G0701

Sector Coupling for Renewable Energy Sources Integration – A Case Study for the German Gas Transmission Network

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Abstract

Sector coupling is a possible way to increase the flexibility of the energy system enabling surplus power generated by renewables to be converted through electrolysis into a fuel, typically hydrogen, that can be transported and dispatched through blending in the natural gas grid or pure in a dedicated backbone. This integration of the electricity and gas sectors aids in stabilising the power grid, mitigating imbalances caused by unforeseen volatilities and excessive renewable power production. However, it is necessary to understand the impacts of transporting and distributing hydrogen on gas networks from multiple perspectives, as explored in this research.
The aim of this work is the assessment of the hydrogen receiving capacity of the gas network under coupling with the power network, in case of a hydrogen blending limit of 20%vol. The addressed case study consists of the simulation of the German gas transmission network with direct green hydrogen injection coming from renewable electricity surplus. Germany, being one of the biggest gas markets, having expressed a strong interest in the development of a hydrogen market and with its highly meshed gas infrastructure is an interesting playground for this case study. The topology, demand and hydrogen data are collected from open-source datasets, while the fluid-dynamic model is an own development in MATLAB.
The regional surplus of electricity produced by renewable energy sources is converted into hydrogen through electrolysis; this fuel is then injected into the gas grid, in the same region where the electricity surplus occurs.
For the day of the highest hydrogen production, an hourly simulation is run: the amount of curtailed hydrogen and its location is obtained, as well as the amount of energy that has been successfully integrated into the gas grid.
The final aim is to quantify the additional flexibility that sector coupling provides while ensuring gas quality requirements.

Introduction

In order to decarbonise the energy sector, renewable energy sources play an important role. In Europe, renewable power generation is steadily increasing, reporting in 2022 a share of 41.2% of the total EU gross electricity consumption [1]. During the same period, Germany witnessed renewable energy sources contributing to 44.1% of gross electricity production, with wind power alone comprising 21.6% [2]. The primary challenge associated with renewable energy sources lies in their intermittency, stemming from the volatility of the available energy from sunlight and wind. Consequently, achieving electrical flexibility becomes imperative for electricity systems with significant penetration of renewable energy, enabling the maintenance of balance between power generation and demand.

Power-to-gas emerges as a promising technology, involving the conversion of excess electricity generated by renewable energy sources, primarily into hydrogen that can be transported via pipeline as a pure gas or in a mixture with natural gas [3]. Such sector coupling between electricity and gas not only supports the operation of the power grid but also addresses issues arising from the unpredictability of power injections from wind parks, which can disrupt the balance between generated and required electric power [4].

Moreover, the production of hydrogen with renewable electricity gains importance when considering the fact that, in Germany, in 2023, 19 TWh of RES has been curtailed, resulting in 3.1 billion euros of congestion management, which represents a consistent loss of money and energy [5]. This problem is not restricted to a specific country, rather it is a common issue among all the power systems with a large share of intermittent renewable generation.

The acceptability of hydrogen into the natural gas pipeline infrastructure is a frequent source of debate in the EU. A recent European Directive [6] established a cap of 2% volume of hydrogen that can be blended for cross-border transport.

Germany, as one of the largest natural gas markets in the EU, has always expressed a strong interest in the further development of its hydrogen infrastructure. In 1938, the Ruhr region saw the construction of its inaugural long-distance hydrogen pipeline spanning 215 kilometres [7]. In November 2023 the country's government unveiled a plan for hydrogen transport via pipelines to the major ports, industries, power plants and storage facilities of the country [8][9]. As well as pure hydrogen transport, the country is also enhancing blending with natural gas, in fact, it reports the regulatory framework with the highest concentration limit at the transmission level (10%) in the EU; furthermore, there are several pilot projects blending even higher hydrogen concentrations [10].

Thus, it can be asserted that the gas network incorporating hydrogen injection constitutes a complex system necessitating safe and predictable operation. Consequently, meticulous monitoring and thorough examination of any alterations to this infrastructure are imperative.

Although some examples of gas network simulation with hydrogen blending and sector coupling can be found in the literature, it is clear that there is a need to fill an important gap: in fact, the requirements of the natural gas network concerning hydrogen blending are not taken into account, even though it is important to understand how much, with respect to the total green hydrogen produced with power-to-gas, can actually be accepted by the network and how much must be curtailed in order to comply with the current regulations.

