

Article

Scenario-Based Modeling and Assessment of the Future European Hydrogen Backbone

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Abstract

The evolving hydrogen transmission network is a key component of Europe's energy transition. This study assesses whether the planned European hydrogen transmission grid can accommodate projected regional supply and demand in 2030, 2040, and 2050. Scenario data from the TransHyDE System Analysis project are combined with GIS-based network models in order to perform European-scale hydraulic simulations. The modeled topology integrates the European Hydrogen Backbone and the German hydrogen core network. The assessment considers operational thresholds for pressure and flow velocity. Results indicate that the fragmented 2030 network can satisfy demand at the time of maximum aggregated regional (NUTS 3-level) consumption. By 2040, the grid develops into a largely meshed system. However, regional supply–demand imbalances and high hydrogen imports from North Africa cause elevated pressures in southern Spain and Italy. The affected pipeline segments have maximum operating pressures of 50–80 bar, whereas simulated pressures reach approximately 130 bar in 2040 and up to 200 bar in 2050. The southern European pipelines and interconnections between the Iberian Peninsula and Central Europe therefore appear insufficiently dimensioned under the investigated scenario.

Keywords: hydrogen transmission networks; hydrogen infrastructure; European hydrogen backbone; hydraulic network simulation; energy system scenarios; hydrogen storage; pipeline repurposing; network bottlenecks



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1. Introduction

Climate neutrality is a core policy goal in Europe because it reduces climate-related risks while maintaining a secure energy supply [1]. Renewable electricity will play a significant role in future energy systems. Nevertheless, molecules such as hydrogen will remain indispensable across different sectors and are expected to support the complete transition away from fossil fuels [2].

From a system analysis perspective, a focused hydraulic assessment of the future hydrogen backbone is necessary to identify potential bottlenecks and supply risks. The importance of this perspective has increased in recent years, as continental geopolitical disruptions such as the Russian invasion of Ukraine have exposed structural vulnerabilities in the European energy system [3]. This fact raises the question of whether planned hydrogen transport infrastructure can reliably connect future supply and demand under

physical network constraints. In response to these challenges, hydrogen infrastructure projects have been incorporated into Europe's Ten-Year Network Development Plan [4]. The recent establishment of the European Network of Network Operators for Hydrogen (ENNOH) further demonstrates the institutional and regulatory significance of dedicated hydrogen infrastructure. ENNOH also supports the coordination of cross-border network planning in Europe. These developments are supported by broader EU strategies, such as REPowerEU [5], the *Energy System Integration Strategy* [6], and the *EU Hydrogen Strategy* [7].

Final energy consumption of hydrogen is projected to reach 289 TWh by 2030, 934 TWh in 2040, and 1,841 TWh by 2050. The industrial section is expected to account for the largest demand [8]. For comparison, *ENTSO's Summer Supply Outlook 2026 with Winter 2026/27 Overview* indicates a reference methane demand of 2,965 TWh for winter 2026/27 across the countries considered [9].

Hydrogen can store energy from surplus renewable electricity and serves as an industrial feedstock and an energy carrier for transport applications. Hydrogen demand and production will be linked by infrastructure, most prominently by the future European hydrogen backbone (EHB). The EHB initiative proposes a comprehensive cross-border pipeline network connecting member states. It is expected to reach approximately 28,000 km by 2030 and 53,000 km by 2040. Around 60% of the 2040 network consists of repurposed natural gas pipelines and 40% of new pipelines. This requires an estimated investment of about €80–143 billion [10–12].

At the same time, the number of hydrogen-related projects continues to grow, as documented in successive updates of the hydrogen project information platform *Hydrogen Infrastructure Map* [13,14]. National planning efforts are aligned with these objectives, with Germany's hydrogen core network plan providing a prominent example [15,16].

Hydraulic network simulations enable a scenario-based assessment of transmission network performance. They also make it possible to evaluate whether hydrogen production and consumption can be reliably connected under physical constraints. This aspect is particularly relevant because renewable energy generation and hydrogen demand are often located in different regions. The resulting spatial mismatch requires sufficient transport capacity to ensure a reliable and secure energy supply.

Scenario-based analyses of production, consumption, and technological development at national and European scales support these policies and planning processes. However, realistic assessments of potential supply bottlenecks require the explicit consideration of physical transport constraints. From a methodological perspective, two main approaches are commonly applied in network assessment. Capacity-based scenario models provide simplified system-level representations of infrastructure [17], whereas hydraulic simulations explicitly calculate pressures, flows, and operational constraints at the level of pipelines and network nodes [18]. This study adopts the latter approach. Hydraulic analysis captures pressure constraints, flow distributions, and operational feasibility. These aspects are not fully represented in capacity-based energy system models.

Publicly available datasets enable the reconstruction and analysis of gas transmission networks at sufficient spatial resolution for research applications [19]. Large-scale simulation of natural gas transmission networks is already an established practice. However, such analyses are often constrained by limited data availability and the complexity of existing networks [19,20]. In Europe, a substantial share of the current natural gas infrastructure is planned to be repurposed for hydrogen transport, offering cost and time advantages compared with new construction. Repurposing is therefore considered a key element of the transition pathway and is consistently emphasized in the scientific literature [18,21,22].

Several recent studies address aspects of this transition. These studies range from national and cross-border simulations to European-scale analyses.

Müller-Kirchenbauer et al. [23] focus on Germany and develop a comprehensive toolchain for transforming the natural gas transmission network into a hydrogen transport network. Their work provides an open database of the existing gas transmission system, together with methods for designing and assessing future hydrogen topologies. The simulation results demonstrate feasible development pathways for green hydrogen transport infrastructure while maintaining security of supply during the transition phase. At the methodological level, hydrogen-specific network simulations can be performed using different software environments. Kuzyaka et al. [24] benchmark MYNTS, pandapipes, and SIMONE using harmonized scenarios and propose a structured framework for evaluating the tools. Their simulations cover a German-scale network rather than a European-scale system.

A further regional analysis is provided by Cavana et al. [25], who examine the Sicilian gateway, a strategic entry point for hydrogen imports from North Africa to southern Italy. They compare hydrogen blending with the repurposing of an existing pipeline for dedicated hydrogen transport. Their steady-state fluid-dynamic analysis evaluates transport capacity, pressure constraints, and compression requirements. This corridor is particularly relevant to the development of the European Hydrogen Backbone.

A recent study by Mielich et al. [26] examines hydrogen transport between Denmark and Germany within the TransHyDE project. Their approach integrates detailed scenario modeling with fluid-dynamic simulation of the hydrogen network. The study assesses the effects of increasing the capacity of the Denmark–Germany interconnector on cross-border hydrogen flows and network compatibility. Despite its regional scope, the study provides insights into the hydraulic implications of cross-border hydrogen trade.

At the European level, Mielich et al. [18] conduct an analysis within the same research project as the present study. The authors apply a spatial resolution at the NUTS (The abbreviation NUTS is derived from the French term *Nomenclature des unités territoriales statistiques* and refers to the European Union’s classification of territorial units for statistical purposes.) 3 level combined with an hourly temporal resolution. They derive an optimized network topology using the Steiner tree approach. Fluid-dynamic simulations are performed for 2030, 2040, and 2050 using the previously mentioned hydraulic simulation software SIMONE. However, their underlying energy system scenario [27] differs from the scenario applied in the present study [17,28]. Furthermore, their assumed network extent in 2030 is substantially smaller than that of the planned European Hydrogen Backbone, on which this study is based. Their results indicate that by 2040 an almost fully retrofitted network is optimal, deviating from original EHB planning assumptions [10–12].

At the European scale, complementary insights are provided by Kountouris et al. [29], who employ a fully sector-coupled energy system model rather than hydraulic simulation. Despite methodological differences, they identify similar infrastructural requirements. These include rapid scaling of electrolysis capacity, expansion of pipeline and storage infrastructure, and parallel deployment of renewable electricity generation. This perspective aligns with conclusions that accelerated renewable expansion reduces the cost of green energy and limits reliance on fossil alternatives [17]. Environmental and thermodynamic assessments further indicate that although hydrogen pipelines can support cleaner energy transport, both retrofitting and new construction entail non-negligible impacts that should be considered in pipeline design and compressor station planning [30].

These studies provide important system-level and environmental insights. However, only a limited number analyze large-scale hydrogen transmission grids with sufficient hydraulic detail, particularly at the European level [18,31–33].

This study supports robust energy system design and informed policy-making by integrating a detailed hydraulic infrastructure perspective to scenario-based energy system

analysis. For this purpose, European and German planning documents are combined to create a coherent network topology. For the years 2030, 2040, and 2050 the topology is simulated using stakeholder-driven hydrogen supply and demand data from the Federal Ministry of Research, Technology and Space (Bundesministerium für Forschung, Technologie und Raumfahrt, BMFTR)-funded TransHyDE System Analysis project [28].

The objective of this study is to identify scenario-specific bottlenecks, operational constraints, and systematic mismatches between the spatially resolved scenario assumptions and the available or planned pipeline infrastructure. The analysis provides a hydraulic plausibility check of the compatibility between the energy-system scenario and the network topology for each target year. The analysis highlights broad regional trends and potential mismatches without providing detailed network planning recommendations.

Against this background, this study makes three main contributions:

1. Development of a European-scale hydraulic representation of the planned hydrogen transmission grid, combining the European Hydrogen Backbone and the German hydrogen core network.
2. The integration of spatially and temporally resolved TransHyDE System Analysis data on hydrogen injection and withdrawal into a hydraulic pipeline model. This approach allows scenario-based supply and demand to be assessed against the physical constraints of the transmission infrastructure. Simulated pressures and velocities are compared with predefined threshold values.
3. A hydraulic stress test of the planned infrastructure for 2030, 2040, and 2050 using steady-state STANET[®] (Version: 10.3.35) simulations.

The remainder of the paper is structured as follows. Section 2 describes the underlying data sources, network modeling, and simulation methodology. Section 3 presents and discusses the simulation results for the considered target years. Finally, Section 4 provides the conclusions and outlook.

2. Materials and Methods

The methodology covers three main components, which build on one another and thus ultimately provide a comprehensive and coherent picture: (i) energy system modeling (Section 2.1), (ii) preparation of the GIS-based network model (Section 2.2) and (iii) hydraulic network simulation (Section 2.3). Energy system modeling provides spatially resolved hydrogen withdrawal and injection time series, while the GIS model represents the topology of the hydrogen transport network as well as associated infrastructure such as storage facilities, terminals and possible compressor station locations. The preparation of the scenario and GIS datasets is performed iteratively to ensure compatibility between both datasets, which is essential for meaningful hydraulic simulations. This step is vital, as the quality of the simulation results is strongly influenced by the quality of the input data.

2.1. Energy System Modeling—Scenario Time Series Preparation

An energy system scenario is a coherent and internally consistent set of assumptions about future drivers such as technology costs, policy frameworks, demand levels and resource availability. It is used to explore how the energy system may evolve under specific pathways or interventions. The scenario used in this study is described by Kigle et al. [17] and was developed within the TransHyDE System Analysis project (the so-called market expectation). It reflects stakeholder-based transition pathways for industry. Renewable capacity expansion is varied from 2025 onward in order to account for system uncertainty.

For a given scenario, energy generation data is compared with consumption data from the industry, electricity generation, heating and transport sectors. This approach enables a comprehensive assessment of hydrogen integration across the energy system. In

a subsequent step, the resulting data are allocated to regions, storage facilities, terminals and import points, as described in the following sections.

