Exploring the role of hydrogen pipeline infrastructure in a sector-coupled European energy system towards 2050

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Abstract

With the aim of reducing carbon emissions and seeking independence from Russian gas in the wake of the conflict in Ukraine, the use of hydrogen in the European Union is expected to rise in the future. In this regard, hydrogen transport via pipeline will become increasingly crucial, either through the utilization of existing natural gas infrastructure or the construction of new hydrogen dedicated pipelines. This study investigates the effects of hydrogen blending on the European energy system by the year 2050, by introducing hydrogen blending sensitivities to the Global Energy System Model (GENeSYS-MOD). Results indicate that hydrogen demand in Europe is inelastic and limited by its high costs and specific use cases. The availability of hydrogen blending has been found to impact regional hydrogen production and trade, with countries that can utilize existing natural gas pipelines, such as Norway, experiencing an increase in exports as the proportion of blending increases. Although the influence of blending on the overall production and consumption of hydrogen in Europe is minimal, the impacts on the location of production and dependence on imports must be thoroughly evaluated in future planning efforts.

Keywords: Energy Infrastructure, Hydrogen, Decarbonization, Energy Policy, Energy System Modeling, Energy Economics, GENeSYS-MOD, Renewables

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Alle Autoren sind Jungautoren.

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1. Introduction

Given the urgent need to decarbonize the European energy system to meet current climate targets and the shock caused by the Russian war of aggression against Ukraine, a rethink and adaptation to the current and future challenges of the European energy system is necessary and already underway (European Commission, 2022c). Renewable hydrogen has the potential to play a crucial role in the decarbonization of the European energy system. As a clean and versatile energy carrier, renewable hydrogen can be produced from a wide range of renewable energy sources, including wind and solar power. This makes it a promising solution for decarbonizing not only the energy system, including heat, transportation and electricity, but also the manufacture of a wide range of chemicals, materials, and products. As such, renewable hydrogen can further reduce the reliance on fossil fuels, leading to substantial reductions in greenhouse gas emissions and a transition towards a more sustainable and low-carbon energy system. But while the potential of renewable hydrogen is widely recognized, its exact scope and role in the European energy system remains subject of discussion.

While small amounts of hydrogen might end up being produced close to the location of its utilization, larger amounts will likely imply a regional separation of production and consumption. Regions with high renewable potentials (i.e., wind (offshore) and solar) could prove to be beneficial for the production of renewable hydrogen, whereas regions dominated by industry could become the main consumers. Transportation via pipeline will either be done by utilizing parts of the existing natural gas infrastructure or building new hydrogen-carrying pipelines (ACER, 2021). The extent of the usage of existing infrastructure and its potential effects on the implementation and usage of hydrogen technology however, remains a much discussed topic. In 2020, a consortium comprised of European gas transmission companies released the first European Hydrogen Backbone, a concept for European hydrogen transport infrastructure that estimates a network covering 40,000 km in 2040 with 75% being built on existing natural gas infrastructure and 25% new dedicated hydrogen pipelines (Guidehouse, 2020). Existing infrastructure has the upsides of being available, being socially accepted, and having lower costs for retrofitting compared to building new pipelines (IEA, 2019; Cerniauskas et al., 2020). Transmission system operators assume the costs for retrofitting to be at around 10-15% of new constructions (Siemens Energy, 2021). Alternative options to pipelines include ammonia and liquid organic hydrogen carriers (LOHCs). Ammonia and LOHCs are much easier to transport than hydrogen, but they often cannot be used as final products and a further step before final consumption is necessary (Aziz et al., 2020; Niermann et al., 2021; Reuß et al., 2017). This entails extra energy and cost, which must be balanced against the lower transport costs. IEA (2019) finds that transmission of hydrogen by pipeline is the generally the cheaper option for distances below 1,500 km. For longer distances, especially overseas, transport as ammonia or LOHC may be a more cost-effective option. There are, however, some caveats related to the transport of hydrogen via pipeline. Hydrogen blend into gas pipelines decrease the transportable energy content (Galyas et al., 2023). To be fed into the transmission system, hydrogen must be compressed to the operating pressure of the network. To maintain pressure despite loss of flow in the pipeline, more and higher-power compressors are required in comparison to natural gas along the pipeline (Guidehouse, 2020; Siemens Energy, 2021). As countries (in the EU) have different norms and legislation on the maximum level of hydrogen allowed (by volume), Vidas et al. (2022) highlight the need for risk-assessment and joint planning across regions and borders. Increasing the share of hydrogen causes costs for applications, re-compression, and retrofitting of pipelines to rise (Bard et al., 2022; Judd and Pinchbeck, 2016; Zhang et al., 2021). A review by Mahajan et al. (2022)

mentions additional techno-economic problems in current hydrogen blending projects. These include the need for new safety standards as risks of leakages and safety concerns increase as well as risks of hydrogen induced corrosion and embrittlement over long term usage. Furthermore, Bard et al. (2022) warn of lock-in effects of hydrogen blending and significant price impacts for end-users despite the general agreement that hydrogen should be used for specifically targeted end-uses instead of area-wide adaption.

Despite the numerous studies that have investigated the techno-economic aspects of hydrogen blending and its effects on the distribution grid and consumers (eg. Giehl et al. (2023)), there is a lack of research on the impacts of hydrogen blending on the European energy system and international trade and transmission. This is an area that requires further investigation in order to gain a comprehensive understanding of the full range of effects of hydrogen blending on the energy sector. This paper aims to compare the impacts of injecting hydrogen into the existing natural gas pipeline transmission system at various percentages on the European energy system. The study builds on low-carbon transition pathways for Europe developed in the Horizon 2020 project *openENTRANCE* (Auer et al., 2020; Hainsch et al., 2022). By introducing sensitivities for hydrogen blending in the Global Energy System Model (GENeSYS-MOD), this paper explores how hydrogen blending options affect production, transport options, and regional localization of hydrogen generation in Europe. The study contributes to the current discussion around hydrogen utilization and transport by generating new insights to help guide the conceptualization of a European hydrogen network best fit for its future purpose. The focus of this paper is not on the techno-economic feasibility of injecting different shares of hydrogen into existing gas pipelines, but the overall effects it would have on the energy system in Europe. The inclusion of financial and technical aspects of hydrogen blending in GENeSYS-MOD is to be added in future research.

The paper is structured as follows: The following sections present the status quo of the European energy sector (Section 2), and the potential of hydrogen in the future European energy sector. Sections 3 and 4 give an overview of the applied model, data, and scenario assumptions. Thereafter, Sections 5 explores the results of the model application, and possible chances and barriers for Europe's low-carbon energy transition. Section 6 discusses implications of the model results, followed by the conclusion (Section 7).

2. Status Quo of the European Energy Sector

The primary energy consumption in the EU in 2021 was 60 EJ, with oil being the main energy carrier, accounting for approximately 35% (BP, 2022, 9) of the total consumption, followed by natural gas with 24%. The EU imports 57% of its energy, with 40% of natural gas, 27% of oil, and 46% of coal coming from Russia (Eurostat, 2022). In 2021, the share of renewables in the primary energy consumption was 18.5% (BP, 2022). The net electricity production in the EU was 2,664 TWh, with wind being the largest source of renewable energy, accounting for 14.7% of total electricity production (Eurostat, 2022). In 2022, the development of the European energy system was mainly determined by increasingly tightened climate targets, the war of Russia on Ukraine and rising energy prices.

