation
Multiple pressure levels and multiple city gates	Multiple and distributed injection of hydrogen at different pressure levels	REDEXIS	Quality perturbances, H2 injection sources interference, possible curtailments, smart managing of pressure and flow
Complex meshed grid with multiple injection points, injection levels and supply profiles	Different injection points with different %H2 injected Time-varying injection profiles	REDEXIS	Quality perturbances, H2 injection sources interference, possible curtailments, smart managing of pressure and flow
Wide range of end-users (industrial, domestic) with very specific quality demands and time-varying demand profiles	Deblending technologies at network significant nodes (either near to sensitive users, specific "controlled hydrogen" areas, cross border etc) where %H2 should be capped Scenarios with re-injections of hydrogen	INRETE	Quality perturbances, re-injections, hydrogen re-injection sources interference, possible curtailments
Limited local storage facilities and limited line-pack	Scenarios with storages of NG and H2 for quality stability	-	Linepack management, storage management
Quality sensors positioning	Multiple and distributed injection of hydrogen with time-varying injection profiles and time/space varying consumptions	REDEXIS	Spot and define “sentinel nodes” for gas quality monitoring

4.7 Scenario description for the optimisation model

The optimisation model applied to the case studies in SHIMMER focuses on modelling the TSO's decision-making. The model’s objective is to help design networks that minimise investment and operational costs while considering the technical constraints of the transmission network and assets.

In addition to this objective, the model will help examine and analyse the goals established in SHIMMER. Table 9 presents the entire description of the goals, identifies their associated challenges to consider in the model, and explains how and whether these can be addressed in the case studies to generate the different scenarios and potential analyses. The analyses are labelled as potential, given that more specific scenarios will be defined in the next phases of the project.

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

Table 9: Overview of the potential scenarios to be analysed for the different realistic cases using the optimisation model.

Realistic case	Scenario	Norway	Italy	Spain	Analysis/Scope of Investigation
Sector coupling of power and gas networks with line-pack management challenge in variable supply/demand profiles	Sector coupling	Electricity to Green H_2 NG to Blue H_2	Electricity to Green H2	Electricity to Green H_2	Curtailments, Injection strategies, Pipeline expansion
	Variable supply and/or demand	✓	✓	✓	
	Line-pack management	✓	✓	✓	
Hydrogen blending and transport from EU neighborhood areas (e.g., North Africa) analyzing compression behavior challenge	Compression behavior	✓	✓	✓	Compressor investments, Flow/pressure control,
	Blending and transport from EU neighboring areas		✓ (North Africa)		Power consumption compressors
Multiple industrial users with deblending technologies at final facilities as quality assurance challenge	Deblending technologies and quality assurance	✓	✓	✓	(De)blending technologies investments, Scenarios with different $\%H_2$, Storage management strategies (e.g., injection and extraction, concentration of blend)
EU-interconnection with deblending towards gas quality harmonization challenge	Deblending technologies and quality harmonization between EU countries	✓ (Germany)			
Storage system as dispatch/asset management challenge	Storage systems	UGS		Surface tanks	Storage investments and management
Multiple gas injection in the network as smart flow/pressure control challenge	Multiple gas injection	✓	✓		Flow/pressure control, Pipeline expansion

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5 Gas Network Model

For the work of WP4 Flow assurance the research partners, TSOs and DSOs collaborate to evaluate the scenarios for the realistic cases. The research partners are responsible for performing the simulations on the selected gas networks and optimize the networks for achieving a smooth hydrogen injection. The current chapter addresses Task T4.1.3 by reviewing the available gas network models (simulation and optimisation) and comparing their features and capabilities. Finally, the most suitable models are selected.

The current chapter comprises five parts. In the section 5.1, each model is introduced, and some background is given for the institution that developed and implements the model, as well as a short description of some important features. The definition of the features and refers to the table in Appendix B where the models are compared based on these features. The conclusion section is given in section 5.2 for the selection of the most suitable models for the current project.

5.1 Overview list of available gas models

Research partners, TSOs and DSOs are performing analyses with gas network models of their choice. As a result, a collection of different gas network models is preferred by the consortium. Below an introduction of each these preferred models are given. In total eight different gas network simulators are presented.

Aurora

Aurora is a software tool which is being developed by TNO for several years. Aurora has become a reference point for the research of the existing natural gas network and for future scenarios where the Netherlands will operate the network with pure hydrogen. The model is not available to the public and it is used only for research purposes by TNO.