2.1.1. End-Use Sectors and Regional Hydrogen Supply

For use in the network simulations, end-use sector scenario data as described in [17] are spatially aggregated to the NUTS 3 level using centroid coordinates and the corresponding NUTS 3 codes. This aggregation is applied consistently across all end-use sectors, including the following:

- Industry,
- Power generation,
- Buildings,
- Commercial and public services,
- Transport.

In addition, NUTS 3 time series are provided for hydrogen production facilities, such as power-to-gas plants injecting hydrogen into the transmission grid. The resulting spatially aggregated hydrogen demand and production data used in the network model are shown in Figure 1.

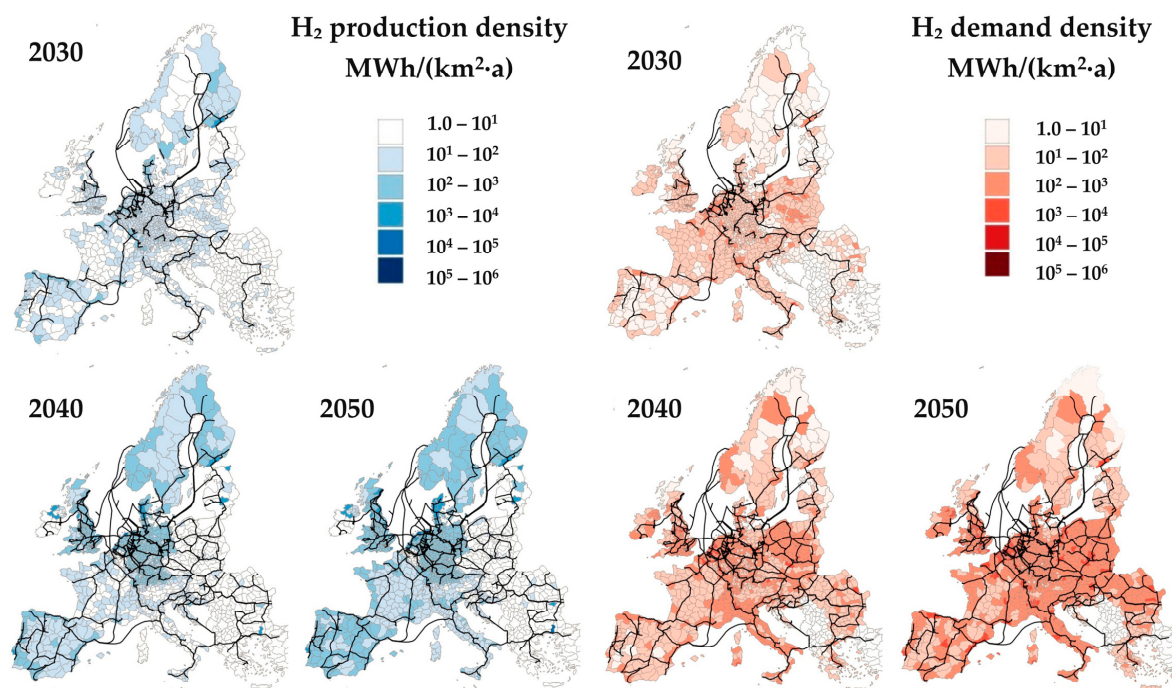


Figure 1. Hydrogen production and demand density for all target years, including the hydrogen transmission grids (black lines).

The results of the hydraulic simulations are strongly dependent on the underlying scenario assumptions. Site-specific modeling of industry, power plants, or other large consumers is not performed. As a result, the representation of connections to regions located far from the transmission network may appear unrealistic, particularly in the early target years. Nevertheless, no regions are excluded based on their distance from the transmission network or on minimum consumption or production thresholds. Some islands would likely not be supplied via direct pipelines for economic reasons, and alternative transport options, such as maritime transport, are likely to be more suitable.

2.1.2. H₂ Underground Storages

From the perspective of a hydrogen transmission grid, storage facilities are important flexibility assets. They can buffer temporal imbalances between hydrogen injection, transport capacity, and regional demand [34].

The simplified analysis focuses on large underground storages, which typically have capacities exceeding 100 GWh. Owing to high uncertainty of long-term planning, differences between storage locations planned for 2040 and 2050 are not distinguished.

Storage time series data are provided at national level (NUTS 0), meaning that a single time series is available for each country. Storage locations are identified using the Hydrogen Infrastructure Map [14] (status Q4 2024), a joint initiative mandated by the European Commission and developed by ENTSOG, EUROGAS, GIE, GEODE, GD4S and CEDEC. The platform aims to visualize publicly reported hydrogen infrastructure projects across Europe, based on publicly available project information.

In contrast to regional supply and demand data, underground gas storages are represented by their explicit geographic locations. When multiple storage facilities are planned within a country, the national-level time series is distributed in proportion to their planned storage capacities. If no storage locations are available in the Hydrogen Infrastructure Map [14], locations identified using information from the European Hydrogen Backbone Initiative [10,35] or placed in proximity to the transmission grid assuming a single national storage site (in Romania and Norway).

Distributing time series proportionally to storage capacity is considered more realistic than assigning the entire time series to a single location. Alternative allocation approaches, such as distributions based on injection and withdrawal capacities, could yield different results. However, these parameters are currently not all publicly available.

2.1.3. Pipeline Imports and Terminals

Both terminals and pipeline import points are represented as unidirectional supply elements that inject hydrogen into the transmission system. Pipeline imports from the Middle East and North Africa (MENA) region are assigned to the southernmost import points in Spain and Italy, which are known entry locations in the network representation as shown in Figures 2 and 3.

H₂ import terminal data are also provided as national-level (NUTS 0) time series. Their preparation follows a procedure similar to that used for storage data. However, the national-level terminal time series are distributed evenly across all terminal locations within a country. Consequently, the disaggregation is not based on projected terminal capacities or other technical characteristics but follows an equal allocation approach due to limited terminal-specific information. This assumption reflects the lack of publicly available information on terminal specific capacities and operational characteristics, which are less comprehensively documented than those of underground gas storages. Furthermore, all terminal types capable of injecting hydrogen into the transmission network are considered, including dedicated H₂ terminals and ammonia-cracking terminals. The identifiable terminal locations are obtained from the Hydrogen Infrastructure Map [14].

For some countries, terminal projects cannot yet be geographically identified with sufficient precision based on [14]. Representative locations are therefore selected for Finland, Estonia, Latvia, Norway, and Sweden.

The scenario does not include terminal time series for the year 2040. This modeling outcome is linked to projected hydrogen prices, particularly the relative competitiveness of different supply options. In the energy system model, ship-based hydrogen imports are generally associated with higher costs than both pipeline imports and domestic hydrogen

production within Europe. As a result, both the overall level and the spatial distribution of hydrogen imports are affected, as discussed in detail by Kigle et al. in [17].

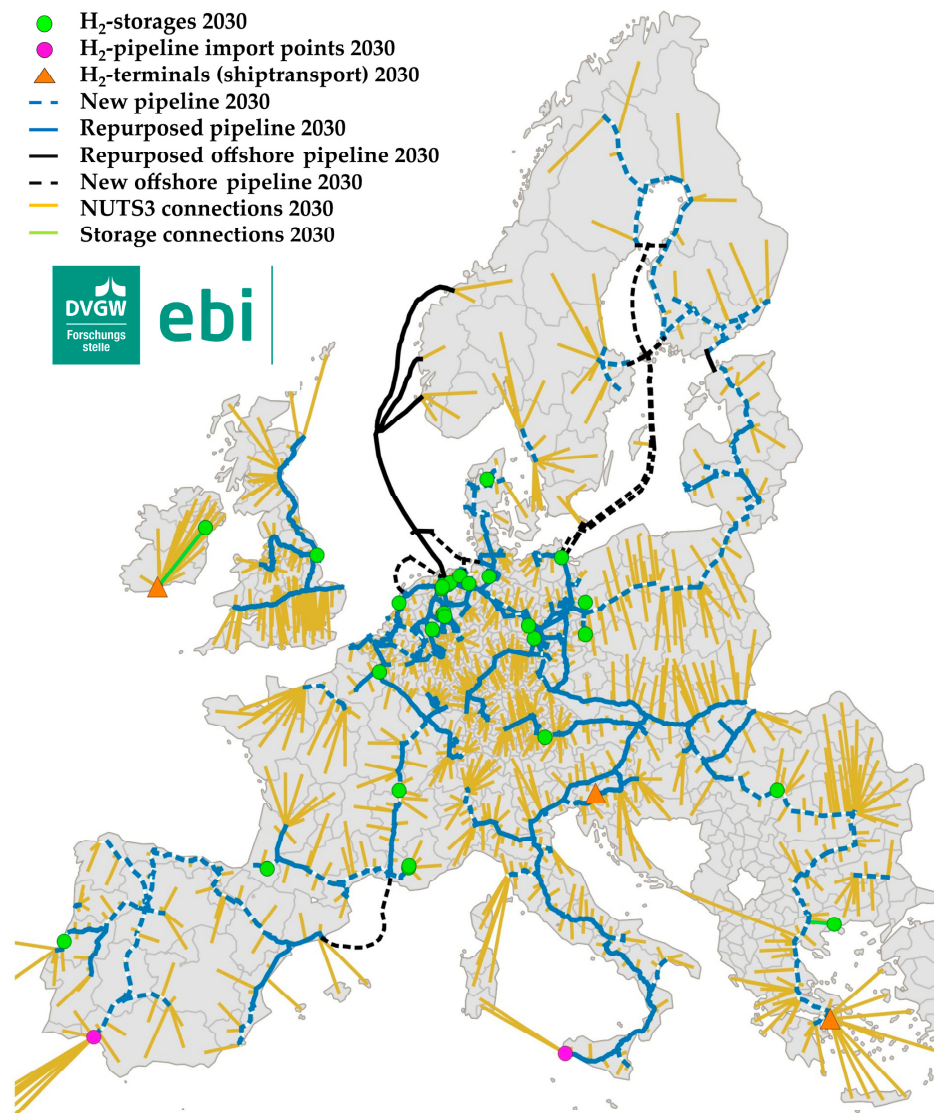


Figure 2. GIS model for target year 2030.

2.2. GIS Model—Network Topology Preparation

The network topologies are developed using georeferenced data in the open-source GIS software QGIS [36]. Key grid junctions and cross border connection points are mapped in all directions to achieve a sufficient level of spatial accuracy. The GIS data used for modeling hydrogen transport networks are based on publicly available planning documents at both the European and national levels. At the European level, the primary source is the European Hydrogen Backbone Initiative [10–12], with the most recent documentation of the European Hydrogen Backbone dates from November 2023 [10,35]. At the German level, the main reference is the documentation published by the Association of Transmission System Operators (TSO) and approved by the Federal Network Agency in October 2024 [15]. The modeled grid topologies for each target year and their corresponding data sources are summarized in Table 1. These target years are consistent with those defined in the underlying scenario data [17].