On the other hand, a quantitative estimation of extra renewable energy integrated within the system by means of sector coupling is necessary as a proxy of the degree of flexibility that power-to-gas options can unlock.

Therefore, the objective of this paper is to present, by using a gas network model, an assessment of the curtailment of hydrogen with the aim of quantifying the actual acceptance of the natural gas network and estimating the potential of sector coupling.

The proposed simulation method is calibrated on the German gas transmission network: the data regarding network topology, domestic consumption, cross-border flow and green hydrogen production are collected from open-source datasets, while the fluid-dynamic model alongside quality tracking and curtailment is developed in MATLAB. Besides the baseline scenario, an additional simulation is conducted wherein hydrogen is blended at different points within the grid to reduce its curtailment as an enhanced operational strategy in sector-coupling scenarios. The concluding section of this study provides a summary of the findings and draws the key conclusions.

1. Model of the German gas transmission network

1.1 Open-Source Input Data

The data needed to run the simulations are mainly of two types: topology data and consumption data.
Topology data is sourced from the SciGRID_gas project, specifically, the dataset labelled SciGRID_gas IGGIELGN [11]. This dataset is compiled from various open-source data outlets, encompassing information about the European gas network.
The processed network dataset comprises 658 nodes and 1019 pipelines, representing the German gas transmission network, as depicted in Figure 1. Each node within the network requires an assignment of natural gas demand, a process detailed in subsequent sections.

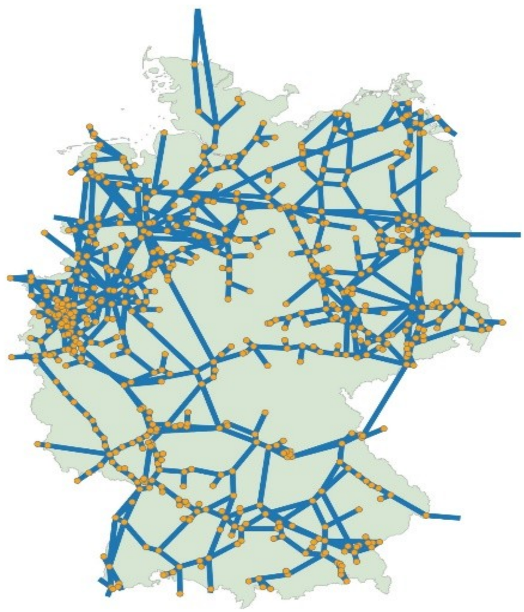

Figure 1 – Network model of the German gas transmission network used in this work

The domestic demand for natural gas is provided by DemandRegio [12], where data and tools for the spatial and temporal breakdown of German electricity and gas demand are provided. The outcomes include three demand time series, each corresponding to an analysed sector (industrial, residential and services). These results are available at a NUTS-3 resolution, with a temporal resolution of 15 minutes for the industrial sector and one hour for households and commercial, trade and services (CTS) sectors.
To accurately simulate the network behaviour, it is crucial to consider the gas import and export into and out of the country. Specifically, regarding gas exchanged between Germany and neighbouring countries, data from the German Network Agency