The EU is facing increasingly stringent climate targets, including a 55% reduction in Carbon dioxide (CO_2) emissions by 2030 and achieving climate neutrality by 2050 (European Commission, 2022b). This requires the decarbonization of the electricity sector, with most EU member states phasing out coal by 2030 (European Commission, 2022a). The residential sector aims to reduce its carbon footprint through efficiency measures and the replacement of fossil fuel-based heating systems with heat pumps and district heating. In the transportation sector, electrification is the dominant strategy for decarbonization, due to the energy efficiency advantages of batteries.

Reforms of the EU ETS in 2021 resulted in a tripling of CO_2-certificate prices from 30€/t CO_2 in January 2021 to over 90€/t CO_2 in February 2022 (Ember, 2022). This, along with a low gas price, led to a fuel switch from coal to gas in the electricity sector. This switch, along with the deployment of renewable energies, led to a 34% reduction in CO2 emissions in the energy supply sector compared to 2005 (Eurostat, 2022). The residential sector has also seen a 25% decrease in CO_2 emissions compared to 2005. However, further decreases are necessary due to the stagnant renovation rates and the slow deployment of heat pumps. The transportation sector has not been able to reduce its CO_2 emissions and would continue to grow without the restrictions imposed by COVID-19 (Eurostat, 2022).

The war in Ukraine has increased the urgency for a transition away from gas and oil, with the European gas price rising from 16€/MWh in March 2021 to 227€/MWh in March 2022 (OECD, 2022; Holz et al., 2022). Germany, which is the main consumer and importer of Russian natural gas (868 TWh in 2020), is facing the threat of a stop in natural gas exports from Russia (Ruhnau et al., 2022). Europe imports approximately 40% of its total gas consumption from Russia, which is partially compensable by higher imports from Norway and LNG imports (Bruegel, 2022). However, the export capacity from Norway is limited and LNG imports are limited by the need for shorter amortization times for floating terminals (Kemfert et al., 2022; Brauers et al., 2021). In the short-term, the industry has reduced its gas consumption by 11% in response to higher gas prices, while households have seen a reduction of 6% (Ruhnau et al., 2022). Independence from Russia can be achieved through investments in the European gas grid and a reduction in consumption by 20% compared to 2021 (Ragwitz et al., 2022). Germany and other European countries are reactivating coal-fired power plants in response to the threat of a gas stop. This does not, however, question the plan of the current German government to phase out coal in Germany by 2030 (German National Government, 2022; Hauenstein et al., 2022).

Due to the war between Russia and Ukraine, the European Union has stepped up its efforts to decarbonize its energy sector through the updated "Fit for 55" program, now known as "RePowerEU." The EU aims to achieve independence from Russian energy imports by 2027 and has pledged to mobilize up to 300 billion euros for investments in renewable energy, energy efficiency, and some fossil fuel infrastructure (European Commission, 2022c). In addition, the EU needs further 80 GW compared to the “Fit for 55” program in order to supply green hydrogen (Baccianti, 2022). The target is to reach 45% renewable energy by 2030, with 1,200 GW of renewable energy capacity, 900 GW of which will come from wind and solar (European Commission, 2022c). Additionally, the EU aims to increase its energy efficiency from 9% to 13% by 2030, and also plans to deploy 6 GW of green hydrogen electrolysis capacity by 2024 and 40 GW by 2030 (European Commission, 2022c, 2020; Wolf and Zander, 2021). The EU’s hydrogen strategy prioritizes green hydrogen in the long-term, but in the short and medium-term, it focuses on blue hydrogen with the application of CCS technology (European Commission, 2020; Wolf and Zander, 2021). The main consumers of hydrogen will be the industry and transport sector (Sachverständigenrat für Umweltfragen, 2021). However, there are differences in the level of ambitions among different EU countries’ hydrogen strategies, and the European Commission is urged to play a leading role in harmonizing efforts and directing investments (Wolf and Zander, 2021).

2.1. Hydrogen's potential in the European energy system

The significance of hydrogen in Europe's energy transformation has been a focus of numerous studies, particularly due to the rising cost of fossil fuels caused by the conflict in Ukraine (European Commission, 2022c). Hydrogen has the potential to play a crucial role in the energy sector decarbonization by serving as a storage medium, replacing processes in the chemical and steel industries, and in transportation, specifically for heavy-duty vehicles, international shipping, and planes (Ausfelder et al., 2017; Sachverständigenrat für Umweltfragen, 2021). In the following, the mains use cases of hydrogen will be presented.

The potential of hydrogen as a storage medium in the power sector has been extensively studied, with findings indicating its high suitability for long-term storage. In particular, hydrogen storage is seen as a solution to address the seasonal fluctuations in renewable energy sources such as wind and solar power (Wolf and Zander, 2021). A number of simulations have revealed that regions with significant wind energy generation can benefit from the use of hydrogen storage to manage these fluctuations (Victoria et al., 2019; Rasmussen et al., 2012; Andresen et al., 2014; Schlachtberger et al., 2017). Hydrogen is commonly stored in either liquid or gaseous form, either in tanks or underground caverns. Liquid storage in tanks is prevalent in small-scale applications, while gaseous storage in underground geological formations is more appropriate for large-scale, long-term storage (IEA, 2019). Salt caverns have been identified as one of the most viable solutions for large-scale hydrogen storage, due to factors such as safety, cost, capacity, and low losses (Gabrielli et al., 2020; Caglayan et al., 2020). Caglayan et al. (2020) estimate a technical potential of 84.8 $\mathrm{PWh_{H_2}}$ in Europe, with at least 7.3 $\mathrm{PWh_{H_2}}$ located in onshore formations.

In the industrial sector, hydrogen is currently primarily used for refining oil, producing ammonia, methanol, and steel (IEA, 2019). Among these, oil refining is expected to have the least future prospects, as demand is projected to decline over the long-term. In the chemical industry, the demand for green hydrogen is anticipated to increase as a low-carbon feedstock for producing ammonia and methanol, which have a wide range of industrial applications and could also serve as indirect hydrogen storage solutions (Sadeghi et al., 2020; Lan et al., 2012). Green hydrogen also has the potential to be utilized for high-temperature heat production and in the direct reduction of low-carbon steelmaking, given its high calorific value, good thermal conductivity, and high reaction rate (Liu et al., 2021; Rechberger et al., 2020; Vogl et al., 2018). However, there are still technological barriers that currently hinder the widespread adoption and large-scale implementation of a hydrogen-based industry. High amounts of low-cost and stable electricity are critical for the economic viability of such an industry (Conde et al., 2021; Öhman et al., 2022; IEA, 2019). To overcome these barriers and enable the use of green hydrogen, it is crucial that energy and industry transitions are aligned and supported by a framework that takes into account the views of all stakeholders involved (Öhman et al., 2022).