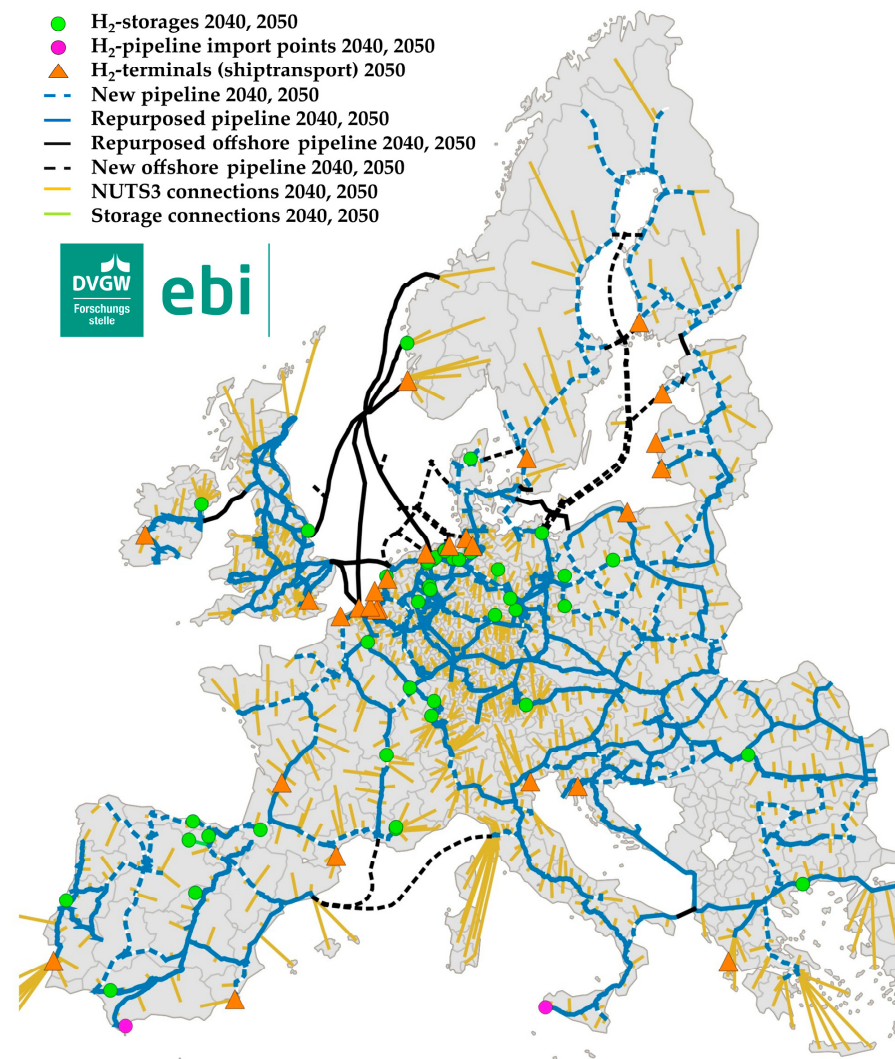


Figure 3. GIS model for target years 2040 and 2050.

Table 1. Modeled hydrogen transmission network topology for each target year and corresponding data sources.

Target Year	German Grid Topology	European Grid Topology
2030	German transmission pipelines planned for commissioning up to and including 2030 according to the German H2 Core Network approval document (10.2024) [15].	European transmission pipelines planned for commissioning up to and including 2030 according to the EHB (07.2023) [10–12], excluding Germany.
2040	All German transmission pipelines planned for commissioning according to the German H2 Core Network approval document (10.2024) [15].	All European transmission pipelines planned for commissioning up to and including 2040 according to EHB (07.2023) [10–12], excluding Germany.
2050	Due to the substantial uncertainties associated with long-term infrastructure planning, the network topology beyond 2040 remains difficult to assess. Therefore, the 2050 topology is assumed to be identical to the 2040 topology.	

Combining the formally approved German hydrogen core network with publicly available information on planned hydrogen infrastructure projects at the European level

enables a more detailed and realistic representation of a potential future European hydrogen transmission network than approaches based solely on announced hydrogen infrastructure projects or conceptual European Hydrogen Backbone visions [10–12]. Pipeline construction timelines are incorporated by assigning the published commissioning dates of individual projects to the corresponding pipelines and activating them in the model only from their respective target year onward. This approach allows the network topology to evolve consistently across the analyzed target years (2030, 2040, and 2050) in accordance with the available planning information.

More recent European infrastructure datasets are available, such as the Hydrogen Infrastructure Map [14], which is regularly updated and therefore reflects a more recent planning status of hydrogen pipeline projects and network topologies across Europe. However, many of the projects listed in such databases are still in early development stages and often have not yet reached a Final Investment Decision (FID). As a result, the European hydrogen infrastructure project landscape remains highly dynamic and subject to frequent revisions. Although the current version of the Hydrogen Infrastructure Map largely shows similar key onshore pipelines notable differences exist in the offshore transmission pipeline network compared with the topology used in this study.

The German network topology includes some pipeline projects that have not yet received final regulatory approval but are incorporated in the model based on the currently available planning information. Transmission pipelines listed as officially withdrawn or rejected in the documentation are excluded from the model.

Integration of Scenario Nodes into the Transmission Grid Model

Several elements derived from the scenario are represented in the model as sources or sinks of hydrogen flow. This section describes the methodological approach used to determine the connection points between scenario nodes and the transmission network and to integrate these elements into the GIS model. The elements considered include regional demand and production nodes, pipeline import points, hydrogen import terminals, and storage facilities.

In the GIS model, each NUTS 3 region is represented by a single node located at the geometric centroid of the region, to which the aggregated NUTS 3 hydrogen demand and production time series are assigned. The connection points to the transmission grid are determined using an automated spatial matching procedure that identifies the nearest transmission pipeline to each centroid node based on the shortest geometric distance. The resulting connections are generated automatically and subsequently reviewed, as the purely distance-based assignment does not account for topological or infrastructural constraints. Manual adjustments are therefore applied to prevent simplified connections from crossing national borders. In addition, they ensure that no grid junctions are located in marine areas.

The length of these connectors is artificially shortened to 100 m. This simplification is applied because the downstream distribution infrastructure is not modeled explicitly. Instead, only its interaction with the transmission grid is represented. Consequently, the purpose of the connecting pipelines is to define the coupling points between scenario nodes and the transmission network rather than to represent actual transport distances. Therefore, the distances between the NUTS 3 centroid nodes and the nearest transmission pipelines are not considered in the hydraulic calculations. Examples of these connections are shown in Figures 2 and 3.

The connection between the NUTS 3 centroid nodes and the selected transmission pipelines represents a simplified interface to the downstream distribution infrastructure. Detailed hydrogen distribution networks are not modeled, as publicly available information on their topology and capacity is currently very limited. Furthermore, each region is

represented by a single connection point to the transmission grid, which may not reflect real network configurations. In reality, some regions may be supplied by neighboring regions, via hub structures, or through multiple transmission connections.

Consequently, potential bottlenecks within regional distribution systems are outside the scope of the present transmission-level analysis. The connecting pipeline can therefore be interpreted as an aggregated representation of downstream transport structures, which may in reality consist of distribution grids, industrial branch lines, or potential hub-based supply concepts for more remote demand regions. The connection diameter is set to 500 mm, which is sufficiently large to avoid influencing results at the transmission grid level.

Pipeline import points are positioned directly at the southern termini of the Italian and Spanish transmission pipelines. The locations of the Spanish import points differ between 2030 and the later target years, 2040 and 2050. This difference results from changes in the European Hydrogen Backbone pipeline topology across the target years. The corresponding Geographic Information System (GIS) network models are shown in Figures 2 and 3.

For storage facilities and terminals, grid connection points are also determined using the shortest geometric distance to the transmission network, analogous to the NUTS 3 region connection approach, as the precise routing of future storage connection pipelines is not yet known.

As shown in Table 2, the European hydrogen transmission network model is summarized in a table-based overview, including pipelines, storage facilities, terminals, import points, and aggregated regional demand and supply nodes at the NUTS 3 level for all analyzed target years. The country codes indicate the location of the respective network elements.

Table 2. Table-based overview of the European hydrogen transmission network model for all target years.

	Year 2030	Year 2040	Year 2050
NUTS 3 nodes (demand and production)	EU-27 +3 (CH, GB, NO)		
Pipeline import points (Number of locations)	2 total—IT (1), SP (1)		
Underground gas storages (Number of locations)	30 total—DE (13), DK (1), FR (5), GB-ENG (1), GB-NIR (1), GR (1), NL (4), PL (1), PT (1), RO (1)	45 total—DE (19), DK (1), ES (5), FR (7), GB-ENG (1), GB-NIR (1), GR (1), NL (4), NO (1), PL (2), PT (1), RO (1)	45 total—DE (19), DK (1), ES (5), FR (7), GB-ENG (1), GB-NIR (1), GR (1), NL (4), NO (1), PL (2), PT (1), RO (1)
Hydrogen import terminals (Number of locations)	3 total—GR (1), CRO (1), IR (1)	Not included due to scenario assumptions.	26 total—BE (2), DE (3), EE (1), ES (1), FI (1), FR (3), GB (1), GR (1), HR (1), IE (1), IT (1), LT (1), LV (1), NL (5), NO (1), PL (1), PT (1), SE (1)

Terminals are excluded from the hydraulic simulations because the underlying energy system scenario assumes no hydrogen imports via terminals in 2040.

2.3. Hydraulic Network Simulation

This section discusses the governing equations and theoretical fundamentals of the steady-state simulation. See Section 2.3.1. Building on this basis, the integration of compressor stations into the network model is described in Section 2.3.2. Their inclusion is relevant because simulations can also be performed without compressor stations. However, incorporating compressor stations improves the representation of flow patterns and pressure conditions in the network. Finally, the boundary conditions and the initialization of the simulation are presented in Section 2.3.3.

2.3.1. Theoretical Fundamentals of Simulation

The relevant gas properties, including density, viscosity and compressibility, are specified through the STANET[®] gas-property settings. STANET[®] is a commercial hydraulic network simulation software widely used in gas infrastructure analysis [37–39].

The thermodynamical standard equation for real gases is as follows in (1):

$$p = \rho R_s T z \quad (1)$$

An isothermal flow assumption is applied within each simulation case. Elevation differences are neglected. The simulation approach follows an established hydraulic pipeline engineering practice and is based on energy-balance equations describing compressible gas flow [40]. Accordingly, gas density is not treated as constant, but depends on pressure, temperature, gas composition, and the real-gas compressibility factor. For gas networks, the frictional resistance (R) is therefore a function of both the flow rate (Q) and the pressure (p).