(Bundesnetzagentur) are employed. These records are based on calculations from the data provided by German transmission system operators for natural gas and they are available at [13].
Lastly, the data concerning hydrogen injection is derived based on the Open Power Systems Data dataset, which provides weather data as well as data about the location and the electrical capacity of the renewable (PV and wind) power plants in Germany [14][15]. These data enable the calculation of renewable energy production: the electricity generated by renewable plants is deducted from the electricity demand in order to calculate the renewable electricity surplus. It is important to point out that this deduction is made on a regional balance: Because in this work the power generation dispatch and the German power transmission system are not modelled, the transmission of the surplus of electricity in a region is not considered, instead, it is fed to electrolysers for hydrogen production.
To dampen this simplification, which leads to an overestimation of the renewable electricity surplus, the maximum domestic electrolyser capacity has been set to 10 GW, according to the German power network development plan for 2030 [16]. If this threshold is overcome, the regional surplus is proportionally redistributed to match the country's total of 10 GW, i.e. regions with higher renewable surplus will be allocated a larger share of electrolyser capacity.
This regional renewable electricity surplus is subsequently introduced into the gas grid as hydrogen. As stated by SRIA Key Performance Indicators [17] for an alkaline electrolyser, the full stack efficiency in 2024 is 68% (LHV based). From this value, another 5% is deducted to take into account the Balance of Plant (BoP) and the fact that the electrolyser will not always operate at its nominal power.
According to the calculations, for 2015, the renewable electricity generated amounts to approximately 192 TWh, aligning with the data presented in [18] for the same year. Wind farms provide the largest share, accounting for 147 TWh, while 46 TWh is obtained from PV plants.
Conversely, the curtailment of this electricity (utilised as surplus for hydrogen conversion) stands at about 38 TWh which accounts for roughly 19.8% of the total renewable energy production. According to [5], the actual curtailment in 2023 amounted to 19 TWh, so the initial hypothesis leads to an overestimation of the curtailed renewable power generation.
The total gas consumption in Germany, as provided by DemandRegio, amounts to 659 TWh in terms of energy. Therefore, hydrogen could potentially meet 4.3% of this demand, with the hypotheses specified above.

1.2 Scenarios definition for sector coupling

The generated dataset comprises data of the German gas transmission grid and hourly demand data at each network node for a year. To illustrate the most unfavourable scenario regarding sector coupling, a one-day hourly simulation is conducted during the peak green hydrogen production day.
To make significant comparisons, several case studies are run:

1. Base-case scenario without hydrogen injection: this is a hourly time-series simulation of the German gas transmission network with natural gas.
2. Full hydrogen injection scenario (no curtailment): here, the whole amount of green hydrogen produced by the renewable energy sources is blended in the natural gas grid and compliance with technical standards (i.e. DVGW G 260 (A) Technical rule, Gas quality) is not taken into account.
3. Technical standard compliant scenario with hydrogen injection and curtailment: compliance with gas network technical standard with hydrogen cap set to 20%. Even if the current injection limit in the country is set to 10%, the authorities report

the existence or the planning of projects aiming to increase the hydrogen acceptance limit of their networks [10].

4 Enhanced sector coupling scenario with localization of hydrogen injection points: in the previous cases, hydrogen is injected near the PV plant or wind farm responsible for the electricity surplus employed for its production, regardless of the characteristics of the site. In some cases, the injection was performed in small pipelines located in regions with low consumption and this led to higher curtailments. To highlight the importance of the injection point and to enable a higher blending of hydrogen, the curtailment analysis is performed on a new configuration in which the electrolyser positions are chosen more carefully. The importance of this choice is highlighted in [19], here the authors accentuate the fact that electrolysers will have a significant impact on both the gas and power grid and that their positioning deserves proper TSO attention. In this new scenario, hydrogen is injected in pipelines that are able to bear higher flow rates but, at the same time, they are not too far from the production site (100 km at maximum).

In the subsequent section, the main results of the simulation of the previously described scenarios are summarized and commented on.

2. Results

Figure 2 shows the hydrogen that is accepted and the gas demand at every hour of the day according to the technical standard compliant scenario (scenario 3). It can be observed that the maximum hydrogen acceptance occurs in the early morning, between 5 and 7 a.m., at the same time, the gas demand peaks as well, in accordance with [20], and when the demand is higher it is possible to mix more hydrogen in the natural gas flow.
The minimum hydrogen acceptance occurs at night, between 11 p.m. and 1 a.m., even if the renewable surplus is high (see Figure 3), the acceptance of hydrogen is low simply because there is low gas demand, so the grid is not accepting blending.
In the middle of the day, gas demand is not as high as in the morning or evening, furthermore, electricity surplus is at its minimum, therefore the network does not experience a high hydrogen concentration.