In the transportation sector, the utilization of hydrogen as a fuel varies based on the mode of transportation. There has been a rising trend of countries adopting battery electric vehicles (BEVs) to reduce carbon emissions in the sector (Ajanovic and Haas, 2021). However, this approach is not suitable for fully electrifying freight road, air, and ship transportation (Ueckerdt et al., 2021). Hainsch (2022) reported that hydrogen has a substantial impact on decarbonizing freight transportation in Germany, which can serve as a sign of future trends in Europe. For larger vehicles such as buses and trucks, the use of electric batteries is limited due to the weight of the batteries, creating a demand for alternative technologies. Fuel cell vehicles (FCVs) powered by hydrogen could provide a solution for this issue, as the weight of the energy storage is comparatively low, and hydrogen could be used directly, eliminating the need for a re-electrification process (Ajanovic and Haas, 2021; Espegren et al., 2021). In air transport, hydrogen can be utilized as a direct fuel in the form of liquid hydrogen or converted into synfuels, however, both options are currently not economically viable, calling for further research and development (Fuel Cells and Hydrogen 2 Joint Undertaking., 2020; Hoelzen et al., 2022). As for ship transportation, hydrogen is the most promising substitute as a propulsion fuel, and although there are differing opinions on the best method of storage, hydrogen is considered a promising solution for decarbonizing maritime transportation (McKinlay et al., 2021; Van Hoecke et al., 2021).

Despite the growing interest in and optimistic outlook towards the use of hydrogen as an energy carrier in various industries, there are also valid concerns and criticisms to consider. One of the significant drawbacks of green hydrogen production is the substantial amounts of land, raw materials, and water required to produce it. Furthermore, it has been argued that hydrogen should only be employed where more efficient options are not available (Sachverständigenrat für Umweltfragen, 2021). These factors must be taken into consideration when assessing the potential of hydrogen as a catalyst for energy transformation.

3. Methodology

In this section, the method employed in the study is outlined. It covers the basics of the model and the modifications made for improved hydrogen representation, as well as the integration of hydrogen blending.

3.1. Model description

GENeSYS-MOD is a linear open source energy system model which is tailored to analyze low-carbon energy transition pathways considering all energy sectors: electricity, buildings, industry, and transportation. First published by Löffler et al. (2017), it extends the Open Source Energy Modelling System (OSeMOSYS) and was expanded by numerous features and functionalities since then. Its main strength lies in the simultaneous optimization of capacity expansion, energy generation, and dispatch of all energy sectors, which leads to an endogenous optimization of electricity demand considering interactions between all energy sectors due to sector coupling. Figure 1 illustrates a simplified version of model inputs, components, and outputs. Climate policies and targets, regional particularities, and technological diversity are all easy to implement, allowing flexible analyses and easy adoption by other users and research groups. Therefore, the framework and data used are fully open source to enable validation and reproducibility.[1]

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[1] For further information on GENeSYS-MOD including a documentation, quick-start guide, and a sample data set, the reader is referred to: https://git.tu-berlin.de/genesysmod/genesys-mod-public

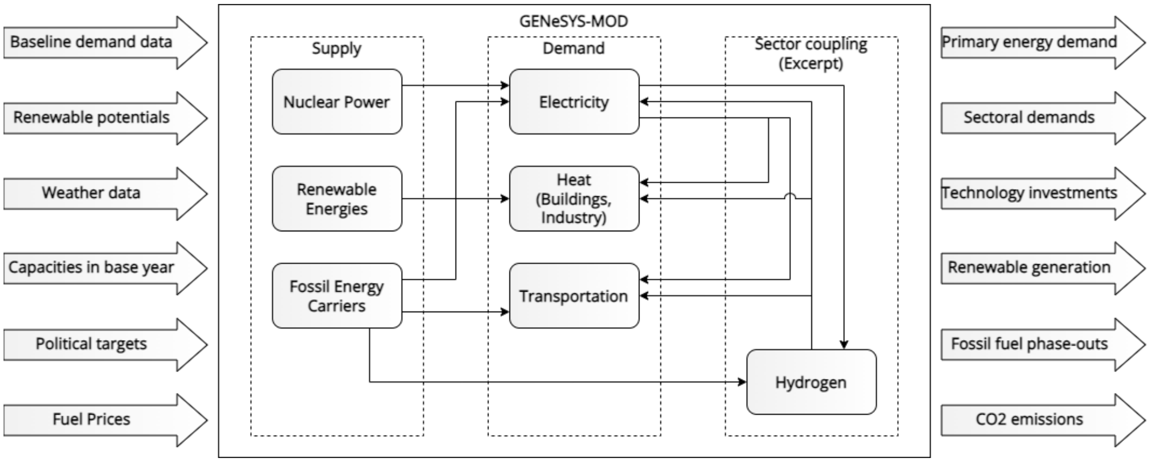

Figure 1: Stylized graph of model inputs and outputs of GENeSYS-MOD.

For this work, a model setup used in the Horizon 2020 project *openENTRANCE* is used in which low-carbon transition pathways for Europe were developed as part of an open modeling platform targeted towards policy and decision makers, stakeholders, and other researchers. The four pathways represent three very ambitious scenarios and one slightly less ambitious, yet still compatible with a 2 °C climate target, taking into account different political, societal, and technological developments (Auer et al., 2020; Hainsch et al., 2022).

The *Gradual Development* has been chosen for further use in this study, representing a moderate mixture of all three dimensions. Europe is disaggregated into 30 regions (mainland EU-25, Norway, Switzerland, UK, Turkey, and an aggregated Balkan region) and a pathway from 2018 to 2050 is calculated in 5-year steps. 2018 is used as a reference year for calibration purposes with generation, capacities, and emissions adjusted to reflect the historic values. To address the question of how different shares of hydrogen in natural gas pipelines affect hydrogen production and transportation infrastructure, various model runs allowing different shares are computed and the results compared.

3.2. Model functionality regarding gas transmission infrastructure & hydrogen blending

Extending the European model version 3.1, some improvements were made to the model, so that hydrogen is represented in a more accurate way in the energy system.

So far, it was only possible to trade hydrogen via truck or in newly built hydrogen dedicated pipelines. However, in reality, hydrogen can also be transported through existing gas infrastructure by blending it with natural gas and transporting it that way. Using this method, existing capacities can be used for transport, saving initial capital costs that would be created by building new dedicated pipelines or re-purposing old gas pipelines. With this, the trade with hydrogen could become more attractive for the model. In order to achieve the hydrogen blending within existing natural gas infrastructure, a new fuel *H2_blend* was added to the model formulation.