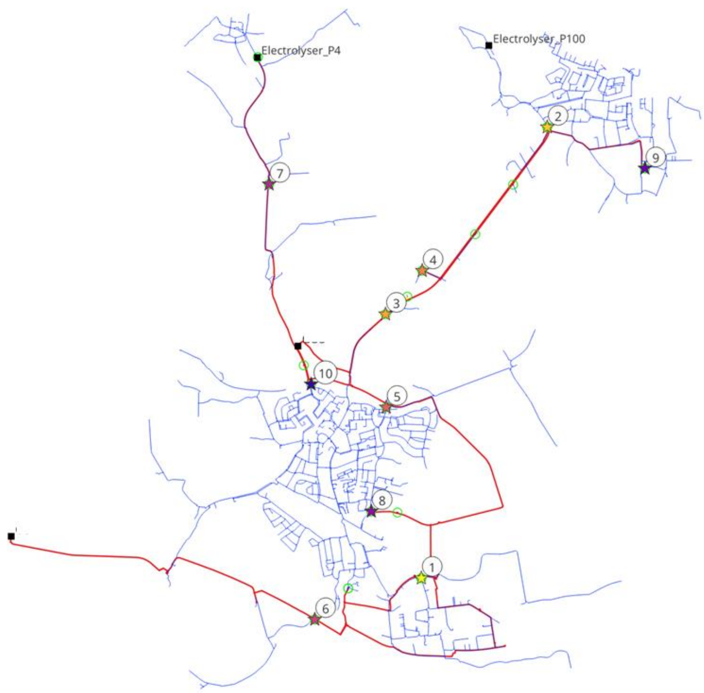

Figure 15: Example output of Aurora gas network simulator from the work done in [4]. The different colours of pipelines indicate different pressure levels. The stars indicate the location of sensors placed by the optimal sensor placement algorithm based on hundreds of random demand scenarios in the network.

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Aurora has the capabilities of simulating district networks with the quasi-steady state solver and transmission networks with the transient solver. The model can calculate the line packing volume and the stored gas at any timestep in a simulation. Multiple gas compositions are possible, as it is up to the user to define the composition of the gas at each inlet point. Aurora then tracks the composition and returns it as part of the results. The model can be coupled with another Python algorithm, Astraia, which also was developed by TNO, and its purpose is to find the optimal sensor locations for pressure, flow, or gas quality sensors [4]. Aurora is coupled with a smart controller which can dynamically regulate the pressure or flow setpoints defined in the scenario to ensure that the supply is achieved.

For a simulation with Aurora several input files are required. The definition of the assets and the geometry of the pipelines can be created in the Energy System Description Language (ESDL) map editor, a web-based tool which allows the user to draw the network and place the assets in a user-friendly graphical user interface. Alternatively, a set of .json files with Geographical Information System (GIS) data is compatible with Aurora, where all the parameters can be defined and adjusted manually. Moreover, the scenario which includes the hourly profiles of demand or supply is given in a .json file. For the prediction of demands, meteorological data are loaded as a separate file.

EnergyModelsX

EnergyModelsX (EMX) is an energy system modelling framework which was recently deployed as an open-source code [5]. SINTEF's development of the EMX model is driven by the vision to enable advanced research through the optimization of energy systems in a clean, concise, and versatile environment, offering numerous opportunities for expansion. The code is written in Julia, a programming language designed for numerical and scientific computing and is using the JuMP language for algebraic modelling for mathematical optimization.

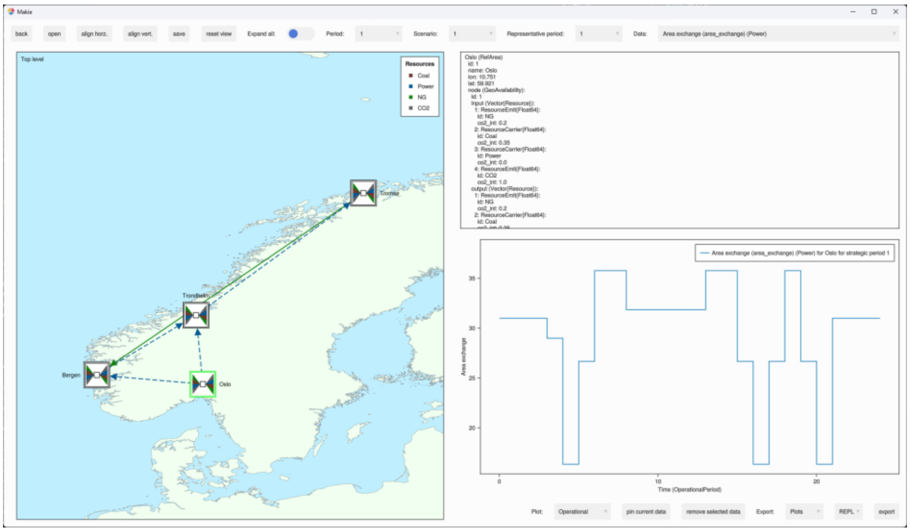

Figure 16: EnergyModelsX User Interface. It is designed to give a simple visualization of the topology of the model and enable the user to interactively navigate through the different layers of the model design.

The EMX code offers versatility with the expansion packages [6]. The packages allow the user to run time-dependent profiles for the input or output assets, to assign any composition to the energy carrier which is the gas in a gas network model and to add renewable producer assets in the model. Furthermore, with an extension package a gas network model can be expanded with geographical data to consider the location of the assets and with investments options to calculate the financial performance of the energy network. At the same time, there are not any specific packages for monitoring a gas network in real-time, for detecting leakages and for taking operational decisions to automatically control the gas network.