The compressibility factor describes the relationship between density and pressure [41]. Since this relationship is gas-specific, it is represented by the pressure factor K_{par} [42]. In STANET[®], a linear pressure dependency of the compressibility factor is used as the standard setting, as shown in (2):

$$K = 1 + K_{par} p \quad (2)$$

The pipeline volumetric flow is defined in a cylindrical pipe with diameter (D) and (v) being the mean flow velocity. See in Equation (3):

$$Q = \frac{\pi}{4} D^2 v \quad (3)$$

For turbulent flow conditions, expected in transmission pipelines, the Prandtl–Colebrook friction law is applied to determine the pipe friction factor (λ). See Equation (4). The formulation is widely used in gas network analysis and consistent with the German technical rules provided by the German Technical and Scientific Association for Gas and Water [43]. The friction factor (λ) characterizes frictional pressure losses along the pipe wall and is required to quantify hydraulic resistance in the pipeline equations. It depends on the Reynolds number (Re) and the relative pipe roughness (k/D), where k is the absolute pipeline roughness in millimeter:

$$\frac{1}{\sqrt{\lambda}} = -2 \lg \left(\frac{2.51}{Re \sqrt{\lambda}} + \frac{k}{3.71 D} \right) \quad (4)$$

A uniform absolute pipe roughness of 0.1 mm is assumed for all pipeline segments in the European network model. The Reynolds number is calculated as (5). Where (v) is the mean flow velocity and (ν) the kinematic viscosity:

$$Re = \frac{v \cdot D}{\nu} \quad (5)$$

The pressure loss in a pipeline segment is a function of the hydraulic resistance and the flow rate, as described in (6). This equation is also called the hydraulic resistance law. It can be expanded into the form shown in (7) [37,43,44]:

$$\Delta p = f(Q) = RQ|Q| \quad (6)$$

$$p(A) - p(B) = \frac{16 p_N \rho_N K T Q |Q|}{\pi^2 (p(A) + p(B)) T_N D^4} \left(\frac{L}{D} \lambda + \zeta \right) - \frac{\rho(A) + \rho(B)}{2} g(h(A) - h(B)) \quad (7)$$

This simulation does not account for elevation differences and assumes a flat network topology. Owing to this the second term in (7) disappears which results in then in $R(A, B) \propto |Q|$ in (8). When dividing with $(Q|Q|)$, the hydraulic resistance factor $R(A, B)$ can be derived. See (9):

$$p(A) - p(B) = \frac{16p_N\rho_NKTQ|Q|}{\pi^2(p(A) + p(B))T_ND^4} \left(\frac{L}{D}\lambda + \zeta \right) = R(A, B) |Q| \quad (8)$$

$$R(A, B) = \frac{16p_N\rho_NKT}{\pi^2(p(A) + p(B))T_ND^4} \left(\frac{L}{D}\lambda + \zeta \right) \quad (9)$$

The pressure and flow state of the meshed pipeline network is described by a system of nonlinear equations based on Kirchhoff's laws. See: node condition (10) and loop condition (11) [43]:

$$\sum Q_i = 0 \quad (10)$$

$$\sum \Delta p_i = 0 \quad (11)$$

Since the pressure-loss relation is nonlinear with respect to the flow rate, it is treated iteratively within the hydraulic network calculation. For the linearized equation system, the pressure difference between two adjacent nodes (i) and (k) can be written using an effective hydraulic resistance ($R(i, k)$) of the pipe section between these nodes. See (12):

$$p(i) - p(k) = R(i, k) \cdot Q(i, k) \quad (12)$$

Here, ($R(i, k)$) represents the effective, iteration-dependent hydraulic resistance used in the linearized form of the pipe equation. It therefore contains the influence of pipe properties and the current hydraulic state of the pipe section. The resulting equation system consists of pipe equations linking pressures, flows and hydraulic resistance, node equations enforcing mass balance, and loop or path equations enforcing pressure consistency. In steady-state simulations, the Newton-Raphson method is applied iteratively until convergence is reached and a hydraulic equilibrium of the network is obtained. The linearized system is solved using (13) and (14), where (i) denotes the node index, (k) the adjacent node index, ($p(i)$) and ($p(k)$) the pressures at nodes (i) and (k), ($Q_e(i)$) the external injection or withdrawal at node (i), and ($G(i, k)$) the conductance of pipe (i, k) [42]:

$$p(i) \cdot \sum G(i, k) - \sum G(i, k) \cdot p(k) + Q_e(i) = 0 \quad (13)$$

$$G(i, k) = \frac{1}{R(i, k)} \quad (14)$$

Convergence is controlled by user-defined precision thresholds and a maximum iteration limit. In this study, a maximum of 50 iterations is allowed and the target accuracy for pressure differences is set to 0.1 bar. During each iteration, the equations are linearized and solved using Gaussian elimination with optimized ordering according to Tinney, which improves computational efficiency for large sparse matrix systems [45].

In steady-state simulations, the system is solved for a single equilibrium state without explicit time dependence [37]. Kirchhoff's laws are enforced algebraically. The resulting solution represents the stationary operating condition of the network. Here flows and pressures are balanced and no further temporal changes occur.

2.3.2. Compressor Stations

Steady-state simulations are performed with compressor stations. The steady-state formulation allows the hydraulic impact of compressor stations on pressure levels and flow

patterns to be analyzed without implementing a detailed operational dispatch strategy. The stations are represented by simplified compressor elements in STANET[®]. Each compressor element operates unidirectionally and provides a pressure increase (pressure difference, Δp) between 2 and 9.8 bar, depending on the operating point along the implemented characteristic curve, see Figure 4. In practice, such large quantities are not handled by one machine but a group of compressors [46].

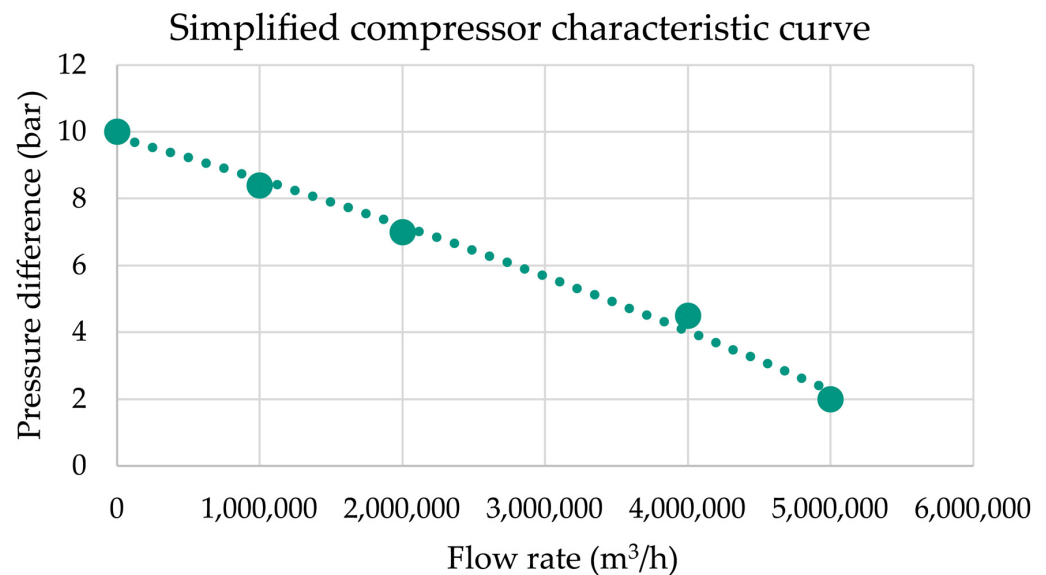


Figure 4. Simplified compressor characteristic curve showing the pressure difference (bar) as a function of the volumetric flow rate (m³/h at NTP). Normal temperature and pressure (NTP) correspond to 20 °C and 1.01325 bar. The circles indicate the supporting points used to define the compressor curve, while the dotted line represents the corresponding trendline.

The uniform compressor characteristic is a simplified representation of an entire compressor station. Internal plausibility checks showed that variations in this characteristic had only a limited effect on the location of critical pressure regions. This study focuses on broad hydraulic trends and the compatibility between the scenario data and the assumed network topology. A detailed sensitivity analysis of station-specific compressor characteristics is therefore beyond its scope.

Candidate compressor locations are primarily identified using SciGrid and Sci2grid datasets [47,48]. SciGrid (Open Source Reference Model of European Transmission Networks for Scientific Analysis) and its successor, Sci2grid, provide open reference models of European energy networks. These projects document compressor stations in existing natural gas transmission networks. Compressor stations located along pipelines assumed to be repurposed for hydrogen transport are therefore considered as plausible locations and are highlighted in dark blue in Figure 5. Since the SciGrid dataset does not include compressor stations along newly constructed hydrogen pipelines, additional candidate locations are identified. These locations indicate areas where additional pressure support may be required to maintain stable operating conditions within the hydraulic model.

The final selection focuses on compressor stations which are located in peripheral regions of the hydrogen transmission grid. This includes northern Europe, Spain and Italy. This placement reflects the large hydrogen import volumes expected from North Africa and the Norwegian coast. In addition, a compressor station is considered at the offshore pipeline connection point in the North Sea, in the vicinity of the Sleipner and Draupner floating platforms. This assumption is supported by existing experience with subsea gas compression in the region [49]. These platforms are described in the European Hydrogen

Backbone documentation [10–12] and are identified as candidates for future repurposing for H₂ transport.

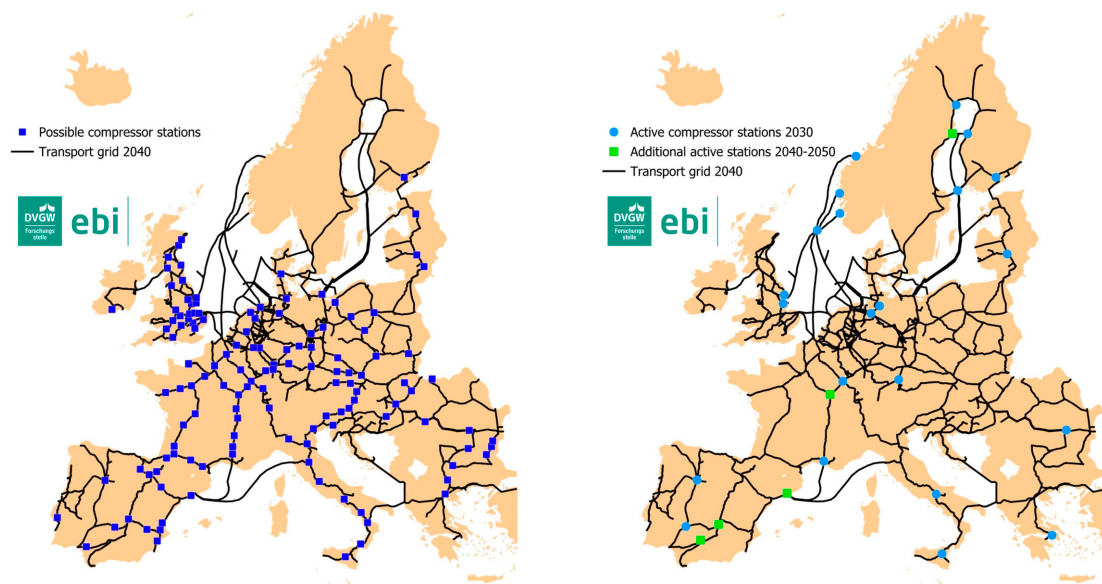


Figure 5. Potential compressor station locations derived from the SciGrid and Sci2grid datasets (**left**) and the set of stations activated in the hydraulic model at the time of maximum aggregated NUTS 3-level demand for each target year (**right**). The compressor station placement for 2040 and 2050 is identical. Sources of possible compressor stations: SciGrid dataset [47,48].

In Germany, three compressor stations are included at Forchheim, Moorburg, and Achim, as documented in the German hydrogen core network plans [15].

The final set of active compressor stations is defined based on simulations of maximum aggregated NUTS 3-level demand in each target year. A more comprehensive analysis would require compressor dispatch and control strategy, which is beyond the scope of the present study. Capital expenditures (CAPEX) and operational expenditures (OPEX) of compressor stations are not considered.