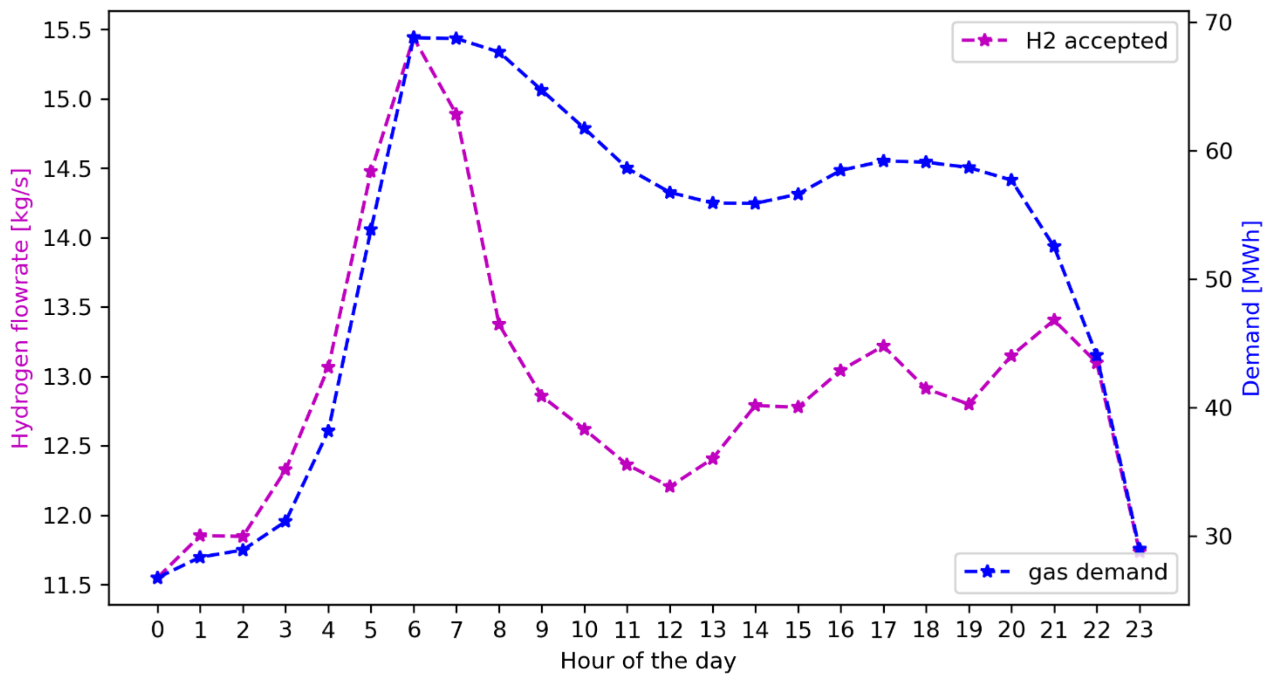

Figure 2 - Hourly hydrogen acceptance and natural gas demand

Figure 4 shows the location of the hydrogen injection nodes and their corresponding curtailment; Figure 5 shows the renewable electricity surplus for the German NUTS-2 regions. It is possible to notice that the highest curtailment corresponds to the zones with the highest renewable plant concentration: in the northern part of Germany, the wind farms are very common, while in the south-east the PV plants are more common [21][22]. Notably, on the considered day of simulation, the areas with surplus are close to each other making difficult and less attractive other flexibility options such as increasing power network interconnections and transmission capacity.