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EMX models may be written and executed in Pluto notebooks or Integrated Development Environments (IDEs) where all the assets are defined, and the input values are given. For larger models, input data can be read from e.g. YAML files and CSV files. The inputs can have the form of single values or time-dependent values, given as arrays by the user in the Julia script. Possible assets are the sources, sinks or network nodes which can be gas producers, consumers, power-to-gas, or other assets, depending on the definition of each node. It is also possible to include storage assets in a gas network model. Finally, after the model for a specific scenario is solved using a general purpose mixed-integer linear problem (MILP) (or potentially non-linear solver), the results can be exported in tabular form to e.g. csv files and plotted or analysed outside of the EMX framework.

PoliTo's gas network simulator

A group of researchers from Politecnico di Torino (PoliTo) developed an in-house gas network simulator on Matlab. The thesis report in [7] gives a detailed description of the simulator's capabilities. The simulator is now being further developed and used for research activities, including the HEU SHIMMER project.

The software is capable of simulating gas networks considering transient effects due to line packing, thanks to its transient solver. It is suitable for simulating mixtures of multiple gas compositions and has a gas composition tracking feature. It is a validated software (against other software results available from the scientific literature) and it is capable of simulating the high-pressure transmission networks or the local distribution networks. Numerous investigations of scenarios with biomethane and hydrogen injection have already been executed. As for the distribution system, the simulator is tested with use cases where an existing natural gas network was injected with biomethane [8] and hydrogen [9]. Concerning the transport tier, it has also been tested for the simulation of the transport of hydrogen blending through the Greenstream pipeline, including the simulation of the compression system [10]. The gas simulator by PoliTo takes as input the geometry of the network either from GIS files or from Excel based tables. In the files, the location and the geometry of pipelines are included as well as the location of gas assets like producers, demands, injection points and non-pipe elements such as compressors or reduction valves. The hourly or sub-hourly profiles for demands and for the injection points are also loaded in the model as a different set of files. Finally, all the boundary conditions and initial values like the gas composition at the suppliers/injection points and the maximum allowable percentage of injectable renewable gases are given in the code.

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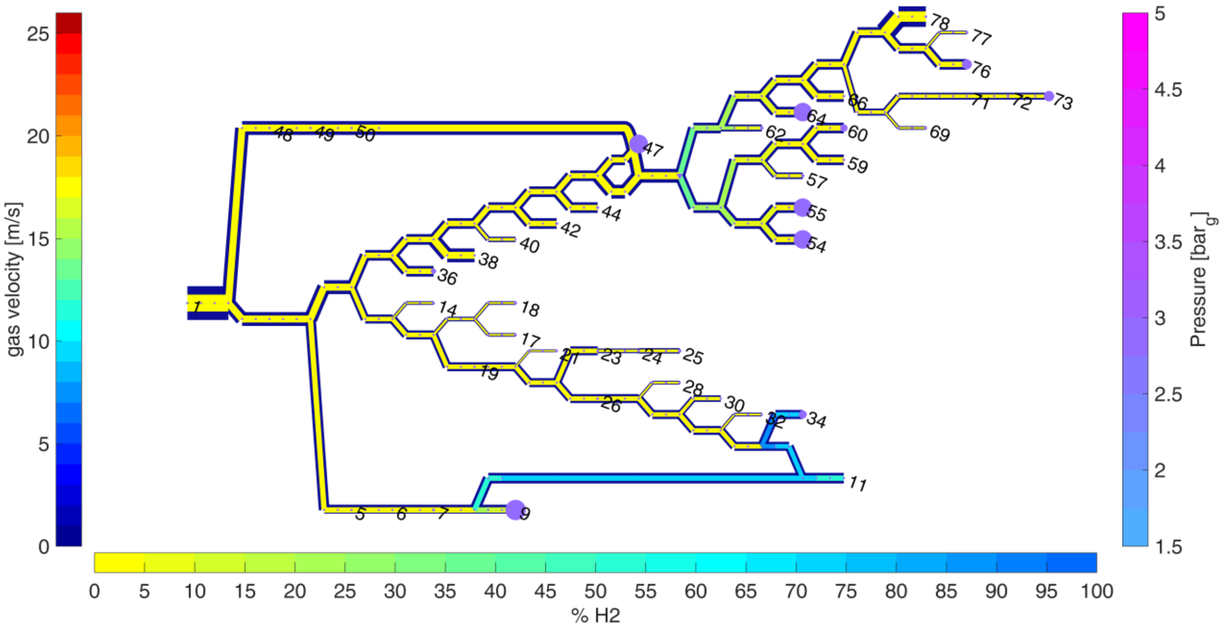

Figure 17: PoliTo's model graphical representation (snapshot) of the result of a transient simulation of a gas distribution network with two hydrogen injection points coupled with solar based hydrogen production.

