Proceedings of the 35th European Safety and Reliability & the 33rd Society for Risk Analysis Europe Conference
Edited by Eirik Bjorheim Abrahamsen, Terje Aven, Frederic Bouder, Roger Flage, Marja Ylönen

doi: 10.3850/978-981-94-3281-3_ESREL-SRA-E2025-P4424-cd

Vulnerability and Robustness Analyses for the Planning of Resilient Hydrogen Networks

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Hydrogen is increasingly recognized as a promising fossil-free energy source and transport vector and thus plays a vital part in many energy-transition scenarios. Computer-aided hydraulic modeling, able to predict the physical conditions within hydrogen grids, is crucial for planning the successful transformation of existing natural gas infrastructures to support hydrogen as a new medium. Given hydrogen's potential key role, the urgency for resilient hydrogen grids is amplified by potential threats such as sabotage and political sanctions, underscoring the importance of simulation tools that can anticipate network behavior under non-standard circumstances. Although transient modelling of hydrogen dynamics is crucial for examining the immediate consequences of extreme contingencies, it is imperative to develop robust algorithms to evaluate the resilience of networks when confronted with such off-design events. Hence, we introduce a framework, specifically designed to evaluate transient responses to extreme events in hybrid or pure hydrogen networks that include storage solutions. This advanced numerical approach enables predictions of system behavior before, during, and after disturbances thereby allowing vulnerabilty, robustness and recovery analyses towards aiding the planning of resilient hydrogen grids.

Keywords: hydrogen grids, numerical modelling, secure supply, robustness analyses, storage modelling.

1. Introduction

Hydrogen is positioned to assume a pivotal role in the reduction of greenhouse gas emissions and the attainment of climate neutrality. Green hydrogen, acyclically produced from surplus renewable electricity from wind and solar power, can be locally stored during excess production phases to be steadily transported to far-away consumers via transmission gas networks. According to the European Commission (2020b,a), existing natural gas networks are scheduled to be repurposed for hydrogen transport due to lower conversion costs compared to building additional pipeline infrastructure. Natural gas infrastructure can handle blended-hydrogen concentrations of up to 40% by volume without significant modifications (Brad et al. (2022); European Union Agency for the Cooperation of Energy Regulators (2021)). Higher concentrations might be feasible with hydrogen-specific modifications. However, relying on hydrogen transport via pipeline networks bears the risk for vulnerabilities in case of disruptive events, such as natural hazards or sabotage. Given hydrogen's promising role in future energy transition scenarios as a key energy vector, thorough planning of resilient hydrogen infrastructure is mandatory to ensure supply safety in transnational energy sectors. Numerical network modelling provides helpful tools to simulate *what-if* scenarios to be utilized in studying potential vulnerabilities of planned hydrogen infrastructure layouts and assessing their robustness against disruptions as well as testing mitigation measures to enhance overall resilience (see, e.g., Liu et al. (2024); Widera (2020) for examples of modelling and analyses towards readying future hydrogen networks for resilient operation). Additionally, such simulation tools can be utilized as a building block in modular co-simulation frameworks, as described in, e.g., Martini et al. (2024). In coaction with simulation tools of other interdependent socio-technical infrastructures, intersectoral cascading effects their impacts can be studied and visualized (see, e.g., Winter et al. (2024)).

In this work, a numerical simulation algorithm for the hydraulic modelling of the transient dynamics in hydrogen pipeline networks in far-off-design-point-operation scenarios is presented. Section 2 summarizes the required extensions of an existing algorithm for the hydraulic simulation of natural gas in order to model pure hydrogen as well as methane-hydrogen blends as the fluid in the network. Additionally, a simple but flexible model of storage units is introduced. In section 3 an example analysis showcasing both new functionalities is conducted. The mitigation capabilities of storage units are studied both for natural gas as well as for hydrogen networks in cases of severe disruptions. The conclusion is given in section 4.