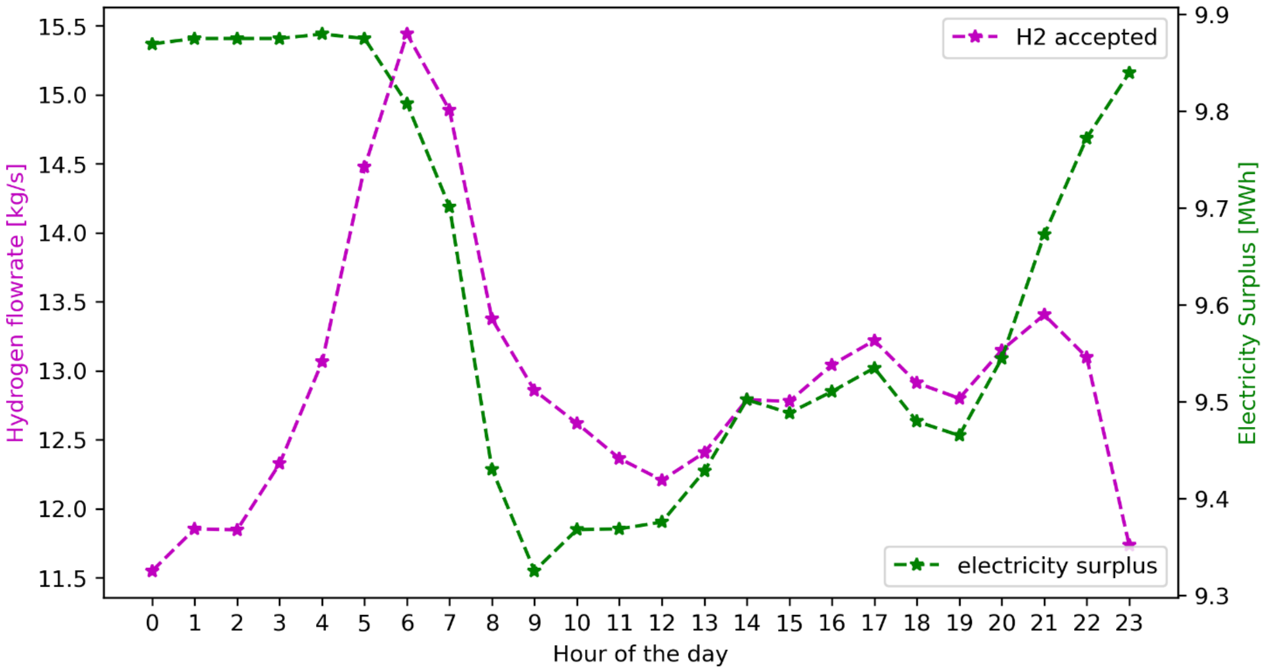

Figure 3 - Hourly hydrogen acceptance versus electricity surplus

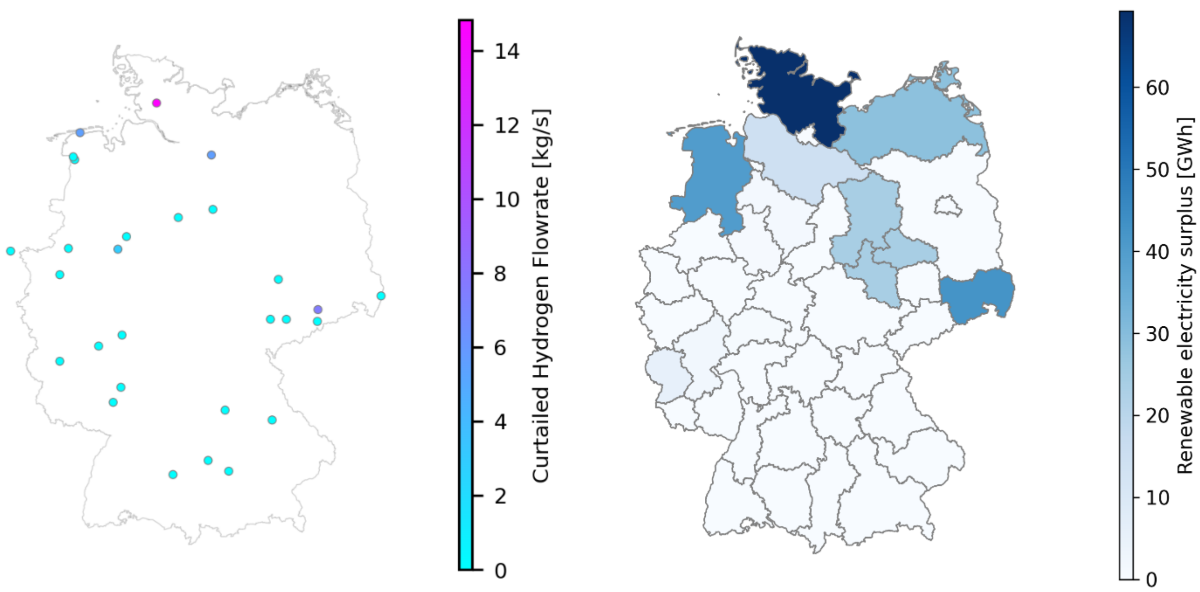

Figure 4 - Hydrogen curtailed from the hydrogen injection pipelines at 6 a.m.