Currently, the hydrogen blend within existing natural gas infrastructure can not be higher than 10% without causing complications that would cause additional costs for application, re-compressing and retrofitting (Bard et al., 2022; Judd and Pinchbeck, 2016). Thus, a parameter called *switch_dedicated _hydrogen_tradecapacity* was introduced. This parameter limits the amount of hydrogen that can be blended into a natural gas pipeline. The switch is implemented in the following constraint (see equation 1) that regulates how much hydrogen blend can be imported in relation to the imported gas in a specific country per timeslice.

$$
\begin{aligned}
&Import_{(y,l,H2\_blend,rr,r)} \\
&\qquad \leq (\%switch\_dedicated\_hydrogen\_tradecapacity\% \\
&\qquad /((11.4/3.0) - \%switch\_dedicated\_hydrogen\_tradecapacity\%)) \\
&\qquad * \sum(GasFuels\$(notsameas(GasFuels, H2\_blend)), Import_{(y,l,GasFuels,rr,r)}))
\end{aligned}
\tag{1}
$$

Furthermore, since the energy density of the blended hydrogen is lower than the energy density of natural gas, this had to be accounted for as well. The formulation of the trade capacity in the model only considers energy as a limit, whereas in reality, the volume of the pipeline restricts the quantity that can be transported. In order to account for that the factor by which the energy density differs (11.4/3) is multiplied on top of the amount of hydrogen that is blend in the natural gas pipeline. The focus of this paper is on the transmission grid in Europe. As the hydrogen blend in the natural gas pipeline would effect the distribution networks and ultimately consumer appliances, the model "separates" hydrogen from gas after transport resulting in the consumption of pure hydrogen.

Another improvement that was made is the introduction of liquifier and gasifier technologies. So far in GENeSYS-MOD only one technology existed respectively, that would liquify/gasify any fuel that was given to the technology. That meant the costs for the processes would be the same for both natural gas and hydrogen. In reality however, the liquification and gasification plants for each fuel differ substantially. Not only the processes are different, but also the capital and variable costs. In order to account for the differences, new technologies were introduced: *X_Liquifier_H2* and *X_Gasifier_H2*.

4. Scenario assumptions

In this section, the base Scenario of this study, as well as the implementation of the hydrogen blending sensitivities are presented.

4.1. The four openENTRANCE storylines

The four openENTRANCE storylines all aim to reach climate neutrality by 2045 or 2050 in Europe but have different focuses and ways to reach that aim. The first three scenarios (Societal Commitment, Directed Transition, Techno-Friendly) aim to reach 1.5°C, resulting in greenhouse gas neutrality around 2045, while the Gradual Development Scenario aims for a less ambitious 2°C. In the following, all four scenario from Hainsch et al. (2022) will be introduced briefly.

The Societal commitment scenario is characterized by high societal engagement and awareness of the importance to become a low-carbon society. Individuals, communities and the overall public attitude support strong policy measures to accelerate the energy transition. Grassroots (bottom-up) and government-led top-down approaches are converging to drive strong acceptance of behavioral change in energy use and choices among European citizens. The main driver is society as a whole embracing cleaner, smarter lifestyles, while the public sector embraces grassroots initiatives.

In the Directed Transition Scenario Low-carbon energy technologies are emerging that need strong policy incentives to facilitate their adoption and development. Grassroots and civic action have negligible impact, but strong policy incentives can drive the citizen engagement needed to achieve climate goals. Low-carbon technology development is advanced by industry and technology developers that form strong relationships with policymakers following a centralized vision.

Techno-Friendly assumes a positive attitude of actors towards new technologies, behavioral change, and energy grassroots movements. Industry and grassroots movements drive the deployment of new technologies and large-scale infrastructure projects. While policy action is scarce, new business models, carbon-mitigating technologies, and social innovations advances this narrative.

Gradual Development, the scenario used in this study, distinguishes itself by reaching its targets through equally including societal, industry, and policy action. Its costs and efficiencies are less optimistic than in in the Techno-Friendly scenario and newer technologies are not implemented. Society is slightly less involved as in the Societal Commitment Scenario and the carbon price is lower than in all other three scenarios. Combining the characteristics of the other three studies to raise commitments of various actors, Gradual Development constitutes an ambitious reference scenario in line with a 2°C climate goal. The Gradual Development scenario is used as the base scenario for this study as it combines aspects of all the other three scenarios and is the most balanced in its ambitions helping the model to easily include new hydrogen related constraints and limitations.

4.2. Hydrogen blending sensitivities

In order to investigate the use of existing gas infrastructures for the transport of hydrogen with the model, the share of hydrogen allowed in the existing natural gas pipelines is adjusted gradually. To do this, the model is allowed to add hydrogen (in volume) to the gas network in 5% increments utilizing the *switch_dedicated_hydrogen_tradecapacity* for each model run from 2018-2050. A model run is performed for each possible ratio from 0% (no hydrogen-blending allowed) to 100% (only hydrogen in existing gas pipelines is allowed), resulting in a total of 21 model runs.

5. Results

Following the description of the openENTRANCE storylines, this section presents some main results of the Gradual Development scenario, as well as the effects of the introduced sensitivities on hydrogen transmission on the energy system.

5.1. Developments of the European energy system in the Gradual Development scenario

As can be seen on the left in Figure 2, the electricity system in Europe is significantly decarbonized from 2018 until 2050. This is mainly driven by the increase in power generation from photovoltaics and wind, supplying more than 80% of power in 2050. Furthermore, hydropower remains a relevant power source. The rapid decarbonization causes a coal phase-out by 2035 and only marginal amounts of natural gas remain until 2050. Nuclear still constitutes a fair amount of power generation in 2050. On the electricity consumption side, hydrogen becomes one of the most important factors, accounting for 25% of total consumption by 2050 in Europe.