2. Modelling of hydrogen networks

Gas networks can be modelled as graphs comprised of point-like node elements (representing junctions, consumers, sources, and storages) and one-dimensional edge elements (representing pipelines, compressors, valves, and pressure or flow regulators) (see, e.g, Osiadacz (1987)). As a gaseous fluid, the medium inside the network obeys physical laws of fluid dynamics and thermodynamics yielding equations of motion and conservation involving its degrees of freedom (see, e.g. Ekhtiari et al. (2019); Hafsi et al. (2017)). These equations form a coupled system of typically non-linear differential equations whose size scales with the number of elements in the underlying network. Due to their complexity, such equation systems are usually solved using numerical methods (see, e.g., Pambour (2018)). For this work, the modelling of the hydraulic state of hydrogen networks is realized as an extension of previous work developed, established and thoroughly validated against literature results in the context of natural gas networks (Ganter et al. (2024); Martini et al. (2025)). Subsection 2.1 summarizes the adaptions necessary to the original natural-gas simulation code in order to facilitate the modelling of pure hydrogen or blends of natural gas and hydrogen as the medium within gas networks. Subsection 2.2 describes how the modelling of storage facilities as node elements is newly incorporated in the existing gas network modelling approach.

2.1. *Hydrogen as the medium in numerical gas network simulation*

The numerical simulation of the hydraulic state of hydrogen networks is based on fluid-dynamical calculations of the gas dynamics based on the physical principles of conservation of energy, momentum as well as mass. Assuming isothermal conditions, requiring momentum and mass conservation suffices for fixing the pressure at each network node as well as the flow through each edge element, which describes the hydraulic state of gas in the network completely. Details of the chemical composition of the gaseous fluid within the network enter the fluid-dynamical equations at two points:

(1) through the calculation of the compressibility factor Z relating pressure p and density ρ

through the gas law

$$\rho = \frac{1}{ZRT}\, p, \tag{1}$$

where R is the specific gas constant and T the temperature of the gas;

(2) through the calculation of the dynamic viscosity μ entering the calculation of the *Reynolds number* characterizing the fluid's flow patterns and thereby friction behaviour.

For the sake of this work, blended-hydrogen gas is simplified as a binary mixture of methane and hydrogen. Calculations for the compressibility factor and dynamic viscosity of various gas mixtures as functions of pressure and temperature are available from the free python library *CoolProp* (Bell et al. (2014)) which is based on the *GERG-2008* model (Kunz and Wagner (2012)). Since the calculations of the gas properties with this library are rather involved, its direct implementation significantly increases the runtime of the simulation. Therefore, look-up tables of values for the compressibility factor and dynamic viscosity for various mixing ratios of methane and hydrogen are pre-produced within typical pressure and temperature intervals for fast online requests by referencing the nearest values using the *RegularGridInterpolator* class from the *scipy.interpolate* library (Virtanen et al. (2020)). To validate this approach, experimental results from the literature for mixtures with 10% as well 20% hydrogen fractions are reproduced. Table 1 shows the relative deviation of the calculated values for dynamic viscosity and density (related to the compressibility factor per equation (1)) from experimental values given in Owuna et al. (2024) for a hydrogen fraction of 10%. Table 2 shows a similar comparison to experimental values also given in Owuna et al. (2024) but for a hydrogen fraction of 20%. According to Lemmon and Huber (2008), the compressibility factor for pure hydrogen can be approximated as a function of pressure (p) and temperature (T) in the form of

Table 1. Deviation of the calculated values for dynamic viscosity and density from experimental values (taken from Owuna et al. (2024)) at a hydrogen mole fraction of 10%.

Input		Deviation [%]	
T [K]	p [MPa]	μ	ρ
298.37	6.66	0.972	-0.194
298.37	3.87	0.306	-0.307
298.37	2.11	-2.877	-0.162
298.37	1.27	-3.865	-0.273
273.32	7.3	0.731	-0.160
273.32	6.39	1.278	-0.159
273.32	3.28	0.778	-0.150
273.32	1.77	-1.429	-0.099

Table 2. Deviation of the calculated values for dynamic viscosity and density from experimental values (taken from Owuna et al. (2024)) at a hydrogen mole fraction of 20%.