Atmos SIM

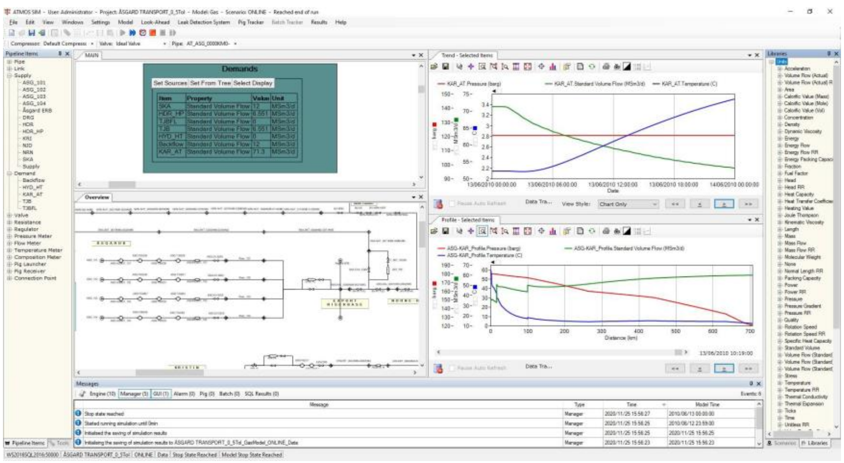

Figure 18: Atmos SIM graphical user interface. The user models the gas network and assigns parameters in this interface. The software makes the modelling quick by allowing the user to select asset types and parameters from its existing libraries.

Atmos International is an English company that specialized in pipeline integrity monitoring tools. The company is known for its leak detection tools and has a few decades of experience in this field. Atmos SIM is implemented by the Norwegian TSO operator GASSCO in every-day operational tasks and integrity checks [11], [12]. The software package is commercial with a paid subscription.

The simulator uses a transient solver, thus the line-pack in high pressure transportation pipes is calculated. The model is connected to a SCADA system which collects measurements of flow, pressure, temperature and fluid

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composition at the inlets and outlets of the network. The model has the capabilities of automatic tunning the roughness and efficiency values, gas composition tracking, thermal modelling and performing lookahead simulations based on the measurements. The leak detection and leak location are what Atmos SIM is mostly known for as it enables the operators to perform integrity checks.

The required inputs for the model are the network geometry, the boundary conditions, the properties of the pipes and fluid, meteorological data, and hourly profiles for the demands. The solver calculates as output the flow, pressure, and gas composition. Based on the measurements and weather forecast, the model also provides the lookahead simulations which are critical data for taking operational actions in the network.

SIMONE

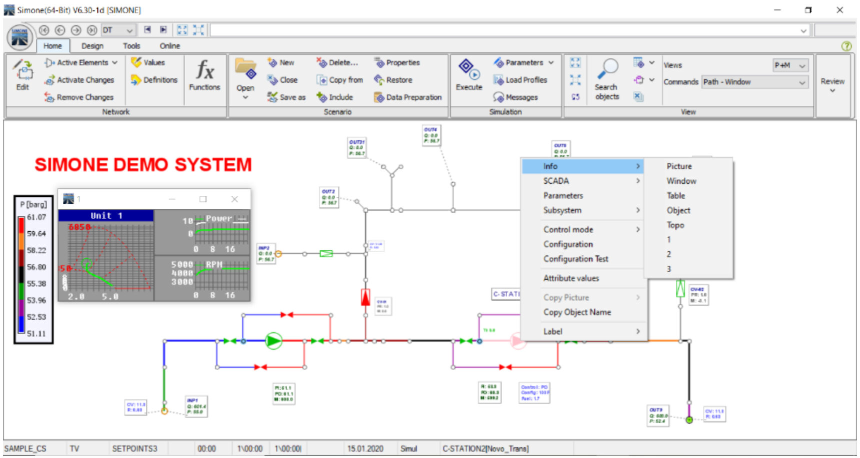

Figure 19: The graphical user interface of the SIMONE model. The screenshot is from the company's website [9].

The **SIM**ulation **O**ptimization **NE**tworks (SIMONE) is an operational gas network model, developed by SIMONE research group s.r.o. The company is a spin-off of the Czech Gas Industry and the Institute of Information Theory and Automation of the Academy of Sciences of the Czech Republic. The SIMONE model is used by the Italian TSO operator SNAM and the Polish TSO operator GAZ-SYSTEM. The software is a commercial package with a paid subscription.

SIMONE implements a transient solver and considers the line-packing effect of high-pressure transportation pipelines. It has the capabilities of gas composition tracking, training tools for trainees, calculation of the calorific value of the delivered gas. The graphical user interface in Figure 19 provides an environment where the user can design and simulate the network. SIMONE is integrated with a SCADA system to retrieve measured values from the field. The operator can monitor in real-time the gas network and optimize the transportation of natural gas [13], [14].

The required inputs for SIMONE are the field measurements of pressure, flow and gas composition, the geometry and properties of the pipelines and the consumption profiles at the demands. SIMONE does not require geographical data as the pipelines can be design in a graphical user interface by the user.