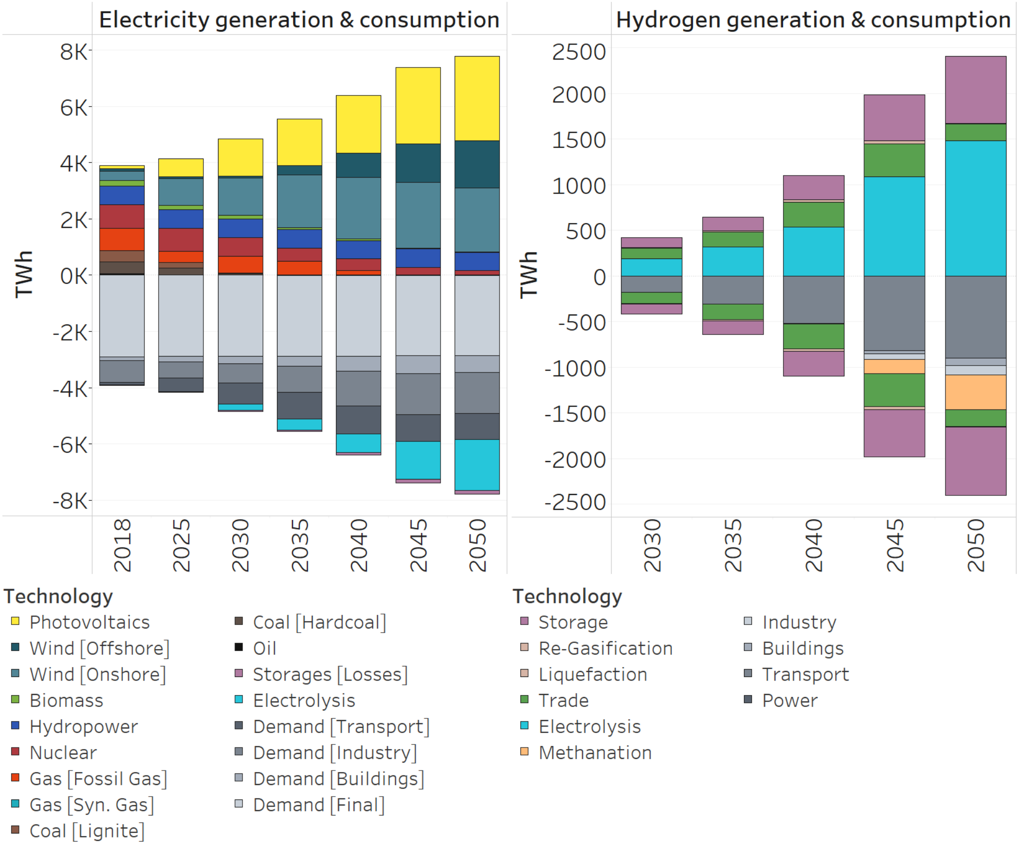

Figure 2: Results for electricity generation and consumption (left) and hydrogen generation and consumption (right) in the Gradual Development pathway.

Regarding hydrogen consumption, the right graph shows that by 2050 most hydrogen (around 40%) will be used in the transport sector. The other two sectors will not be affected as much by hydrogen, with around 120 TWh and 100 TWh respectively in the industry and buildings sector. It has to be noted that no demand for hydrogen as feedstock is considered which would shift these shares towards higher importance of the industry sector. Starting in 2045, methanation is another process hydrogen will be used in, accounting for around 20% of hydrogen consumption by 2050. As for the generation side, hydrogen will only be produced by means of electrolysis throughout the whole model period. Hydrogen storage plays another important role in this transition, with around 35% of total hydrogen being stored for later usage in 2050.

Figure 3 shows regional results for various key indicators for the Gradual development Scenario in 2050. The upper left graph shows the hydrogen generation in Europe by 2050. The main producer of hydrogen in 2050 will be Turkey with 390 TWh. Besides Turkey, Germany and Spain can be identified as the next biggest producers of hydrogen with 185 TWh and 173 TWh respectively. Wind and Solar generation is most prominent in countries with the highest renewable potential but still heavily influenced by the overall energy demand.

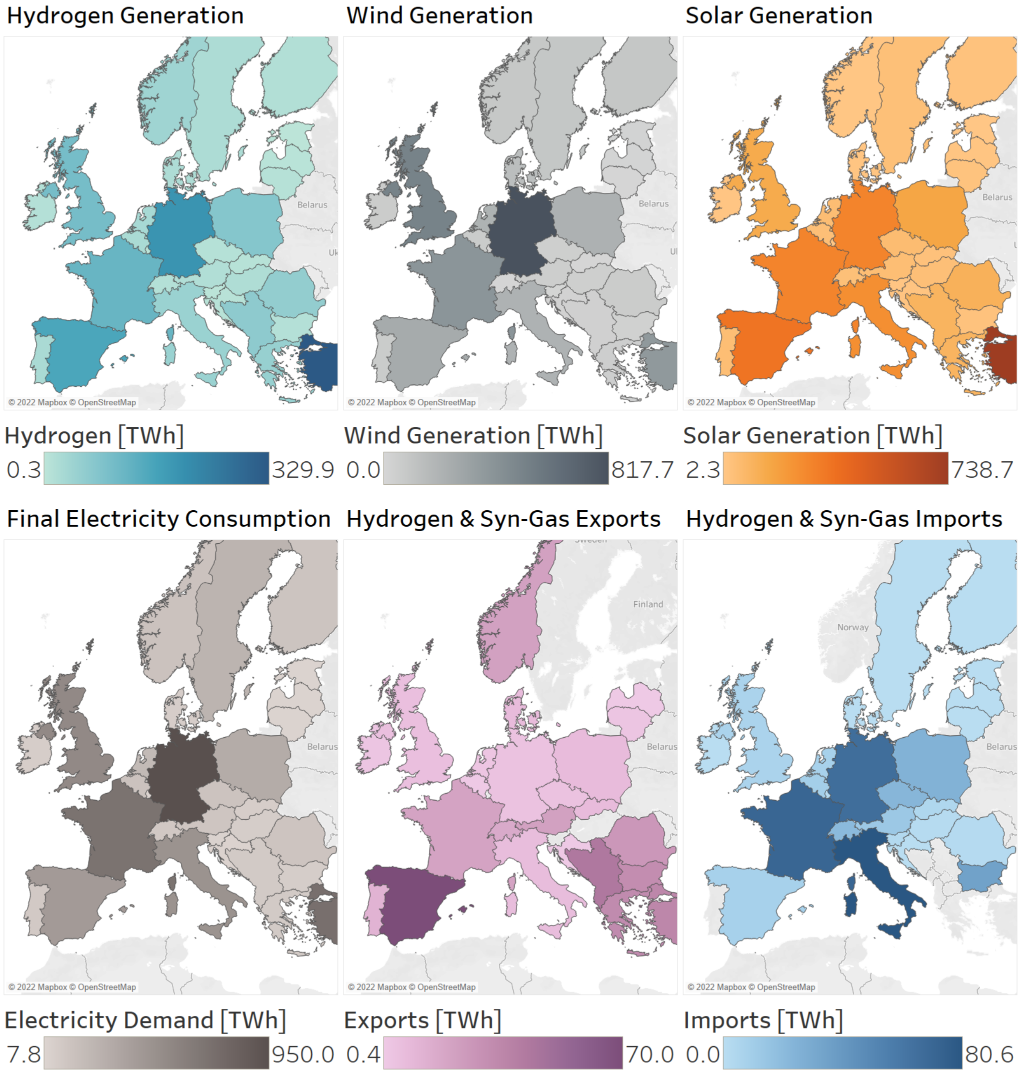

Figure 3: Geographic distribution of hydrogen generation, electricity generation from wind and solar, final electricity consumption, hydrogen and syn.-gas exports and imports.

Electricity demand is highest in the most populous countries, namely Germany, France, Turkey, UK, and Italy. Regarding Hydrogen & Syn-Gas Exports, Turkey & Spain lead the other countries while Germany imports the most Hydrogen & Syn-Gas. It is important to note, that countries like

Bulgaria exhibit high import and export numbers as the hydrogen produced in Turkey is transported through them.

5.2. Sensitivity analysis on gas transmission infrastructure

Following the description of the results for the openENTRANCE Gradual Development scenario, the results for hydrogen blending in the existing natural gas infrastructure and its impacts on the European Energy System will be presented.

5.2.1. Pan-European effects

The overall energy production and consumption within the EU exhibits no changes with different shares of hydrogen allowed in existing gas pipelines (see Figure 4).