Input		Deviation [%]	
T [K]	p [MPa]	μ	ρ
298.27	6.82	5.003	-0.131
298.27	3.99	3.063	-0.195
298.27	1.63	1.818	-0.395
298.27	1.07	0.622	-0.070
273.42	7.54	7.199	-0.174
273.42	5.57	7.016	-0.229
273.42	3.77	6.799	-0.269
273.42	1.82	2.987	-0.067
273.42	1.21	1.382	0.055

$$Z = 1 + \sum_{i=1}^{9} B_i \cdot (0.01\, T)^{C_i} \cdot (10^{-6}\, p)^{D_i}, \tag{2}$$

with respective values for the coefficients B_i, C_i, D_i given in Lemmon and Huber (2008). Wei et al. (2023) give an approximation formula for the dynamic viscosity of pure hydrogen depending on pressure (p) and temperature (T) as

$$\mu = B_1 \cdot T^{B_2} + B_3 \cdot \frac{1}{T^{B_4}} \cdot p^{B_5}, \tag{3}$$

with respective values for the coefficients B_1, B_2, B_3, B_4, B_5. For the sake of performance, the simple algebraic expressions in equations (2) and (3) are implemented for the case of pure hydrogen. To check the validity of the employed equations (2) and (3), experimental measurement values quoted in the literature are reproduced. The deviation of the calculated values for the dynamic viscosity and the density (related to the compressibility factor per equation (1)) of pure hydrogen from the experimental results given in Michels et al. (1953)

Table 3. Deviation of the calculated values for dynamic viscosity and density from experimental values (taken from Michels et al. (1953)) for pure hydrogen.

Input		Deviation [%]	
T [K]	p [MPa]	μ	ρ
298.15	2.68	0.335	-0.124
298.15	3.10	0.442	0.001
298.15	3.49	0.771	-0.117
298.15	3.70	0.659	-0.036
298.15	4.55	0.761	-0.026

is shown in table 3. The comparisons shown in tables 1, 2 and 3 verify that the implemented calculation methods for the compressibility factor yield results which agree with experimental results on the sub-percent level for temperature and pressure ranges typical for gas network operation. For the dynamic viscosity the calculated values deviate from experimental results on the percent level with higher deviations being observed for mixtures with a higher hydrogen fraction at lower temperature and higher pressure values. To validate the implementation, previously published benchmark results for a sample blended-hydrogen network (Hafsi et al. (2017)) have been reproduced with sub-percent agreement.

2.2. *Modelling of hydrogen storage*

Storage facilities are modelled as nodal elements in the gas network graph. In the model, storage nodes have two modes of operation: injection, where gas is taken out of the network to fill the storage in times of gas surplus and withdrawal, where gas is taken from the storage and introduced in the network to support gas supply. Which of the two modes is realized at any time is an external operational decision and thus has to be supplied as part of the scenario definition. Depending on the mode of operation, the storage either acts as an additional consumer taking gas at an externally specified injection flow rate Q_{inj} or as a gas source supplying gas inflow to the network at an externally specified withdrawal flow rate Q_{wit}. These flow rates depend on the momentary filling level, i.e. the inventory, of the storage $I(t)$. Thus, the current inventory has to be tracked at each time step $t = t' + \Delta t$ during the simulation run according to

$$I(t) = I(t') + (Q_{\text{inj}}(t) - Q_{\text{wit}}(t))\,\Delta t. \tag{4}$$

The relationships between injection Q_{inj} or withdrawal flow rates Q_{wit} and the inventory I are characteristic properties of the modelled storage and have to be externally specified. Figures 1 and