Figure 5 – Renewable electricity surplus for the day in which it is maximum

Figure 6 shows the concentration of hydrogen in all the nodes of the network, without and with curtailment (left and right respectively). It is possible to notice that the most stressed parts of the grid, in terms of hydrogen concentration, are the same in the two cases. However, in the latter case, hydrogen concentration does not overcome the user-specified limit of 20% and, in general, remains lower than 10%, as per the regulatory framework [10].

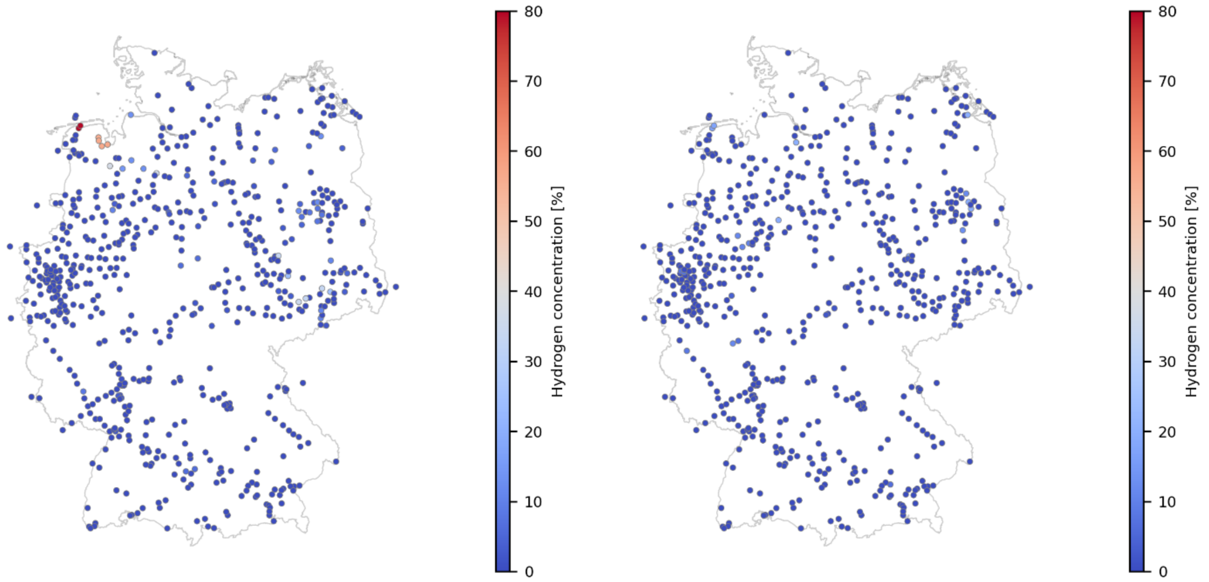

Figure 6 - Hydrogen concentration in the nodes of the network before (left) and after (right) curtailment at 6 a.m.

The hydrogen acceptance depends on the amount of natural gas flowing in the pipelines. In order to increase the acceptance, it is possible to explore some strategies for the localisation of the hydrogen injection points; notably, hydrogen can be injected where the gas flow rate is high, so that a higher amount can be blended. However, it is also important to inject the fuel at a point that is sufficiently near to the production site, in order to reduce transportation costs. Therefore, new injection points are chosen relaxing from the requirements about the distance from the production site (from 20 to 100 km), but enabling injection in bigger pipelines that can bear higher flow rates. As a result, the hydrogen acceptance is increased, as displayed in Table 1.

	Technical standard compliant	**Enhanced sector coupling**
Total hydrogen available [kg/s]	51.9	51.9
Accepted hydrogen [kg/s]	15.4	21.4
Curtailed hydrogen [kg/s]	36.5	30.5
Curtailed percentage [%]	70.3	58.7