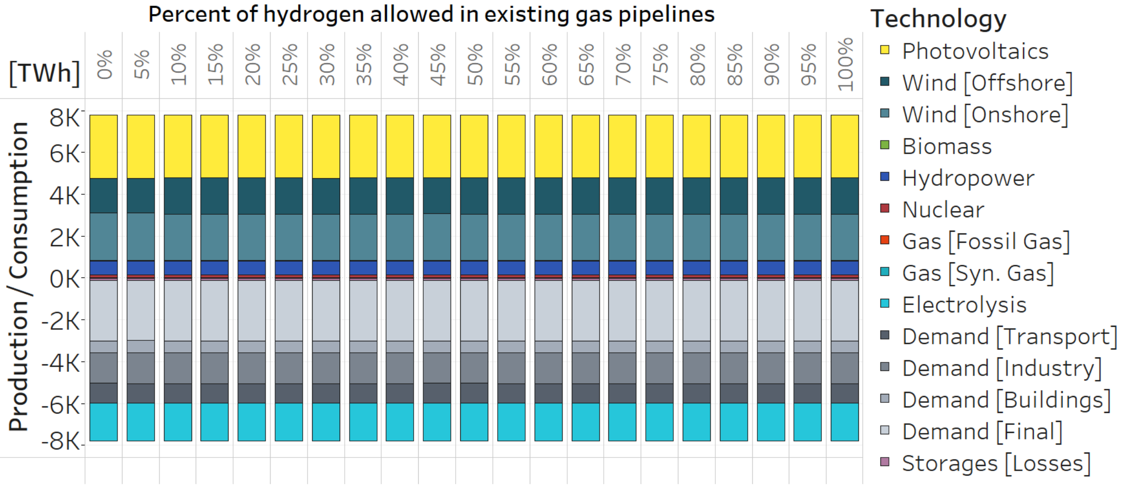

Figure 4: Change in electricity generation and consumption.

This counter-intuitive result can be explained by a very inelastic demand in hydrogen as a results of its specific use cases and its higher costs compared to other technologies. Production and consumption of hydrogen is still associated with high costs which in many cases exceed those of direct electrification. Despite no additional costs needed to increase the share of hydrogen in the existing natural gas infrastructure hydrogen, does not become significantly more competitive economically. As a result, Europe as a whole consumes similar amounts of hydrogen across all sensitivities. However, the next section will show that regional production patterns are much more affected by the availability of pipeline transportation of hydrogen.

5.2.2. Regional effects

While the overall production and demand of hydrogen within the EU barely change over the different sensitivities, significant changes can be found at national level as shown in Figure 5. With increasing shares of hydrogen allowed in existing pipelines, Norway's hydrogen exports raise from

3.6 TWh (0%-blending) to 66.8 TWh (100%-blending)[2]. When able to use 100% of the natural gas pipelines, Norway becomes the second biggest exporter of hydrogen after Spain. As one of the biggest exporters of natural gas, Norway can leverage the existing pipelines to export its hydrogen across Europe.

Spain stays the most important exporter of hydrogen due to its vast renewable potential. While the amount of hydrogen exports increases when blending is allowed compared to when it is not allowed, the amount of hydrogen exported decreases with rising blending shares. This is a result of other countries in Europe (eg. Norway) steadily increasing their hydrogen exports as the blending share rises. Turkey is the biggest exporter of Syn-gas when no hydrogen blending is allowed. It utilizes its renewable potential to produce and export more than 170 TWh of Syn-gas that is transported through the natural gas pipelines. However, when the share of hydrogen allowed in existing gas pipelines rises, Turkey loses relevance as other countries much closer located to customers in central Europe (eg. Spain & Norway) use existing pipelines to export more hydrogen.

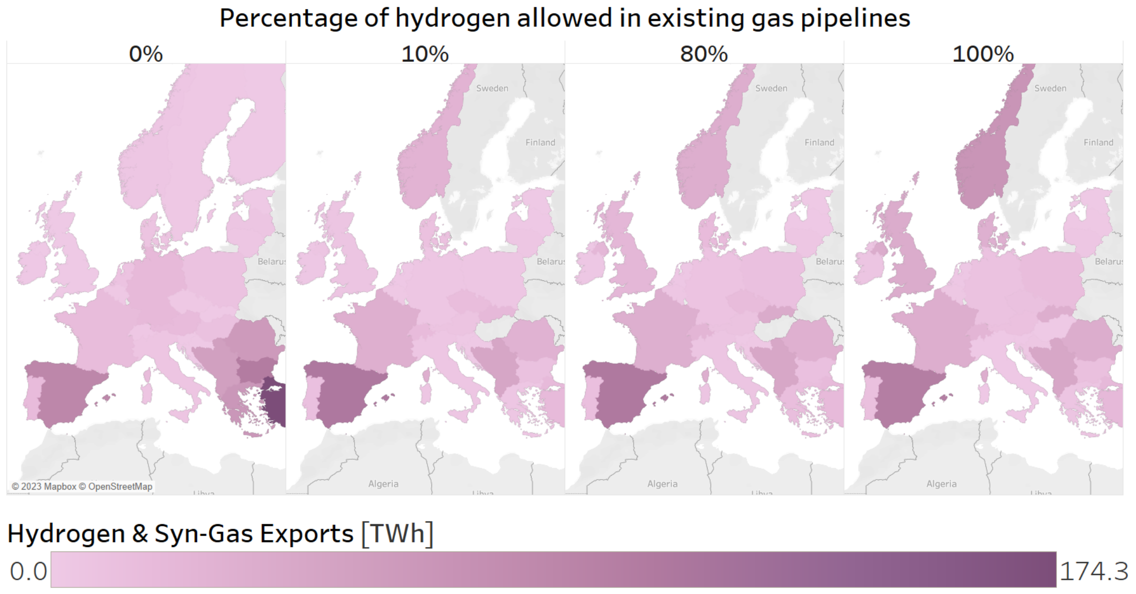

Figure 5: Hydrogen and Syn-Gas Exports for selected blending shares.

Figure 6 shows the change of hydrogen and syn-gas imports in the European countries in 2050. France, Germany, and Italy are the largest importers. While they consume significant amounts, another reason is that hydrogen and syn-gas from Spain and from Norway, as shares rise, are being transported through them to reach the other countries in Europe. Particularly Germany exhibits a steep increase in imports from 10% to 100% of hydrogen allowed in existing gas pipelines. In line with the results for exporting, France imports slightly decline with rising shares as a result of

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[2] For further information on the utilization of hydrogen bledning see Appendix B.2

Spain’s shrinking exports. While Norway still imports small amounts when no blending is allowed, it ceases all imports as soon as existing gas infrastructure can be used.