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NextGen

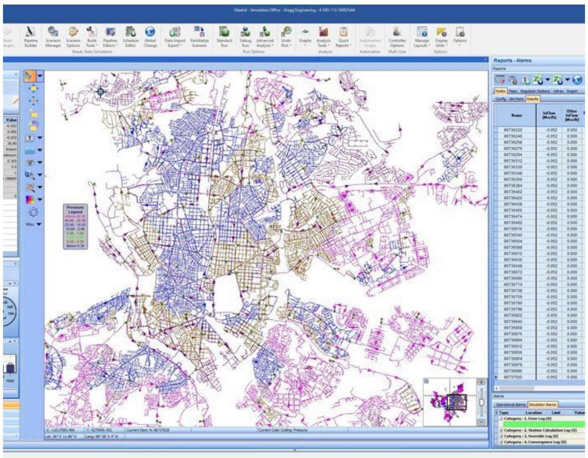

Figure 20: NextGen user interface from Gregg Engineering's website [15]. The user can model the gas network, prepare the scenario, and run the simulation via the graphical user interface. NextGen is presenting the pipelines with different colours to help the user read the results easier.

NextGen Simulation Suite is the gas and liquid network simulator developed by Gregg Engineering [15], a U.S.-based company specializing in developing simulation software packages for the pipelines industry. The NextGen software is used by the TSO operator ENAGAS on the Spanish gas network. It is a commercial type of tool, distributed by Gregg Engineering.

The software package includes both steady state and transient models, which makes the simulator capable of calculating and considering the effect of line packing in a high-pressure network. It can simulate different composition of gases and track the gas composition; it is coupled with a SCADA system for monitoring in real-time the gas network and it includes a graphical user interface. The software has various applications, some examples are:

- Steady state: a model for simulating the gas network model during the design or the operation of the grid.
- Transient-Predictive model: For performing Predictive and Look Ahead analysis considering any number of scenarios or external factors.
- Leak detection model which works with real time data to identify a failure or leak in the pipelines.
- System optimization: tools for optimizing the operation of the gas network on a day to day or long-term basis.

The gas networks are either imported as shape files or GIS data, or in the case of new pipelines the integrated designed tools can be used to draw new pipelines and add components like valves, stations, injections points etc. The network The Scenario Manager application is used to define the scenario and prepare the simulations.

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Synergi Gas

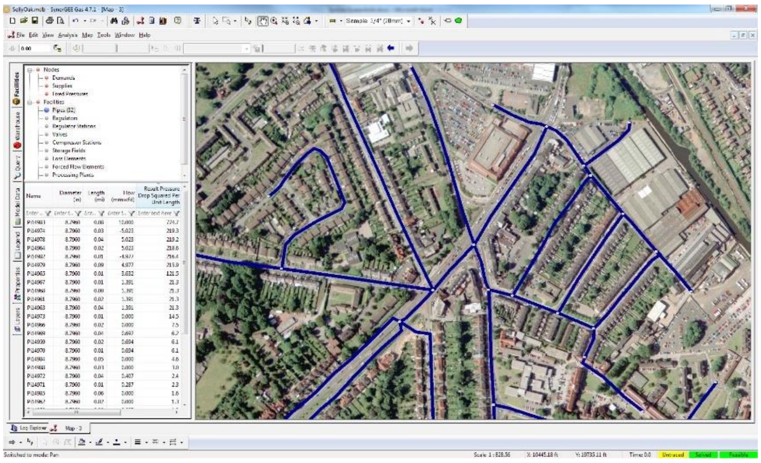

Figure 21: Synergi Gas graphical user interface. The user can draw, prepare and simulate the network in the Synergi Gas environment.

The Synergi Gas software developed by DNV GL offers operators the tools for planning, maintenance, and operation of the gas network [16]. DNV is a company based in USA and has expertise in the gas network analysis, innovation, and gas software domain. The software is not currently implemented but it is intended to be implemented for future studies by Redexis, DSO operator in Spain.

The software utilizes a steady-state hydraulic model, and the simulations are used for the design, planning and operational decisions. The absence of a transient solver indicates that the time-dependent effect of line-packing is not calculated for high pressure and volume transmission pipelines. The software allows the modelling of various gases, for example natural gas, hydrogen, biogas, ammonia, and carbon dioxide. At the same time, it is capable of modelling blends of gases and track the composition of the gas flow in the pipes. It is a monitoring tool as it is coupled with a SCADA system, and it allows the operator to monitor in real-time the network. It does not include a leak detection functionality, nor an automatic controller for operational decisions. The Synergi Gas software has additional features like:

- Day-to-day planning and operational support.
- Capability of linking the customer database for integrated operation of the network.
- Optimization of compressors and regulators operation for lower fuel cost and maximum profile and system capacity.

A gas network is modelled with Synergi Gas by importing GIS data of an existing network topology or designing new pipelines. The assets that are compatible with the software are pipes, regulators, valves, compressors, storages, and production wells.

ReteGas

ReteGas is the gas network simulator developed by the Italian DSO operator INRETE. The simulator is a commercial software which can be licensed to external users.