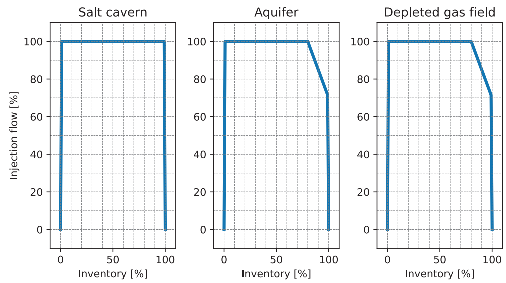

Fig. 1. Relationship between injection flow rate (%) and inventory levels (%) of salt caverns, aquifers, and depleted gas fields (as given in Pambour (2018)).

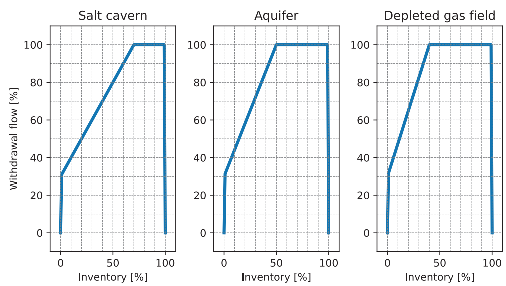

Fig. 2. Relationship between withdrawal flow rate (%) and inventory levels (%) of salt caverns, aquifers, and depleted gas fields (as given in Pambour (2018)).

2 depict simplified characteristics for three types of storage options as quoted by Pambour (2018). Together with information on the maximal $I_{\max}$ and initial inventory I_{ini} as well as maximal injection $Q_{\text{inj, max}}$ and withdrawal rates $Q_{\text{wit, max}}$ the respective storage is fully specified to be modelled in the simulation. To check this modelling approach, plausibility checks regarding the storages' performance have been succesfully conducted.

3. Example application

To showcase both the newly incorporated hydrogen as well as the storage modelling capabilities of the hydraulic gas network simulation tool for off-design scenarios, a generic but representative gas network (see topology depicted in figure 3) is investigated. This basic network layout (nodes 1 to 25) has been extensively featured in the literature regarding natural gas network simulation. See, e.g., Martini et al. (2025); Ganter et al. (2024); Osiadacz (1987) for details on the network parameters and benchmark results. In Martini et al.

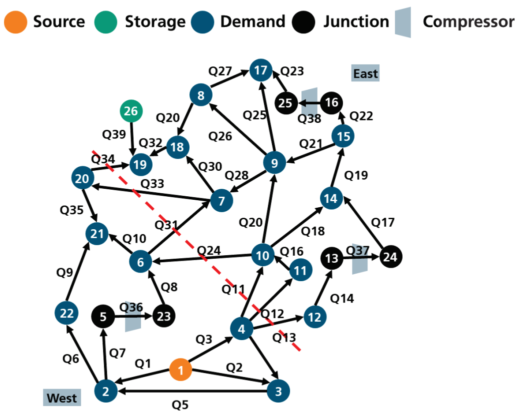

Fig. 3. Topology of the example network, augmented by a storage connected to node 19.

(2025); Ganter et al. (2024) a disruption scenario of multiple pipeline disconnections has been assumed in order to assess the behaviour of the gas network in far-off design point operation. The pipelines which are taken out of service according to the scenario are depicted in figure 3 by a dashed red line dividing the network into two disjoint parts: the western part remaining connected to the source (node 1) and the eastern part which is detached from the source after the disruption. Assuming this separation of the network, the robust transient approach presented in Martini et al. (2025) allows to study the survival time of the eastern network part after detachment from the source; i.e., the time span for which all claimed demands and pressure requirements can still be fully supplied from the natural gas stored within the network itself. For the specific natural-gas example depicted in figure 3 without the storage node, all claimed demands in the eastern part of the network can be supplied for roughly 14 hours past the detachment. After this time span, the pressures at consumer nodes fall to the required minimal pressure boundary leading to a reducing amount of natural gas actually delivered to the respective consumers. Thus, assuming a repair time of around 30 hours leaves the consumers in the eastern part of the network in a potentially insufficient supply situation for roughly 16 hours (see Martini et al. (2025) for the detailed study and parameters).