Table 1 - Comparison with different hydrogen injection points

The controlled hydrogen blending i.e. curtailment, can enable hydrogen usage in the natural gas network, thereby lowering CO_2 emissions, while maintaining the physical

properties of the mixture near to the case with conventional natural gas transport. It can, therefore, be a way of utilising hydrogen without disrupting the natural gas grid reliability. As per German regulations, the heating value of the gas mixture circulating in the network has to be in the range of 30.2 – 47.2 MJ/m^3 [23]. In the case of curtailment, the heating value is compliant with the regulations, reaching a minimum value of 32.2 MJ/m^3.
The findings indicate that approximately 230 GWh of renewable energy would be curtailed during the day. By converting it into hydrogen, with the efficiency specified in section 1, the potential renewable energy integrated by sector coupling (e.g., therefore switching from electricity energy carrier to hydrogen energy carrier) amounts to about 173 GWh. With hydrogen injection, it becomes feasible to utilize 44 GWh, thereby enabling the utilization of 29% of the renewable energy that would otherwise be curtailed. The remaining 129 GWh are not directly injected into the natural gas network in the form of hydrogen to be compliant with the gas network requirements. However, this amount of hydrogen can still be stored or used for other purposes than blending, enabling different business models.

3. Added Values/Conclusion

Examining the integration of hydrogen into the high-pressure natural gas transmission system holds significant importance, as it is a means for renewable electricity integration and CO_2 emission reduction. However, as hydrogen possesses markedly different properties compared to natural gas, it is imperative to thoroughly investigate the implications of power and gas sector coupling from the point of view of the natural gas infrastructure, since operators of the natural gas transmission system are keen on preserving the existing operational conditions of the network while increasing the hydrogen content in the gas mixture.
Besides the fluid dynamic simulation, this paper models as well the curtailment of green hydrogen, which is crucial to control the composition of the mixture flowing in the grid. This model is then applied to the German gas transmission network and two main conclusions are drawn:

- The hydrogen curtailment depends on natural gas demand, a low demand leads to a high curtailment. Therefore, it would be possible to schedule the **hydrogen injection operation** based on the hourly gas demand.
- The careful **localization of injection points** is crucial since it can enable a higher acceptance rate of hydrogen as shown in this work.
- Sector coupling possesses the capacity to utilise renewable electricity that might otherwise go unused.
- Sector coupling and, more in general, integration of renewable gases within the gas network requires careful monitoring and availability of real-time operational data for safe operation.

Although this study has some major limitations, including the fact that the power system is not analysed and a simplified analysis of the surplus potential/profile, it gives some quantitative insights about opportunities of sector coupling, the need to introduce operational strategies of gas networks for optimal hydrogen injection schedule and of guidelines for site-selection of injection points. Further study is needed, especially about business case analysis exploring the feasibility of pure sector coupling upon potential low capacity factors of electrolysers; more complex dispatch strategies could be explored by looking at gas network integration and other uses of hydrogen in pure form. Finally, similar simulations could be explored in the view of exploring sector coupling between power network and future hydrogen backbone where relaxation of gas quality constraints may be beneficial.

References

[1] European Union, “Electricity from renewable sources up to 41% in 2022,” 2024. [Online]. Available: https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240221-1#:~:text=In%202022%2C%20renewable%20energy%20sources,coal%20(less%20than%2017%25). [Accessed 03 05 2024].

[2] F. S. O. o. Germany, “Gross electricity production in Germany,” 05 4 2023. [Online]. Available: https://www.destatis.de/EN/Themes/Economic-Sectors-Enterprises/Energy/Production/Tables/gross-electricity-production.html [Accessed 10 05 2024].

[3] L. G. S. H. C. Bin Miao, “Long-distance renewable hydrogen transmission via cables and pipelines,” *International Journal of Hydrogen Energy,* vol. 36, pp. 18699-18718, 2021.

[4] S. C. M. C. R. Giulio Guandalini, “Power-to-gas plants and gas turbines for improved wind energy dispatchability: Energy and economic assessment,” *Applied Energy,* vol. 147, pp. 117-130, 2015.

[5] B. Wehrmann, «Curtailing of renewable power increases in Germany in 2023 as re-dispatch costs recede”, Clean Energy Wire, Available: https://www.cleanenergywire.org/news/curtailing-renewable-power-increases-germany-2023-re-dispatch-costs-recede

[6] D. ST-16522-2023, “Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the internal markets for renewable and natural gases and for hydrogen (recast),” 2023.

[7] Z. T. G. Z. C. Z. e. a. Hantong Wang, “Research and demonstration on hydrogen compatibility of pipelines: a review of current status and challenges,” *International Journal of Hydrogen Energy,* 2022.