2.3.3. Boundary Conditions and Initialization

Multiple groups of simulation iterations are performed in order to identify errors from earlier processing steps, improve numerical robustness, and reduce deviations from the boundary conditions defined by the scenario data [17].

The grid topology from QGIS and the scenario data are imported into STANET[®]. To ensure numerical stability, pipelines are subdivided into segments of approximately 10 km, while a minimum pipeline length of 100 m is enforced. This avoids numerical instabilities caused by large disparities in pipeline lengths within the equation system.

Steady-state simulations require initial boundary conditions in the form of pressure nodes to solve the underlying equation system. A pressure node represents a user-defined degree of freedom that provides a reference pressure level for the iterative solution of the equation system. If the network is not fully connected, each disconnected subnetwork requires at least one pressure node. Pressure levels assigned to these nodes must respect the maximum operating pressure of the pipelines. However, due to limited information on future operating conditions, representative pressure levels remain uncertain.

It is assumed that average pressure levels in 2040 and 2050 are higher than in 2030, reflecting the ramp-up phase of the hydrogen transmission network. As shown in Figure 6 and Table 3, pressure nodes are set to 30 bar for the target year 2030, reflecting this ramp up phase of the H₂ transmission grid. For the target years 2040 and 2050, the pressure level

of the pressure nodes is increased to 60 bar, reflecting a more mature and interconnected network with higher hydrogen transport volumes.

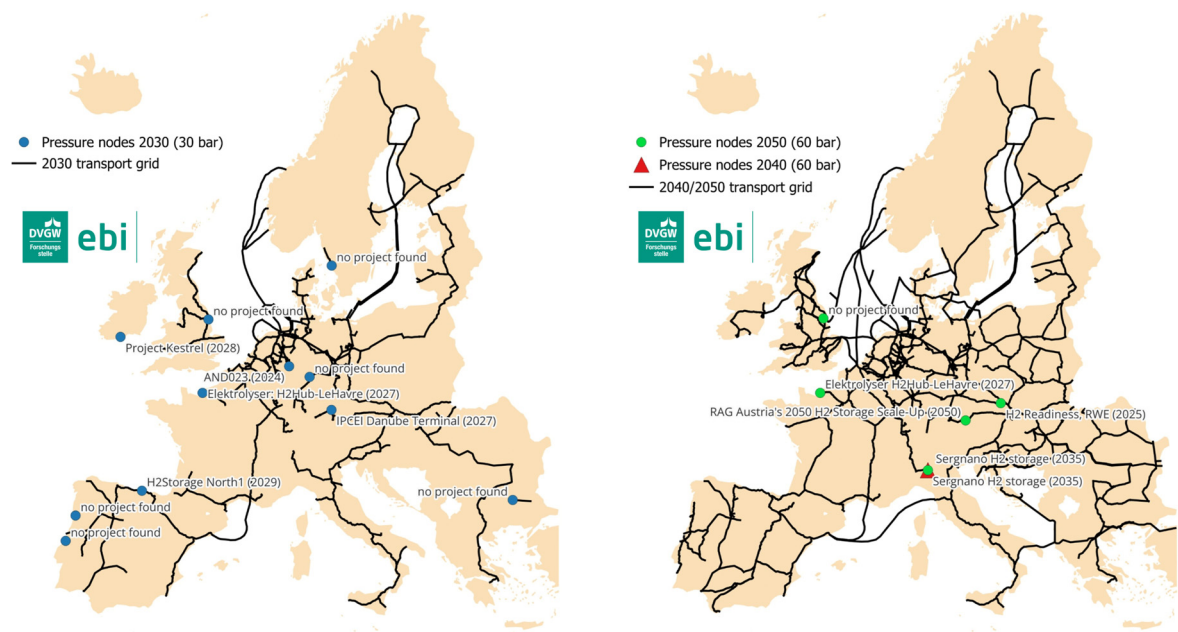


Figure 6. Pressure node-project pairings and the corresponding transport grids for all target years.

Hydraulic simulations are sensitive to extreme values in the scenario time series and are therefore well suited for identifying structural bottlenecks in the transmission grid. For this reason, the time step corresponding to the maximum aggregated regional (NUTS 3 level) demand is selected for evaluation (see Table 3). This maximum aggregated regional consumption at the NUTS 3 level is approximately 33 GW in 2030, increasing to 115 GW in 2040 and 278 GW in 2050. These values illustrate the substantial growth in total regional hydrogen demand across the analyzed target years.

Table 3. Key characteristics of the simulation used in this study.

Modeling Goal	Stable, Steady-State Simulations Including Compressor Stations
Set pressure at pressure nodes	2030: 30 bar (ramp-up) 2040: 60 bar 2050: 60 bar
Placement of pressure nodes	Pressure nodes are assigned to real hydrogen projects if found, preferably underground gas storages
Steady-state simulations	Yes—evaluated at the time of maximum aggregated regional (NUTS 3-level) consumption

In the simulation, pressure nodes are preferentially assigned to real hydrogen projects if found, particularly to underground gas storage facilities (see Figure 6). Storage facilities are favored because they can operate both as sources and sinks, enabling them to compensate for imbalances. This allocation also allows for an approximate quantification of the required compensation (i.e., net injection or withdrawal) at project-related locations.

The pressure-node configuration differs between the investigated target years. Each subnetwork requires at least one pressure node.

In 2030, the network consists of ten hydraulically disconnected subnetworks and includes eleven pressure nodes. The largest subnetwork requires two pressure nodes because

parts of the network are located far from the North African import points and can only be supplied through long, indirect flow paths. Moreover, domestic hydrogen production remains limited in 2030, making imports particularly important (see the production density in Figure 1). An additional pressure node was therefore placed in central Germany to maintain feasible pressure levels.

In 2040, the fully interconnected network requires only one pressure node, located at the Sergnano underground gas storage site. The same initial configuration did not produce a numerically stable and physically feasible solution for 2050. Additional pressure nodes were therefore placed in regions with the most critical or nonphysical pressure values. The 2050 simulation showed particular sensitivity to both the number and placement of these pressure nodes. Their final number and locations were determined through manual iteration rather than an exhaustive parameter sweep. After a feasible solution was obtained, pressure nodes were successively removed until the minimum configuration of five nodes was identified. Configurations with additional pressure nodes also produced stable solutions. However, each additional node introduced another prescribed-pressure boundary condition with a balancing flow determined by the simulation. This increases the deviations from the boundary conditions specified by the scenario data. The selected configuration therefore represents the minimum number of pressure nodes required to obtain a stable and physically feasible steady-state solution while minimizing deviations from the scenario boundary conditions.

Accordingly, no gas transport across the outer European border-crossing points is modeled. The exceptions are only the two pipeline import points and ship-based transport flows (terminals) considered in the scenario data.

In addition, pressure-level and flow-velocity limitations are only considered indirectly in the simulation. A simulation failure would occur only at pressure or velocity values far outside the physically plausible operating range. Therefore, pressures and flow velocities are evaluated after a successful simulation run. Extreme values are analyzed in the post-processing step.

3. Results and Discussion

For the target year 2030, the network topology is fragmented and not fully meshed. The transmission grid is not fully interconnected; see Bulgaria, GB, Ireland, and Portugal as examples. Flow velocities are generally within acceptable ranges. Some elevated velocities can be observed next to the pressure nodes. Only two pipeline segments exceed 40 m/s in the NUTS 3-connecting pipelines. These outliers are located at the German–French border and result from several high-demand NUTS 3 regions being connected to a single transport corridor. NUTS 3-connections are not visible in Figure 7.

In the target year 2040, the gas grid is fully interconnected (Figure 8). Terminal time series are not included at the 2040-stage, in line with the assumptions of the underlying energy system scenario. Only a single pressure node (i.e., single degree of freedom) is required, minimizing distortion relative to the scenario boundary conditions. This pressure node is linked to the Sergnano underground gas storage site in Northern Italy. Under peak-load conditions, no critical flow velocities are observed. However, elevated pressure levels occur in southern regions due to the accumulation of large H₂ import volumes from MENA. The southern regions of Spain are affected the most strongly with around 130 bar.

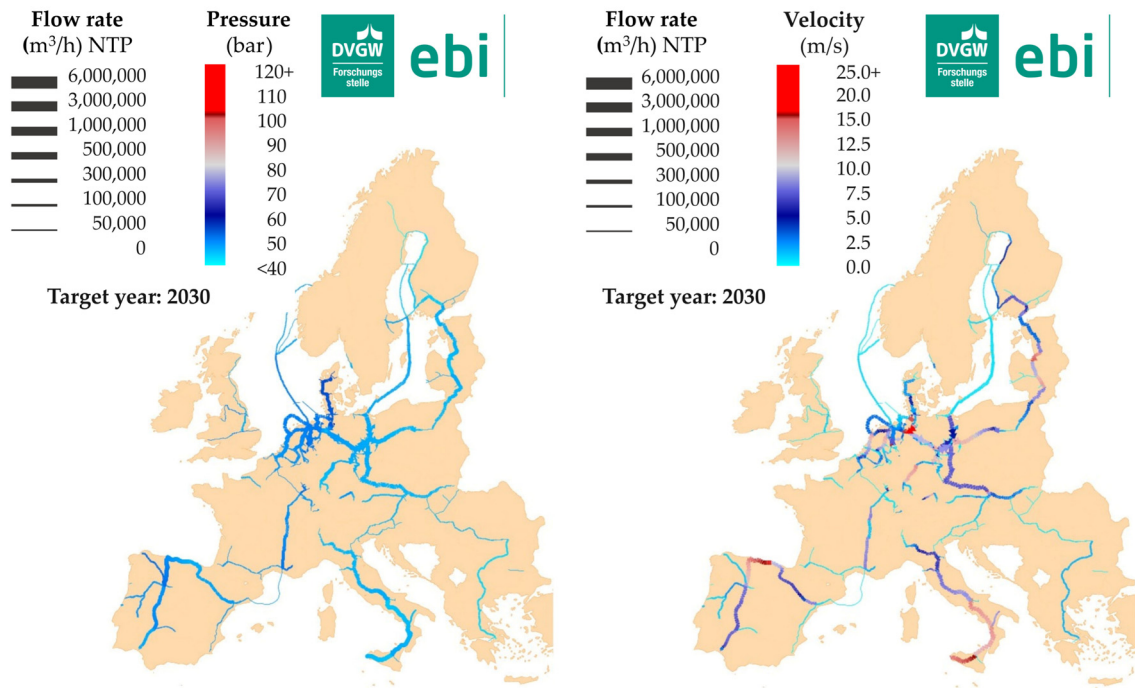


Figure 7. Simulation results at maximum aggregated regional (NUTS 3-level) consumption, target year 2030.