For the first analysis of the work presented here, the original natural gas network layout featuring gas sources, consumers as well as compressors is extended by a salt-cavern storage unit with a capability to supply 50% of the total demand of all consumers in the eastern part of the network for at least 36 hours (node 26 in figure 3 with parameters given in table 4). Simulating a similar disruption scenario as outlined above and detailed in Martini et al. (2025) but now with the additional storage supply, reveals that a strategically placed, properly designed storage unit can extend the survival time significantly, thereby bridging the supply gap until the completion of the repair of the network without consumers experiencing any loss of gas supply. This is exemplified in figure 4 where pressures at selected consumer nodes in the western and eastern parts of the network are shown before, during, and after the disruption. During the disruption starting at $t = 0$ h the pressures of the eastern nodes fall steadily. However, the additional storage supply manages to maintain pressures above the minimal pressure requirement during the whole repair time span of 30 hours. Thus, due to the aptly dimensioned storage, no reduction of the delivered flows is necessary while the respective pipelines are out of service as in the case without the storage. Storage facilities play an increasingly important role for realizing a steady supply of green hydrogen from potentially unsteady production cycles due to volatile environmental conditions. Therefore, the performance of storage units in hydrogen grids

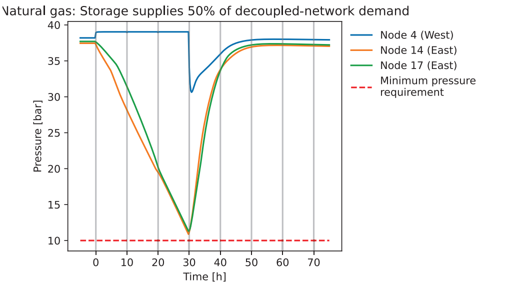

Fig. 4. Pressures in selected nodes (node 4 in the western part of the disrupted natural gas network; nodes 14 and 17 in the eastern part) with a storage supplying 50% of the demand of the decoupled network.

is a key indicator for resilient grid design. Consequentially as a next step, the gaseous medium in the network at hand is changed from natural gas to pure hydrogen as outlined in section 2.1 thereby reflecting the practical approach of refurbishing an existing natural gas network for hydrogen operation. Accordingly, the same energy demand of the consumers is assumed as in the natural gas case. Since the volumetric heating value of pure hydrogen is roughly a third of that of natural gas, approximately a threefold increase in the volumetric flow rate of hydrogen delivered to the consumers is thus required. Although hydrogen has a lower density and is less viscous than natural gas, this increase in flow rate still results in greater pressure drops leading to lower nodal pressures in the hydrogen network compared to the natural gas network. The interplay of lower density, volumetric heating value and nodal pressures together with higher required volumetric flow rates also results in less hydrogen which is packed in the network itself. Consequently in contrast to the natural gas case, a storage unit with the capability to supply 50% of the demand of the decoupled network (cf. parameters in table 4) is not sufficient to bridge the assumed repair time gap of 30 hours after a disruption as can be seen in figure 5: The nodal pressures shown for the two representative nodes in the eastern network part drop to the minimally required consumer threshold at around 7 hours after the disruption leading to a reduction of actually delivered hydrogen flow to the consumers

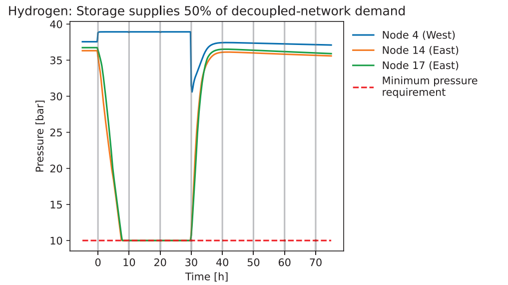

Fig. 5. Pressures in selected nodes (node 4 in the western part of the disrupted hydrogen network; nodes 14 and 17 in the eastern part) with a storage supplying 50% of the demand of the decoupled network.