Retegas consists of a calculation code that processes the input data and returns the results. The commercial software Infoworks WS by Autodesk is employed for preparing the network model and visualizing the results. The simulator includes steady state solver and does not include a transient solver. Therefore, the effect of linepacking in high pressure transportation networks is not calculated. Besides, the software can simulate low-, medium- and high-pressure pipelines. Multiple gas species can be defined. Retegas can simulate scenarios

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with equipment outages or future scenario, and it is not able to monitor the operation of the network as there is no coupling with real-time measurements. The algorithm cannot track the gas composition in the pipelines, detect leakages nor perform operational decisions since there is not an automatic controller [17].

For a simulation with ReteGas, GIS data are imported and prepared with an external software like Inforworks WS. Then, the GIS data are imported in ReteGas with the definition of the assets and the scenario.

5.2 Conclusion on gas simulator comparison

In the current chapter the available gas network models were introduced and compared to each other with the purpose to identify the most suitable models for the simulations that are performed in Task 4.2 and 4.3. The selected models will be used for determining the operational strategies of gas networks with hydrogen blending by investigating different scenarios. The selection is made by taking into account the type of scenarios and the components included in the Realistic cases. As discussed earlier, the test cases are simple networks that can be performed with most if not all of the available gas network models. The realistic cases included more complex networks and more complex inputs. Some important network complexities that need to be compatible with the selected gas network models are the high-pressure pipelines and the effect of line packing, mixing of two gas species, evolving gas quality, compressor assets, deblending assets and tank or underground gas storage assets.

Consequently, the gas network simulation models need to include some key features to perform simulations on the realistic cases' networks. The most important features required for are:

- Transient solver capable of capturing line pack storage effects in high-pressure pipelines
- Gas properties to include gas composition and a mixture model to calculate properties of any kind of gas mixture.
- Gas quality tracking feature that tracks the gas composition of each pipeline and calculates the new gas composition at mixing points.
- Simplified compressor model
- Simplified gas separator model. An asset which is able to deblend hydrogen and natural gas, and ensure the required natural gas purity to sensitive users
- Simplified storage model

where concerning the las three points, the simplified models of those network items consist of "black box models" simulating the impact on the network fluid-dynamics of the behaviour of each element.

These features are the minimum for performing the decided scenarios. The research partners have proposed and reported the scenarios and their goals in chapter 4.6 and 4.7 of the current report.

Additionally, the gas network models need to be compatible with the input data format and provide sufficient output. The DSO and TSO network data are in GIS format and includes layers with the location of the assets. The input data will include geographical data, in the form of GIS data, demand profiles and control strategies at the storages and conversion assets. The minimum output data are defined by the research questions or the goals of the current study. The required output values are timeseries data of pressure, flow rate and gas quality in the grid.

Based on the feature requirements, a selection of gas network models was made. The three gas network models developed and implemented by the research partners were selected: Aurora, PoliTo's model, and EnergyModelsX. The first two models include the required features that enough to perform the defined scenarios and bring their unique features which will be valuable for answering the research questions. Any missing feature (e.g. the gas separator model) shall be added along with the development of Task 4.2. Meanwhile, EnergyModelsX was chosen as the optimisation model for evaluating and finding optimal blending strategies as well as for delivering guidelines to TSOs in Task 4.3.

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6 Conclusions and Future Works

The activities carried out as part of Task4.1 resulted in several Test and Realistic Cases, as well as a detailed comparison of multiple gas network infrastructure models. Three gas network models were selected to be used in the subsequent WP4 tasks, namely, Aurora, EnergyModelsX and PoliTo's model. In total, we have five realistic networks with detailed topology information (pipe diameter, length, thickness, material, location, compressor, reduction station, etc.). This information is essential for achieving accurate simulation results mimicking the actual gas network infrastructure.

Furthermore, TSO/DSO partners are supportive and cooperative in providing topology of the network and in contributing on the definition of the scenarios. Collecting sensitive data related to operational gas networks (e.g., flow rate, consumption, pressure, temperature, gas composition, etc.) faced several challenges., mainly due to privacy and security issue. However, TSO/DSO partners have agreed that the measurement data will be provided as long as the data stays within the project share point, only accessible by consortium members, and it is removed at the end of the project.

All the resources gathered and created as part of Task 4.1 will be used for answering the objectives of WP4 subsequent tasks in SHIMMER. Particularly, the realistic cases and scenarios will be used in Task 4.2 by SINTEF to optimize network design and in Task 4.3 by TNO and PoliTo for operational strategies for injection and flow transport management. The research partners will use their own gas network model for analysis and the use of commercial tools from TSO/DSO partners are for cross comparison and validation.

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A Appendix A

TSO Network and Data Requirements

Topology	Requirement
Component	Find the existing network that has elements: NG inlet point, demand (outlet point or reducer station), pipe, 2 pressure levels with reducer station (optional), NG storage (optional)
NG inlet point	Minimum two NG inlet points. The outlet pressure setpoint information
H2 injection point	If there is any plan for H2 injection points, otherwise we will create artificial location for the scenario.
Pipeline	A (regional) area that has 100-1000 km pipeline length with a tree-shape or a ring-shape topology with < 5 loops. The pipeline operating pressure range
Demand	All outlet points in the network, it can be direct consumer, export or reducer station to a lower pressure level
Compressor station	Minimum 1 compressor station in the pipeline. The compressor information (outlet pressure, compressor maps, operating mode)
Reducer station	(optional) if the network has 2 pressure levels with reducer station. Please provide any relevant information about operating/control mode (delta P range, max/min flow rate etc.)
NG storage	(optional) if the network has underground gas storage
H2 storage	(optional) If there is any plan for H2 storage, otherwise we will create artificial location for the scenario.
Deblending facility	(optional) If there is any plan for deblending, otherwise we will create artificial location for the scenario.