[8] Hydrogeninsight, “German hydrogen pipeline network will begin transporting H2 in 2025, with 9,700km in place by 2032, says government,” 2023. [Online]. Available: https://www.hydrogeninsight.com/policy/german-hydrogen-pipeline-network-will-begin-transporting-h2-in-2025-with-9-700km-in-place-by-2032-says-government/2-1-1554455.

[9] Reuters, “Germany presents hydrogen core network plan in bid for 2045 climate neutrality,” 2023. [Online]. Available: https://www.reuters.com/business/energy/germanys-core-network-hydrogen-fuel-cost-20-bln-euros-by-2032-fnb-gas-chairman-2023-11-14/.

[10] A. f. t. C. o. E. Regulators, “ACER Report on NRAs Survey -Hydrogen, Biomethane, and Related Network Adaptations,” 2020.

[11] A. P. a. W. M. Jan Diettrich, “SciGRID_gas IGGIELGN,” 17 05 2021. [Online].

[12] F. Gotzens, B. Dr.-Ing. Gillessen, S. Burges, W. Hennings, J. Prof. Dr.-Ing. Müller-Kirchenbauer, S. Seim, P. Verwiebe, T. Dr.-Ing. Schmid, F. Jetter and T. Limmer, “DemandRegio – Harmonisierung und Entwicklung von Verfahren zur regionalen und zeitlichen Auflösung von Energienachfragen – Abschlussbericht,” *Forschungszentrum Jülich GmbH, Jülich; Technische Universität Berlin, Berlin; Forschungsstelle für Energiewirtschaft e. V., München.*

[13] Bundesnetsagentuur, “Daily data,” [Online]. Available: https://www.bundesnetzagentur.de/DE/Gasversorgung/aktuelle_gasversorgung

/start.html. [Accessed 04 03 2024].

[14] Stefan Pfenninger and Iain Staffell. *Open Power System Data*. Version 2020-09-16. Data Package Weather Data, 2020. doi: 10.25832/weather_data/2020-09- 16. url: https://doi.org/10.25832/weather_data/2020- 09- 16

[15] Ingmar Schlecht and Milos Simic. *Open Power System Data*. Version 2020-05-20. Data Package Renewable power plants, 2020. doi: 10.25832/renewable_power_plants/2020-05-20. url: https://doi.org/10.25832/renewable_power_plants/2020-05-20

[16] Bundesministerium für Wirtschaft und Klimaschutz, Fortschreibung der Nationalen Wasserstoffstrategie: NWS 2023, 2023/07

[17] EU Commission, Clean Hydrogen JU – SRIA Key Performance Indicators (KPIs). url: https://www.clean-hydrogen.europa.eu/knowledge-management/strategy-map-and-key-performance-indicators/clean-hydrogen-ju-sria-key-performance-indicators-kpis_en

[18] U.S. Energy Infomation Administration. Germany's renewables electricity generation grows in 2015, but coal still dominant. url: https://www.eia.gov/todayinenergy/detail.php?id=26372#:~:text=Renewable%20electricity%20generation%20in%20Germany,the%20country%27s%20gross%20electricity%20generation

[19] A. a. S. N. a. S. e. S. N. a. I. A. European Commission and Directorate-General for Energy and Iliceto, "Hydrogen's impact on grids – Impact of hydrogen integration on power grids and energy systems," Publications Office of the European Union, 2023.

[20] M. P. et al., "Capturing variation in daily energy demand profiles over time with cluster analysis in British homes (September 2019 – August 2022)," *Applied Energy,* vol. 360, 2024.

[21] L. Holm, "Wind power Germany 2016 fact sheet: electricity generation, development, investments, capacity, employment and the public opinion. Data: Strom-Report, BWE, BmWi, Dt. WindGuard, Fraunhofer, AEE, EWEA (WindEurope)," 2016.

[22] L. Holm, " Solar power Germany 2016 fact sheet: electricity generation, development, investments, capacity, employment and the public opinion.," 2017.

[23] bayernwerk, "Gasfamilien nach DVGW-Arbeitsblatt G 260 (Gasbeschaffenheit)," [Online]. Available: https://www.bayernwerk-netz.de/content/dam/revu-global/bayernwerk-netz/files/kommunen/installateure/bayernwerk-gasfamilien-erdgase-gasgeraetekategorien.pdf.