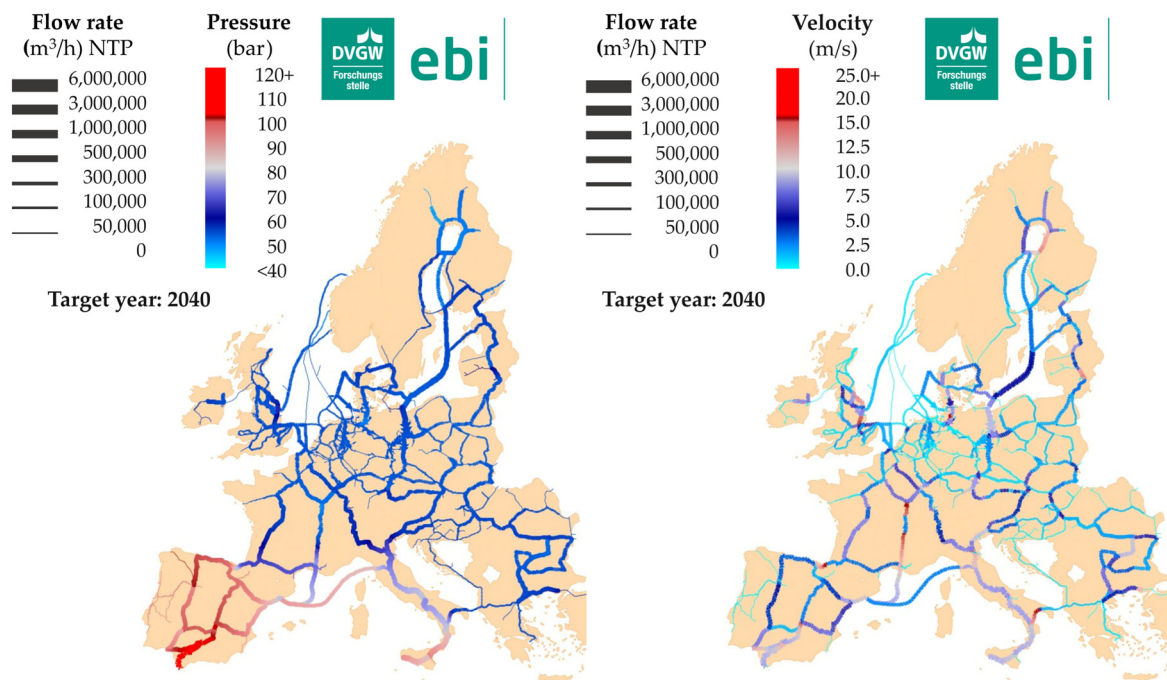


Figure 8. Simulation results at maximum aggregated regional (NUTS 3-level) consumption, target year 2040.

For the target year 2050, terminal injections are reintroduced in accordance with the underlying energy-system scenario. The network topology remains unchanged from 2040. However, additional pressure nodes are required because of increasing regional imbalances. Under these conditions, pressures exceeding 200 bar occur near the MENA pipeline import points, particularly in Spain. The affected pipeline segments in Spain typically have diameters of 700–900 mm and maximum operating pressures of 50–80 bar. By comparison, the corresponding segments in Italy generally have diameters of approximately 1200 mm

and a maximum operating pressure of 80 bar. However, some newly constructed segments in southern Italy have diameters of only 500 mm. These characteristics indicate that the assumed pipeline imports exceed the transport capacity of individual network sections under the 2050 scenario.

Pressure nodes linked to storage sites and other H₂ related projects are insufficient to compensate for these peaks. Notably, flow velocities exhibit fewer critical outliers than pressure values. Sudden changes in flow velocity can occur due to pressure differences resulting from strong regional imbalances between neighboring feed-in and withdrawal levels. These effects are particularly evident in the results for the target year 2050 shown in Figure 9.

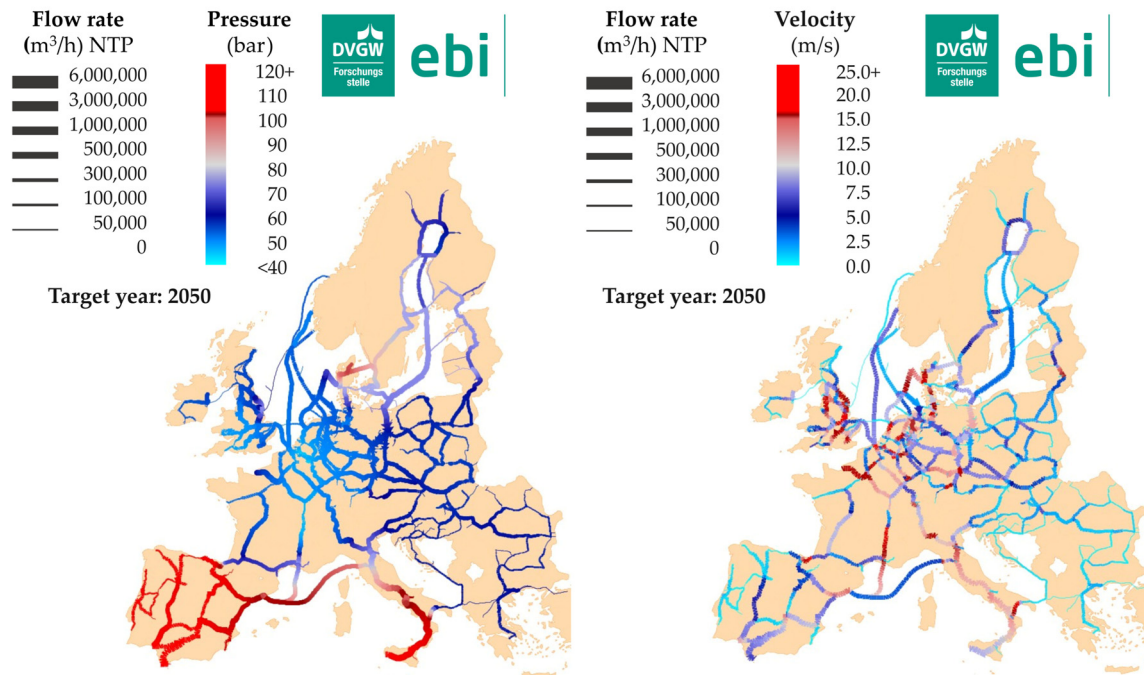


Figure 9. Simulation results at maximum aggregated regional (NUTS 3-level) consumption, target year 2050.

Simulation results are evaluated during postprocessing using visual indicators for critical pressure levels and flow velocities. Flow velocities above 25 m/s are highlighted in bright red, although values up to approximately 40 m/s are generally considered acceptable according to external sources, with an upper conservative technical limit around 50 m/s [50]. Pipeline pressures above 80 bar are indicated in light red coloring, while pressures exceeding 100 to 120 bar are classified as critical and likewise highlighted in bright red. These thresholds are used as indicative guidance rather than strict operational limits. The classification represents a simplification as offshore pipelines typically tolerate higher operating pressures than onshore pipelines, some of which have published maximum operating pressures as low as 40 bar.

In the target year 2030, no high-pressure values are observed, although some regions experience pressures below 20 bar, partly due to insufficient H₂ production during the early ramp-up phase (see Figure 10).

In 2040, 0.8% (0.2% + 0.6%) of the simulation nodes exhibit pressures above 100 bar, while 9.5% (0.8% + 8.7%) have pressures above 80 bar. In 2050, pressures above 100 bar occur at 9.5% (7.8% + 1.7%) of the simulation nodes, coincidentally matching the share of nodes with pressures above 80 bar in 2040. Pressures above 80 bar occur at 12.6% (9.5% + 3.1%) of the nodes in 2050 (see Figure 11). In 2050, simulated pressures above

200 bar are limited to the Gibraltar–Córdoba corridor. The affected pipeline sections have a combined length of approximately 320 km.

Target year 2030 pressure distribution

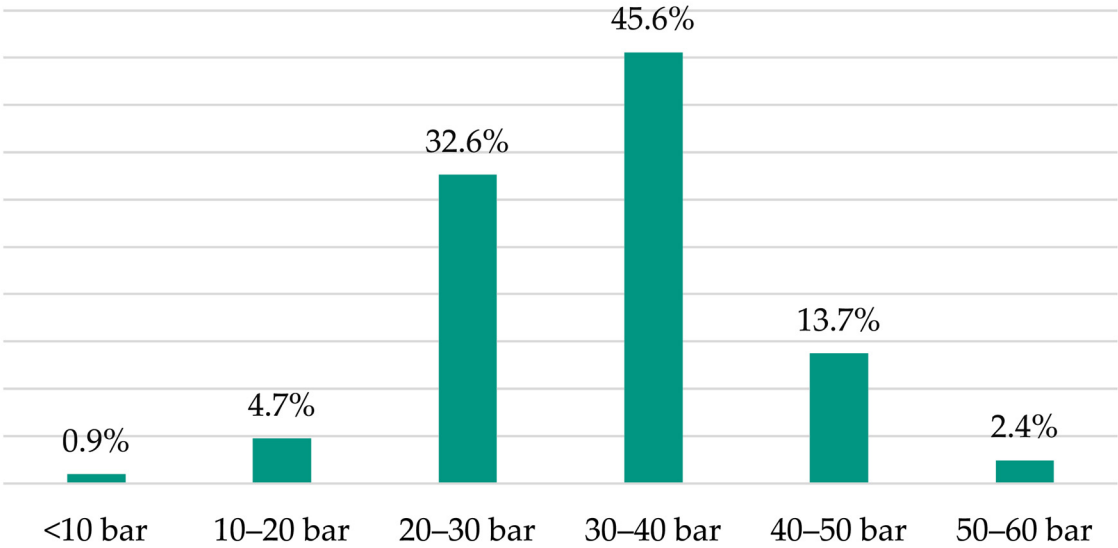


Figure 10. Target year 2030 pressure distribution among grid nodes. Number of grid nodes: 7117.

Target year 2040 and 2050 pressure distribution

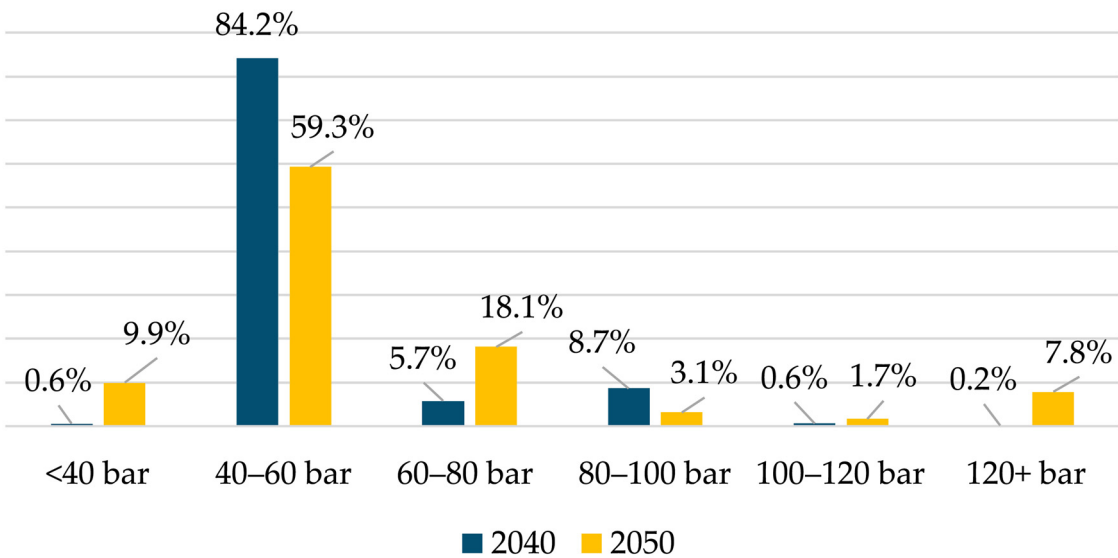


Figure 11. Target year 2040 and 2050 pressures among grid nodes. Number of grid nodes for both 2040 and 2050: 11,298.