Data	Requirement
Demand Flow	Hourly flow profiles in 1 year of each outlet point
Demand Pressure	Hourly pressure profiles in 1 year for each outlet point
Supply Flow	Hourly flow profiles in 1 year for each inlet point
Supply Pressure	Hourly pressure profiles in 1 year for each inlet point
Compressor Flow	Hourly flow profiles in 1 year for each compressor
Compressor Pressure	Hourly pressure inlet and outlet profiles in 1 year for each compressor
Compressor Power	Hourly power profiles in 1 year for each compressor
Storage (if any) Flow	Hourly flow profiles in 1 year for each flow, initial fill capacity
Gas composition	Complete composition, but at least hourly Calorific Value and relative density at all entry points of the grid

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Pressure Measurement	Any pressure measurements available in the grid, next to supply and demand pressures. (hourly, 1 year)
Flow Measurement	Any flow measurements available in the grid, next to supply and demand flows (hourly, 1 year)

DSO Network and Data Requirements

Topology	**Requirement**
Component	Find the existing network that has elements: NG inlet point, demand (combination small industrial cluster and residential), pipe with meshed grid, 2 pressure levels with reducer station
NG inlet point	Minimum two NG inlet points. The outlet pressure setpoint information
H2 injection point	If there is any plan for H2 injection points, otherwise we will create artificial location for the scenario.
Pipeline	A (regional/city) area that has 1-500 km total pipeline length with a meshed grid. Multiple pressure levels (e.g. 8 bar, 3 bar, 100 mbar)
Demand	All outlets point in the network, it can be direct consumer (domestic and small industry) or reducer station to a lower pressure level
Compressor station	Not needed
Reducer station	All reducer stations in the network. The outlet pressure setpoint information. Please provide also any relevant information about operating/control mode (delta P range, max/min flow rate etc.)
NG storage	Not needed
H2 storage	Not needed
Bi-directional Booster	(optional) if there is any network with this component

Data	**Requirement**
Demand Flow	Hourly flow profiles in 1 year of each outlet point
Demand Pressure	Hourly pressure profiles in 1 year for each outlet point
Supply Flow	Hourly flow profiles in 1 year for each inlet point
Supply Pressure	Hourly pressure profiles in 1 year for each inlet point
Reducer Station Flow	Hourly flow profiles in 1 year for each reducer station
Reducer Station Pressure	Hourly pressure inlet and outlet profiles in 1 year for each reducer station
Gas composition	Complete composition, but at least hourly Calorific Value and relative density at all entry points of the grid

The research leading to these results has received funding from Horizon 2020, the European Union's Framework Programme for Research and Innovation (H2020) under grant agreement n° 101111888.

Pressure Measurement	Any pressure measurements available in the pipeline (hourly, 1 year)
Flow Measurement	Any flow measurements available in the pipeline (hourly, 1 year)

B Appendix B

This is part of Task 4.1.3 Operational gas network models. A comparison of the main features of all the available simulators was made in chapter 5. A more in-depth comparison is made in the current appendix based on the most important and relevant to the simulations.

The appendix comprises two parts. The first part is the definition of the gas network simulators which are considered for the comparison. The features are defined to set a common reference point for a clearer comparison. The second part is the comparison table. The table gives a simplified comparison about the features by stating if a feature is included or not in each gas network simulator.

B.1 Definition of features

1. Software availability

The simulators are characterized by their availability. The categories are:

- Not publicly available: A software which is developed, owned, and maintained by the same company. The software is not available to other parties.
- Open source: The software is maintained by one company/research group. It is freely available to everyone to implement and develop without any license.
- Commercial: The software is developed, owned, and maintained by one company. It is available to implement with a paid license.

2. Network compatibility

The gas network simulator could be capable of simulating a transportation network (TSO) or a distribution network (DSO). The two types of networks have differences in the pressure, the length of the pipes and the effect of line packing.

3. Steady state solver

The equations solved by a steady-state solver do not include a time-dependent term. Therefore, time does not influence the solution. The steady state solver calculates the fluids properties when the flow has reached the steady state. This type of solver is suitable for quasi-steady state flows, which change very slowly with time and can be assumed steady.

4. Transient solver

The equations solved by a transient solver include at least one time-dependent term, and it requires a timestep value. The solution changes as time moves forward because each solution is dependent on the previous timestep and the timestep value. This solver is suitable for high pressure gas networks with high line pack effect.

5. Line pack calculation

The ability of the simulator to estimate the volume of line pack which acts as a storage. The volume of line pack is also the storage capacity of the pipelines, and it affects the pressure increase/decrease rate.