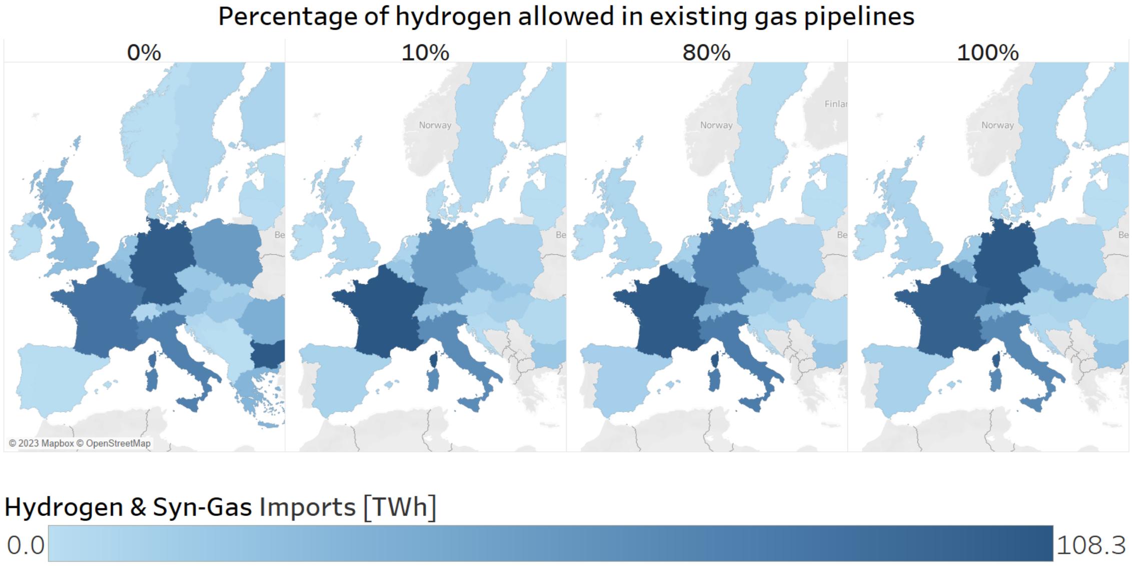

Figure 6: Hydrogen and Syn-Gas imports for selected blending shares.

The hydrogen generation in Europe, shown in Figure 7, changes congruently with exporting and importing numbers. Hydrogen generation increases the most in Norway, it sharply rises from 14.5 TWh at 0%-blending to 45.5% at 10%-blending and then steadily increases to 85.1 TWh at 100%. The main producers are Turkey (390 TWh at 0%-blending), Germany (185 TWh at 0%-blending), and Spain. Spain’s generation decreases with rising shares yet it remains higher with 180 TWH at 100%-blending compared to 173 TWh when no blending is allowed. Germany’s and most other countries’ generation rises as natural gas pipelines can be utilized for hydrogen trade.

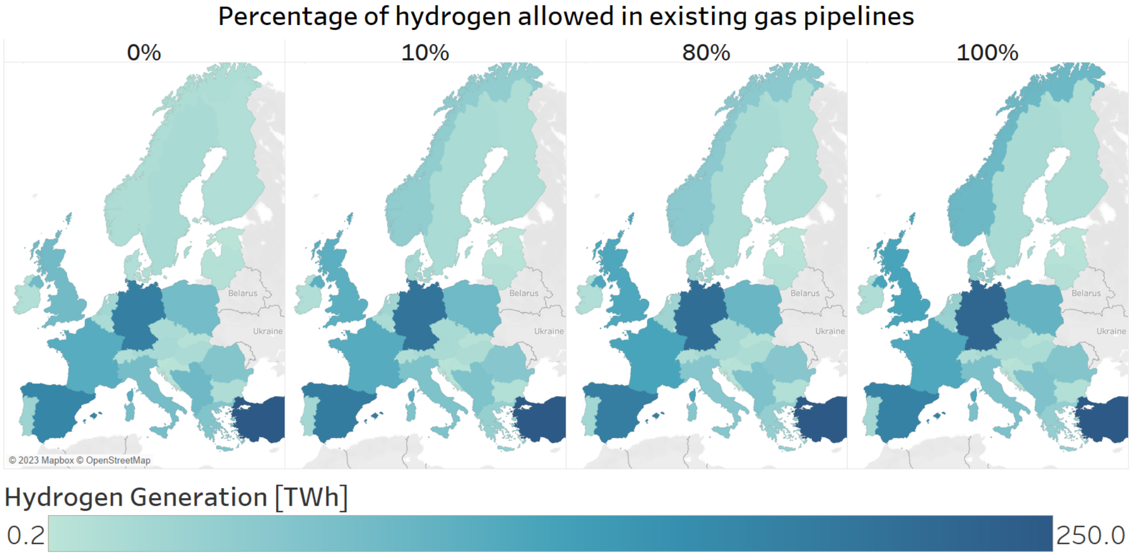

Figure 7: Hydrogen Generation for selected blending shares.

Figure 8 reinforces previous findings and shows the impact of the different percentages of hydrogen allowed in existing gas pipelines on the the main hydrogen producing and trading countries in Europe. Norway increases its hydrogen production and trade most with rising shares and a significant jump at 100% of the gas infrastructure being usable. Spain's generation and trade increase sharply as blending becomes available and then steadily decline. Germany's hydrogen generation also increases sharply as blending becomes available but in contrast to Spain steadily rises afterwards. Turkey's hydrogen production and trade decrease most as a results of hydrogen blending. Overall, these results show that the biggest change happens when hydrogen blending is allowed vs. when it is not (0% to 5%) and when natural gas pipelines can be "repurposed" for hydrogen trade at 100%.

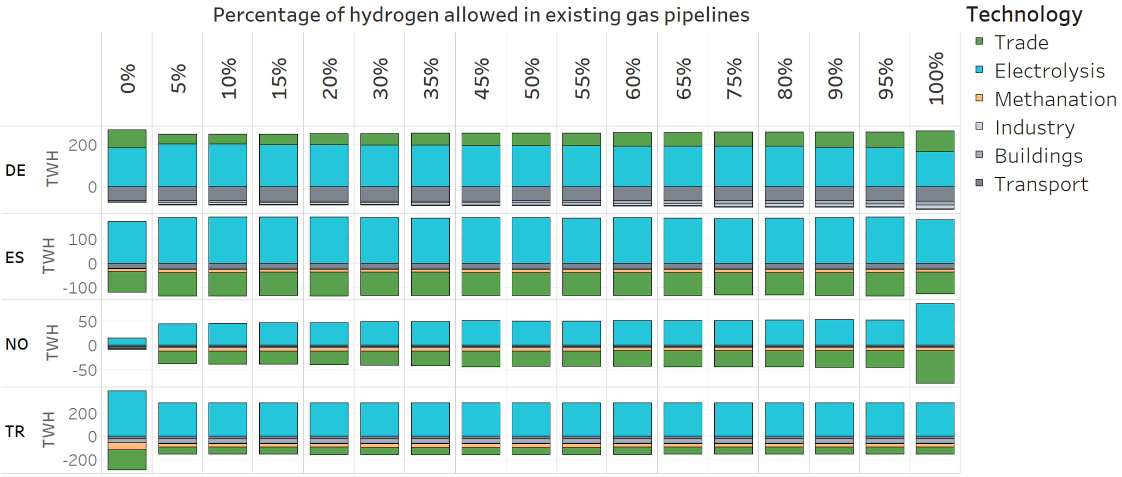

Figure 8: Hydrogen generation and use at country-level for select countries.

6. Discussion of Model Results and Limitations

This section discusses the main findings from the previous section to understand how hydrogen blending affects the European energy system and discuss any developments arising from hydrogen blending. Furthermore, this section explains and discusses limitations of the study and further research steps are shown.