The primary drivers of the extreme pressure levels observed in southern regions in 2040 and 2050 are the large gas import volumes from the MENA region and insufficient transport capacity toward Central Europe, both of which lead to excessive gas accumulation. In Spain, substantial domestic H₂ production further amplifies this effect. The pipeline section in Spain between Gibraltar and Córdoba seems to be undersized. This corridor exhibits the most critical pressure levels in 2050 and already shows elevated pressures in 2040. It is important to note that the planned H₂ pipelines connecting the North-Africa to Europe are largely based on retrofitted or repurposed infrastructure. Consequently, pipeline diameter is not a freely adjustable design parameter. Although the compressor

stations facilitate the transport of excess hydrogen toward Central Europe, they do not resolve the underlying pressure constraint.

Overall, the 2030 network is capable of meeting peak demand, although grid fragmentation complicates the reliable supply of hydrogen (Figure 7). However, the results indicate that the network configuration for 2040 and 2050 are not fully compatible with the underlying energy system scenario (Figures 8 and 9). The grid is unable to accommodate the projected supply volumes while maintaining subcritical pressure levels, particularly, though not exclusively, in regions connected to MENA. The Tunisian-Italian connection appears to be moderately undersized, while the Spanish MENA connection is clearly undersized under the given scenario assumptions. Furthermore, the transport capacity between Spain and France is insufficient, as both the number and the diameter of the interconnection pipelines are inadequate to transport the accumulated hydrogen volumes across the Franco-Spanish border toward Central Europe.

A broader implication of these findings is that, if the MENA region (focusing now on North Africa) remains a major contributor to Europe's hydrogen supply strategy, the robustness of the connecting infrastructure requires closer consideration. Retrofitted pipelines alone may not be sufficient to accommodate sustained high import volumes. In the underlying scenario, either additional infrastructure or a diversification of network utilization across multiple import corridors ought to be considered, rather than concentrating flows in a limited number of high-capacity routes. Any additional capacity would likely require at least partial construction of new pipelines. At the same time, extensive repurposing must not compromise CH₄ transport capability in scenarios where methane demand persists.

4. Conclusions and Outlook

This paper presents a large-scale simulation that assesses the hydraulic capabilities of the planned European H₂-grid for the target years 2030, 2040, and 2050. This study addresses the lack of hydraulically detailed, European-scale hydrogen network analyses covering multiple target years and network-wide stress conditions. The study provides a scenario-based plausibility check of the compatibility between the assumed network topology and the energy-system scenario rather than detailed network planning.

The three pillars of the study are the scenario data of the energy-system modeling being an input from the TransHyDE-System Analysis project, a GIS model and hydraulic simulation using STANET[®]. The topology reflects a combination of the European Hydrogen Backbone (07.2023) and the German core network (10.2024). An enhanced emphasis is placed on the maximum aggregated regional (NUTS 3-level) consumption because it is the largest offtake within the system. Where possible, the pressure nodes (degrees of freedom) are assigned to real-life H₂-related projects. In addition, selected large compressor stations are represented in the model.

Several conclusions can be drawn from the H₂-transport grid simulation. For target year 2030, a fragmented, not fully interconnected network can cover the maximum regional demand. For the target year 2040 and 2050, a fully meshed network enables stable simulation. Both in 2040 and 2050, elevated pressures occur in southern regions (Spain, Italy) due to regional supply–demand imbalances and high pipeline import volumes from the North-Africa. The southernmost pipelines in Italy and especially in Spain seem undersized for these assumed import quantities. Assuming these scenario-given import volumes, investments into new parallel pipelines or into the repurposing of additional CH₄-pipelines may be necessary. The southern pressure peaks are primarily driven by the regional imbalance between high pipeline imports and the transport capacity of the assumed topology. Internal plausibility checks indicate limited sensitivity to the simplified

compressor representation, whereas the number and placement of pressure nodes have a substantially greater influence on the simulation results.

The gas network model is continually updated to reflect real-world changes and therefore requires ongoing adjustments. However, this does not invalidate the conclusions drawn from the previous results. Our overall assessment is that, despite some coarse modeling resolution, the network models can highlight potential weaknesses and bottlenecks in the future hydrogen infrastructure as a virtual stress test. If the pipeline imports from North Africa remain important, this region's political and economic stability should be examined more closely in future assessments.

Several extensions of the present model are possible in future work. First, the plausibility of H₂-related infrastructure projects, such as storage facilities and import terminals, could be examined in greater detail. This would allow a more precise assessment of whether the assumed injection and withdrawal capacities are technically realistic or consistent with the surrounding network infrastructure. Second, higher-resolution regional case studies could be developed to investigate the interaction between transmission and distribution grids. Such studies could provide insights into regional bottlenecks, local pressure behavior, and the technical requirements for connecting decentralized demand and supply structures to the transport grid.

In addition, the operational strategy of network coupling points could be analyzed in more detail. Instead of using fixed or simplified boundary conditions, future models could incorporate dispatch strategies that reflect import availability, regional demand, network constraints, and cross-border coordination.

Finally, the model could be combined with resilience analyses to investigate where gas-fired power plants should be built or deployed in the future. This would make it possible to identify locations where flexible generation capacity could strengthen the robustness of the hydrogen transport system. It would also indicate where such plants could most effectively support the integration of renewable energy.

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Data Availability Statement: The network topology developed in this study was constructed exclusively from publicly available data sources, all of which are cited in the manuscript. The energy-system scenario data used as model inputs were provided by the Forschungsstelle für Energiewirtschaft e.V. (FfE) within the TransHyDE-Sys project. Restrictions apply to the availability of these third-party data, which cannot be made available by the authors and may be obtained from FfE subject to its permission. The processed network-model data and hydraulic simulation results generated in this study are available from the corresponding authors upon reasonable request, subject to any restrictions arising from the underlying third-party data.

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Abbreviations

The following abbreviations and symbols are used in this manuscript:

BMFTR	Federal Ministry of Research, Technology and Space (Bundesministerium für Forschung, Technologie und Raumfahrt)
CAPEX	Capital expenditures
CH ₄	Methane
EHB	European Hydrogen Backbone
EU	European Union
FID	Final Investment Decision
GIS	Geographic Information System
H ₂	Hydrogen
MENA	Middle East and North Africa
MYNTS	Multi-physics network simulator
NTP	Normal temperature and pressure
NUTS	Nomenclature des unités territoriales statistiques
OPEX	Operational expenditures
QGIS	Quantum Geographic Information System
SciGrid	Open Source Reference Model of European Transmission Networks for Scientific Analysis
Sci2grid	Successor project to SciGrid
STANET [®]	Hydraulic network simulation software
TSO	Transmission System Operator

Symbols

A, B	End nodes of a representative pipe segment
D	Pipe diameter
f(Q)	Pressure-loss function depending on flow rate
g	Gravitational acceleration
G(i,k)	Conductance of pipe segment between nodes i and k
h(A), h(B)	Geodetic elevation of nodes A and B
i, k	Generic running indices for network nodes
K	Compressibility factor
K _{par}	Gas-specific pressure factor of the compressibility factor
k	Absolute pipe roughness
k/D	Relative pipe roughness
L	Pipe length
p, Δp	Pressure, Pressure difference
p(A), p(B)	Pressure at nodes A and B
p(i), p(k)	Pressure at nodes i and k
p _n	Reference pressure under normal conditions
Q	Volumetric flow rate
Q(i,k)	Volumetric flow rate between nodes i and k
Q _e (i)	External injection or withdrawal at node i
R	Hydraulic resistance
R(A,B)	Hydraulic resistance of pipe segment between nodes A and B
R(i,k)	Hydraulic resistance of pipe segment between nodes i and k

R_s	Specific gas constant
Re	Reynolds number
T	Absolute temperature
T_n	Normal temperature
v	Mean flow velocity
Δp	Pressure difference/pressure loss
Δp_i	Pressure difference in pipe segment i
ζ	Local loss coefficient
λ	Pipe friction factor
ν	Kinematic viscosity
π	Pi, mathematical constant
ρ	Gas density
$\rho(A), \rho(B)$	Gas density at nodes A and B
ρ_n	Gas density under normal conditions

References

1. EU Climate Law: MEPs confirm deal on climate neutrality by 2050 | News | European Parliament. Available online: <https://www.europarl.europa.eu/news/en/press-room/20210621IPR06627/eu-climate-law-meps-confirm-deal-on-climate-neutrality-by-2050> (accessed on 11 December 2025).
2. International Energy Agency (IEA). *Global Hydrogen Review 2024*; IEA: Paris, France, 2024.
3. Graf, F.; Wachsmuth, J.; Pflüger, B.; Müller-Kirchenbauer, J.; Nolden, C.; Wietschel, M.; Heneka, M.; Ausfelder, F.; Lenivova, V.; Malzkuhn, S. *Hintergrundpapier zu Gasinfrastrukturen im Lichte des russischen Angriffskriegs auf die Ukraine*; TransHyDE: Hamburg, Germany, 2021. [CrossRef]
4. ENTSG. Ten-Year Network Development Plan 2024: TYNDP 2024 Annex A—Projects. Available online: <https://www.entsoe.eu/tyndp#entsoe-ten-year-network-development-plan-2024> (accessed on 15 May 2024).
5. European Commission. REPowerEU: Affordable, Secure And Sustainable Energy for Europe. Available online: https://commission.europa.eu/topics/energy/repower_eu_en (accessed on 27 August 2025).
6. European Commission. Powering a Climate-Neutral Economy: An EU Strategy for Energy System Integration, COM(2020) 299 Final, 2020. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0299> (accessed on 10 September 2026).
7. European Commission. A Hydrogen Strategy for a Climate-Neutral Europe, COM(2020) 301 Final, 2020. Available online: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301> (accessed on 10 September 2026).
8. Dechema, F.; Fraunhofer, I.K.T.S. Wasserstoffinfrastruktur-Roadmap: Ergebnisse aus dem TransHyDE-Projekt Systemanalyse. Available online: https://www.wasserstoff-leitprojekte.de/lw_resource/datapool/systemfiles/elements/files/23d87cb2-d9a4-11f0-ad78-fa163ebab5e5/live/document/Wasserstoffinfrastruktur-Roadmap_final.pdf (accessed on 19 June 2026).
9. ENTSG AISBL. ENTSG Summer Supply Outlook 2026: With Winter 2026/27 Overview. Available online: https://www.entsoe.eu/sites/default/files/2026-04/SO0069-26_Summer%20Supply%20Outlook%202026.pdf (accessed on 19 June 2026).
10. EHB. European Hydrogen Backbone Interaktive Karte. Available online: <https://www.ehb.eu/maps/202307/index.html#4/51.37/19.73> (accessed on 6 August 2025).
11. van Rossum, R.; Jens, J.; La Guardia, G. *European Hydrogen Backbone: A European Hydrogen Infrastructure Vision Covering 28 Countries*; EHB: Utrecht, The Netherlands, 2022. Available online: <https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf> (accessed on 1 October 2024).
12. Sagdur, Y.; Slowinski, R.; van Rossum, R.; Kozub, A.; Kühnen, L.; Overgaag, M.; Michelet, A.; Kandathiparambil, S.; London, P. *European Hydrogen Backbone: Implementation Roadmap—Cross Border Projects and Costs Update*; EHB: Utrecht, The Netherlands, 2023. Available online: <https://ehb.eu/files/downloads/EHB-2023-Implementation-Roadmap-Part-1.pdf> (accessed on 1 October 2024).
13. Entsoe, G.I.E.; EUROGAS; Cedec, G.D.; GEODE. H₂ Infrastructure Map Europe Q4/2023: Showcasing Concrete European Hydrogen Infrastructure Projects and Possibilities for Transport Routes and Corridors. Available online: <https://www.h2inframap.eu/> (accessed on 15 November 2024).
14. Entsoe, G.I.E.; EUROGAS; Cedec, G.D.; GEODE. Hydrogen Infrastructure Map Q4/2024: Showcasing Concrete European Hydrogen Infrastructure Projects and Possibilities for Transport Routes and Corridors. Available online: <https://www.h2inframap.eu/#map> (accessed on 10 August 2025).
15. Bundesnetzagentur. Genehmigung eines Wasserstoff-Kernnetzes. 2024. Available online: https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/Wasserstoff/_DL/Genehmigung.pdf?__blob=publicationFile&v=6 (accessed on 10 August 2025).