and thus a potentially insufficient supply situation lasting approximately 23 hours until repair. How-

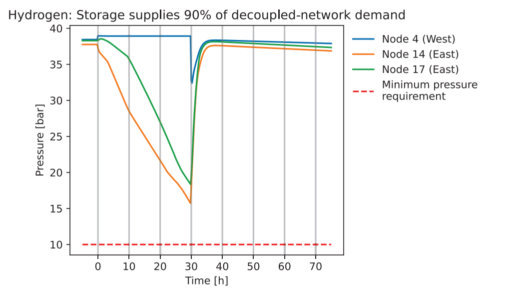

Fig. 6. Pressures in selected nodes (node 4 in the western part of the disrupted hydrogen network; nodes 14 and 17 in the eastern part) with a storage supplying 90% of the demand of the decoupled network.

ever, scaling the storage unit such that it is able to supply 90% of the eastern network's consumer demands for at least 36 hours (cf. parameters in table 4) secures sufficient hydrogen supply for all consumers during the full repair time window as is exemplified for representative nodes in figure 6. As can be seen from figures 5 and 6 in contrast to the natural gas case, for hydrogen a much bigger storage is needed to slow down the decline in pressure enough to mitigate the supply loss during the time of the network disruption. The effectiveness of differently dimensioned storage units considered here as mitigation measures in case of source-decoupling scenarios as depicted in figures 4, 5 and 6 is summarized for natural gas

Table 4. Comparison of the mitigation strategies through integrated storage units for natural gas and hydrogen networks facing source detachment for 30 hours.

Medium	Natural gas	Hydrogen	
Storage supply capability (% of detached network demand)	50%	50%	90%
$Q_{\text{wit, max}}$ [sm^3/s]	84.5	275.24	495.11
$I_{\text{ini}} = I_{\text{max}}$ [Msm^3]	36.504	118.9	213.9
Time until failure [h]	> 30	≈ 7	> 30
Secure supply during disruption	✓	✗	✓

and hydrogen networks in table 4.

4. Conclusion

This work focuses on the numerical simulation of the system state of hydrogen networks in off-design scenarios and the assessment of possible mitigation strategies. To this end, respective functionalities allowing for modelling the fluid medium as pure hydrogen and flexible hydrogen blends and for implementing simple but versatile storage models are presented. These capabilities are realized as extensions of the existing robust transient gas network simulation algorithm originally introduced by Ganter et al. (2024); Martini et al. (2025) in the context of natural gas network modelling. The validity of the calculated fluid properties for the new media is cross checked against experimental values from the literature. In combination with the storage modelling capabilities, the presented developments enable the simulation algorithm to be used for vulnerability and robustness analyses of hydrogen networks. This is showcased for a benchmark gas network model, representative for typical natural gas transport grids. The original network is equipped with a storage node in order to study mitigation potentials in case of significant disruption scenarios. It is demonstrated that a strategically dimensioned storage can significantly extend the operational time of a gas network after even a complete detachment from any gas source. Additionally, simulating the dynamics of hydrogen instead of natural gas allows for the assessment of storage properties required for robust network operation if existing natural gas infrastructure is to be refurbished in the course of future hydrogen roll out. Due to hydrogen's lower density and volumetric heating value compared to natural gas, storages with significantly higher capacities are needed as mitigation measures in case of disruptions. This kind of information, obtainable through the newly developed algorithm, constitutes vital input for the planning of resilient hydrogen networks.

Acknowledgement

Part of the authors' research and development, as presented in this paper, is conducted within the Fraunhofer Center for the Security of Socio-Technical Systems (Fraunhofer SIRIOS) funded by the German federal government and the state of Berlin.

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