6. Real-time monitoring

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The gas network software is receiving real-time measurements from the actual gas network for the calculations. This feature enables the simulator to act as a monitoring tool for the operator.

7. Multiple gas compositions

The composition can be defined by the user as a list of fractions of each gas species, or a predetermined gas mixture is selected. Gases that are required for the tasks of the current project are natural gas, hydrogen, and biogas.

8. Gas composition tracking

The composition of the flow is estimated at each pipe for each timestep. With these values, the composition changes can be show in the results.

9. Forecasting, Look-ahead simulations.

An algorithm that considers meteorological data and historical data of supply and demand. It can predict the future supply and demand values to enable the network operator to make proactive decisions.

10. Graphical user interface

The simulator includes a user-friendly interface and does not require any programming skills from the user. The operation of the software is done by drawing the network on a map, importing input files, or taking actions with buttons on the interface.

11. Spatial resolution

- **Map based:** The pipeline path is identifiable on a map and the path follows the existing pipelines or the design of the new pipelines that will be installed in the future. The length, diameter and roughness of the pipelines directly affect the pressure drop and flow velocity in each pipeline. The calculation of the pressure drop due to the friction in the pipelines is **more** accurate.
- **Connection between assets, no map:** The assets can be distinguished from each other. The geometry of pipelines is simplified. The effect of length, diameter and roughness are approximated or not considered for the calculation of the pressure drop and flow velocity of the gas. The calculation of the pressure drop due to the friction in the pipelines is **less** accurate.

12. Time resolution

The time step used for the simulations. If the time step is one hour, then for a one-day simulation the solution is calculated at 24 instances in a day. Consequently, the solved variables can be also plotted as a function of time.

13. Components compatibility

A list of available components which can be included in the gas network model. Common components for a gas network are:

- Pipeline
- Supply/Injection point

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- Demand
- Storage
- Power-to-gas asset, for example electrolyser
- Gas-to-power asset, for example fuel cell
- Pressure reducing valve/Pressure reducing station.
- Shut-off valve.

14. Unique features

Features that are not common across the available simulators investigated by the current literature review study. The feature might not be immediately required for the research purposes of the HEU Shimmer project. Though, the unique features may be key features for the intended applications of each gas network simulator.

B.2 Comparison of simulators based on available features.

Table 10: Features of available gas network simulators.

Simulator	AURORA	PoliTo	ATMOS INTERNATIONAL	SIMONE	NextGen	SYNERGI™ GAS	ReteGas
Proposed by	TNO	Politecnico di Torino	GASSCO	SNAM, GAZ-SYSTEM	ENAGAS	REDEXIS	INRETE
Software availability	Not publicly available	Not publicly available	Commercial	Commercial	Commercial	Commercial	Commercial
Network compatibility	TSO + DSO	TSO + DSO	TSO	TSO and DSO	TSO	DSO	DSO
Steady state solver	✓	✓	✓	✓	✓	✓	✓
Transient solver	✓	✓	✓	✓	✓	✗	✗
Linepack calculation	✓	✓	✓	✓	✓	✗	✗
Real-time, Monitoring	✗	✗	✓	✓	✓	✓	✗

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Simulator	AURORA	PoliTo	ATMOS INTERNATIONAL	SIMONE	NextGen	SYNERGI™ GAS	ReteGas
Multiple gas compositions	✓	✓	✓	✓	✓	✓	✓
Gas composition tracking	✓	✓	✓	✓	✓	✓	✗
Forecasting, Look-ahead simulations	✗	✗	✓	✗	✓	✓	✗
Graphical user interface	✓	✗	✓	✓	✓	✓	✗
Spatial resolution	Map based	Connection between assets (possibility to visualize results on maps),	Connection between assets, no map	Map based	Map based	Map based	Map based
Time resolution	1 hour	1 hour or less	1 minute	1 hour	1 hour	1 hour	1 hour
Components compatibility	pipe, supply, demand, compressor, pressure reduction	pipe, supply, demand, compressor, pressure reduction	Pipe, supply, demand, valve, reduction station, storage	Pipe, supply, demand, pressure reducing station, valve,	Pipe, supply, demand, compressor, pressure reduction	pipes, regulators, valves, compressors, storages, production wells	Pipe, supply, demand, pressure reducing stations, shut-off valves

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	station, storage, valve	station, storage, valve		compressor, storage	station, storage, valve		
Simulator	AURORA	PoliTo	ATMOS INTERNATIONAL	SIMONE	NextGen	SYNERGI™ GAS	ReteGas
Unique functionalities	Smart sensor placement for flow, pressure and quality sensors, dynamic pressure control	Dynamic city gate and compression stations controls (ON-OFF status according to calculated network conditions); nodal maximum injectable hydrogen calculation	Leak location, automatic model tunning	Modelling and optimization of compressor stations	Training application	Optimization of compressors/regulators, customer information, thermal tracking	✗

* The EnergyModelsX (EMX) model by SINTEF was not included in the comparison table because the table is about the comparison of gas network simulators. EMX is mostly used as an optimization tool for gas networks therefore the features could not be immediately compared to other available gas network simulators.

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