16. Bundesministerium für Wirtschaft und Klimaschutz (BMWK). *Entwurf eines Klimaschutzprogramms 2023 der Bundesregierung*: BMWK; BMWK: Berlin, Germany, 2023. Available online: https://www.bundeswirtschaftsministerium.de/Redaktion/DE/Downloads/klimaschutz/entwurf-eines-klimaschutzprogramms-2023-der-bundesregierung.pdf?__blob=publicationFile&v=6 (accessed on 19 August 2025).
17. Kigle, S.; Helmer, N.; Schmidt-Achert, T. Fast Enough? The Consequences of Delayed Renewable Energy Expansion on European Hydrogen Import Needs. *Appl. Energy* **2024**, *400*, 126556. [\[CrossRef\]](#)
18. Mielich, T.; Dobler, R.; Hollnagel, J.; Akca, O.; Müller-Kirchenbauer, J. Europe's way from natural gas to green hydrogen: Modeling and simulation of the transforming European gas transport infrastructure. *Int. J. Hydrogen Energy* **2025**, *135*, 156–171. [\[CrossRef\]](#)
19. Rövekamp, J. Transportnetzberechnung zur Feststellung der Erdgasversorgungssicherheit in Deutschland Unter Regulatorischem Einfluss. Ph.D. Thesis, Universitätsbibliothek der TU Clausthal, Clausthal-Zellerfeld, Germany, 2015.
20. Lohmeier, D.; Cronbach, D.; Drauz, S.R.; Braun, M.; Kneiske, T.M. Pandapipes: An Open-Source Piping Grid Calculation Package for Multi-Energy Grid Simulations. *Sustainability* **2020**, *12*, 9899. [\[CrossRef\]](#)
21. Dejonghe, M.; van de Graaf, T.; Belmans, R. From natural gas to hydrogen: Navigating import risks and dependencies in Northwest Europe. *Energy Res. Soc. Sci.* **2023**, *106*, 103301. [\[CrossRef\]](#)
22. Hanto, J.; Herpich, P.; Löffler, K.; Hainsch, K.; Moskalenko, N.; Schmidt, S. Assessing the implications of hydrogen blending on the European energy system towards 2050. *Adv. Appl. Energy* **2024**, *13*, 100161. [\[CrossRef\]](#)
23. Müller-Kirchenbauer, J.; Evers, M.; Hollnagel, J.; Kuzyaka, B.; Jiang, D.; Akça, O.; Mielich, T.; Kalz, M.; Verwiebe, P.A. Germany's Way from Russian Natural Gas to Green Hydrogen: Network Data, Procedures, and Topologies for Feasible Transition Paths to a Green Hydrogen Transport Infrastructure in Germany, GreenHyDE. *Energy Technol.* **2025**, *13*, 2300976. [\[CrossRef\]](#)
24. Kuzyaka, B.; Akça, O.; Klaassen, B.; Ben Safta, K.; Anvari, M.; Müller-Kirchenbauer, J. Framework for evaluating integrated gas network simulation tools: A comparative study of MYNTS, pandapipes, and SIMONE. *Next Energy* **2026**, *12*, 100629. [\[CrossRef\]](#)
25. Cavana, M.; Spadavecchia, A.; Di Francesco, L.; Leone, P. Evaluating hydrogen transport scenarios at the Sicily gateway: Technical analysis of hydrogen-blended natural gas and dedicated hydrogen pipelines. *Int. J. Hydrogen Energy* **2026**, *227*, 154547. [\[CrossRef\]](#)
26. Mielich, T.; Jiang, D.; Hollnagel, J.; Abid, H.; Ridjan Skov, I.; Müller-Kirchenbauer, J. Technical assessment of cross-border hydrogen network compatibility—Impacts of Denmark-Germany trade. *Int. J. Hydrogen Energy* **2026**, *260*, 156643. [\[CrossRef\]](#)
27. Fleiter, T.; Fragoso, J.; Lux, B.; Alibas, S.; Al-Dabbas, K.; Manz, P.; Neuner, F.; Weißenburger, B.; Rehfeldt, M.; Sensfuß, F. Hydrogen Infrastructure in the Future CO₂-Neutral European Energy System—How Does the Demand for Hydrogen Affect the Need for Infrastructure? *Energy Technol.* **2025**, *13*, 2300981. [\[CrossRef\]](#)
28. Kigle, S.; Mohr, S.; Kneiske, T.; Clees, T.; Ebner, M.; Harper, R.; Jahn, M.; Klaassen, B.; Köppel, W.; Ausfelder, F.; et al. TransHyDE-Sys: An Integrated Systemic Approach for Analyzing and Supporting the Transformation of Energy Systems and Hydrogen Infrastructure Development. *Energy Technol.* **2024**, *13*, 202300828. [\[CrossRef\]](#)
29. Kountouris, I.; Bramstoft, R.; Madsen, T.; Gea-Bermúdez, J.; Münster, M.; Keles, D. A unified European hydrogen infrastructure planning to support the rapid scale-up of hydrogen production. *Nat. Commun.* **2024**, *15*, 5517. [\[CrossRef\]](#)
30. Tsiklios, C.; Hermesmann, M.; Müller, T.E. Hydrogen transport in large-scale transmission pipeline networks: Thermodynamic and environmental assessment of repurposed and new pipeline configurations. *Appl. Energy* **2022**, *327*, 120097. [\[CrossRef\]](#)
31. Triesch, T.; Klütz, T.; Linßen, J.; Stolten, D. Evaluation of possible network states in the future German hydrogen network 2025 and 2030. *Sustain. Energy Grids Netw.* **2024**, *39*, 101455. [\[CrossRef\]](#)
32. Azimipoor, A.; Zhang, T.; Qadrdan, M.; Jenkins, N. Operational implications of transporting hydrogen via a high-pressure gas network. *Energy Convers. Manag. X* **2025**, *26*, 100937. [\[CrossRef\]](#)
33. Clees, T. Contingency analysis for gas transport networks with hydrogen injection. *Math. Methods Oper. Res.* **2022**, *95*, 533–563. [\[CrossRef\]](#)
34. Yang, M.; Hunger, R.; Berrettoni, S.; Sprecher, B.; Wang, B. A review of hydrogen storage and transport technologies. *Clean Energy* **2023**, *7*, 190–216. [\[CrossRef\]](#)
35. Guidehouse, E. *EHB Implementation Roadmap: Public Support as Catalyst for Hydrogen Infrastructure: European Hydrogen Backbone*; EHB: Utrecht, The Netherlands, 2024. Available online: <https://www.ehb.eu/files/downloads/EHB-2024-Implementation-Roadmap-Part-2.pdf> (accessed on 10 August 2025).
36. Documentation for QGIS 3.40: Index. Available online: <https://docs.qgis.org/3.40/en/docs/index.html> (accessed on 28 October 2025).
37. Ingenieurbüro Fischer-Uhrig. STANET Network Analysis (2020). Available online: <https://www.stafu.de/de/home.html> (accessed on 10 August 2025).
38. Kisse, J.M.; Braun, M.; Letzgus, S.; Kneiske, T.M. A GIS-Based Planning Approach for Urban Power and Natural Gas Distribution Grids with Different Heat Pump Scenarios. *Energies* **2020**, *13*, 4052. [\[CrossRef\]](#)

39. Jakob, J.; Uhlemeyer, B.; Koralewicz, M.; Garzon-Real, J.; Zdrallek, M.; Ruf, J.; Köppel, W.; Bauhaus, B. Simulation of an integrated planning of power and gas distribution grids considering power-to-gas and gas-to-power units. *CIREN-Open Access Proc. J.* **2020**, *2020*, 70–73. [CrossRef]
40. Horlacher, H.-B.; Helbig, U. (Eds.) *Rohrleitungen 2: Einsatz, Verlegung, Berechnung, Rehabilitation*, 3rd ed.; Springer: Berlin/Heidelberg, Germany, 2023. [CrossRef]
41. Gugat, M.; Schultz, R.; Wintergerst, D. Networks of pipelines for gas with nonconstant compressibility factor: Stationary states. *Comp. Appl. Math.* **2018**, *37*, 1066–1097. [CrossRef]
42. Ingenieurbüro Fischer-Uhrig. *Internes Schulungsmaterial 2015: Rechenverfahren*. Available online: <https://www.stafu.de/de/produkt.html> (accessed on 10 August 2025).
43. DVGW GW 303-1 (A); Berechnung von Gas-und Wasserrohrnetzen—Teil 1: Hydraulische Grundlagen, Netzmodellierung und Berechnung. DVGW Deutscher Verein des Gas-und Wasserfaches e. V.: Bonn, Germany, 2006.
44. Eberhard, R.; Huening, R. *Handbuch Der Gasversorgungstechnik: Gastransport U. Gasverteilung*, 2nd ed.; Oldenbourg: München, Germany, 1990.
45. Tinney, W.F.; Walker, J.W. Direct solutions of Sparse Network Equations by Optimally Ordered Triangular Factorization. *Proc. IEEE* **1967**, *1967*, 1801–1809. [CrossRef]
46. Fleer, A.-C.; Sciancalepore, M.; Spreckelsen, E.-M.; Verbücheln, R.W. *Verdichtung und Wasserstofftransport: Eine Technische und Wirtschaftliche Analyse*; Wasserstoff-Leitprojekt TransHyDE: Hamburg, Germany, 2025.
47. BMWK. Europäische Gasnetze Mit Open-Source Genauer Abbilden: Projekt SciGRID_Gas. Available online: <https://www.energieforschung.de/de/aktuelles/projekteinblicke/2022/scigrig-gas> (accessed on 27 October 2025).
48. Institute of Networked Energy Systems. Sci2grid—Open reference models of European energy networks: Modelling Tool. Available online: <https://www.dlr.de/en/ve/research-and-transfer/research-infrastructure/modelling-tools/sci2grid> (accessed on 27 October 2025).
49. Yeaw, S.; Storstenvik, A.; Vesterkjaer, R. Learning and development from the world’s first operating subsea compression system. *APPEA J.* **2017**, *57*, 683–686. [CrossRef]
50. Raj, A.; Larsson, I.S.; Ljung, A.-L.; Forslund, T.; Andersson, R.; Sundström, J.; Lundström, T. Evaluating hydrogen gas transport in pipelines: Current state of numerical and experimental methodologies. *Int. J. Hydrogen Energy* **2024**, *67*, 136–149. [CrossRef]

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