The aim of this study was to examine the impact of hydrogen blending on the European energy system. The results of the study showed that hydrogen blending has little effect on the overall use of hydrogen by 2050. The demand for hydrogen is relatively constant due to the high CO_2-prices and the ambitious emission reduction targets set by the European Union. This suggests that the consumption of hydrogen is not limited by the transportation or supply side, but rather by the demand for it. The results of the study showed that, despite the ability to utilize existing natural gas pipelines for hydrogen transport, the production of hydrogen is not increased. This is because hydrogen is almost never the most cost-effective and sensible option, and the demand for hydrogen is already being met where it is needed. This indicates that for each application, e.g. heating or transportation, there exists a cost-optimal solution such as heat pumps or BEV. Even with the lower transportation costs of blended hydrogen, the solution using hydrogen cannot compete with the previously cost-optimal technology and hence has no effect on the overall hydrogen consumption and production.

Contrary to the effects on overall production in Europe, the ability to blend hydrogen into the existing natural gas pipelines affects the regional distribution of hydrogen production and trading. As the share of hydrogen allowed in existing pipelines increases, Norway's hydrogen exports increase and it becomes the second largest hydrogen exporter after Spain. Spain remains the largest exporter of hydrogen due to its abundant renewable energy resources. Turkey is the largest exporter of Syn-gas when no hydrogen blending is allowed, but loses significance as other countries closer to central Europe export more hydrogen with increasing blending shares. France, Germany, and Italy are the largest hydrogen and syn-gas importers in Europe in 2050. They import from Spain and

Norway, with Germany's imports rising steeply from 10% to 100% hydrogen allowed in existing gas pipelines. However, France's imports decline with rising blending shares due to Spain's declining exports and Norway stops all imports as soon as the existing gas infrastructure can be used. The production of hydrogen in Europe changes in correlation with the exporting and importing numbers. Norway experiences the largest increase in hydrogen generation. The main producers are Turkey, Germany, and Spain. While Spain's generation decreases with rising blending shares, Germany's and other countries' generation increases as natural gas pipelines can be used for hydrogen trade. Turkey experiences the biggest decrease in production and trade as a result of hydrogen blending.

Looking at the results in Figure 8, the most stark effects of blending occur between 0%-5% and then between 95%-100% (esp. for Norway). These sudden changes compared to the relatively unchanged pattern for the shares between 5% and 95% root in the current model setup. For 0%, the model is restricted to built an entirely new hydrogen grid in order to trade hydrogen between the regions, which explains the changes when suddenly the model can use the existing gas grid when blending is allowed (5% to 100%). When reaching the threshold of 100%, the share for blending then refers to the capacity of the pipeline since no natural or synthetic gas is present in the pipelines. For all the shares between 5% and 95%, the share of blending refers to the overall quantity of gases in the pipeline. Hence, the model needs to transport natural or synthetic gas in order to transport the H2 within the existing natural gas grid. While blending has no significant impact on the overall production and demand of hydrogen, the location of production can have severe implications for the European energy system. The import of hydrogen from countries such as Turkey can bring the European Union into a new dependency on energy imports. This highlights the importance of careful planning when it comes to the creation of hydrogen "backbones". On the other hand, the possibility of transporting hydrogen from Turkey could also diversify the hydrogen supply and reduce the dependence on a single source.

Hydrogen blending includes a wide variety of techno-economic aspects. There are a multitude of factors and details that can be incorporated in a model to allow for a realistic representation. In the following some limitations are highlighted when considering the results of this study and guide future research with GENeSYS-MOD. The model only considers the transmission network of the gas grid for the transportation of hydrogen between countries via pipeline. The model does not account for the regional hydrogen transport as it lacks the representation of a distribution grid within the countries. Therefore, only effects on a country basis can be deduced.

It is important to acknowledge, that the current model setup allows for hydrogen to be blended into the gas network up to 100% without additional investments into technical devices such as valves and compressors. However, in reality, this is only possible up to around 10% (Bard et al., 2022). Considering costs related to retrofitting will decrease the economic viability of some of the transport routes, that currently are used by the model.

Additional points to consider are the various challenges such as hydrogen's combustion behavior, which can affect the materials used in natural gas infrastructure. The key issues include effects on end-use appliances and safety, impact on the longevity of existing natural gas pipelines, changes in pipeline leak rates, vulnerability of valves, fittings, materials, and welds to hydrogen embrittlement, and effects on natural gas storage facilities (Mahajan et al., 2022).

The gas grid is only considered as a mode of transportation in the GENeSYS-MOD, but it can also serve as a gas or hydrogen storage. Considering the possibility of hydrogen storage in the gas grid might reduce the overall costs and increase the blending of hydrogen in some parts of the grid. Further adjustments to the model are needed to account for this and examine the effects of different hydrogen shares in the grid.

In order to further enrich the discussion on the use of green hydrogen in the European energy system of the future, effects of a more detailed representation of the techno-economic aspects of increasing proportions of hydrogen blending in pipelines in GENeSYS-MOD are future research aims.

7. Conclusions

The purpose of this study was to explore the effects of hydrogen blending on the European energy system by the year 2050. The Global Energy System Model (GENeSYS-MOD) was modified and enhanced to incorporate hydrogen representation. The study used the Gradual Development net-zero emission by 2050 scenario from openENTRANCE as a base for the European energy system (Hainsch et al., 2022). By varying the percentages of hydrogen allowed in existing gas pipelines, the production, blending, and trade of hydrogen across Europe were analyzed. Results show the demand for hydrogen is not very elastic due to its specific use cases and high costs compared to existing competing technologies (e.g. heat pumps and BEV). Hydrogen production and consumption still have high costs which often exceed direct electrification. The cost to increase the use of hydrogen in the existing natural gas infrastructure does not make it more economically competitive. Europe's consumption of hydrogen remains similar regardless of other factors, but regional production is more impacted by the availability of hydrogen transportation through pipelines. As blending becomes more prevalent, Norway becomes a major hydrogen exporter while Turkey's significance decreases. France, Germany, and Italy are the largest hydrogen importers in 2050. However, France's imports decline while Norway stops importing as their own hydrogen production increases.

To summarize, the addition of hydrogen to the existing energy mix does not significantly affect the production and consumption of hydrogen - even when not considering additional costs related to retrofitting. However, its impact on the location of production and the reliance on imported hydrogen, as well as the possibility of creating new dependencies, must be carefully evaluated when planning for hydrogen's future in Europe.

Data availability. The model and data used in this research can be found at the public GitLab page of GENeSYS-MOD (https://git.tu-berlin.de/genesysmod/genesys-mod-public) and the open Zenodo repository for GENeSYS-MOD datasets (https://zenodo.org/communities/genesys-mod/). Also, the openENTRANCE scenario explorer (https://data.ene.iiasa.ac.at/openentrance/) can be used to visualize and download key results from the Gradual Development scenario that was used in this paper.

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References

ACER, 2021. Transporting Pure Hydrogen by Repurposing Existing Gas Infrastructure: Overview of existing studies and reflections on the conditions for repurposing. Technical Report. European Union Agency for the Cooperation of Energy Regulators (ACER). Ljubljana. URL: https://extranet.acer.europa.eu/Official_documents/Acts_of_the_Agency/Publication/Transporting%20Pure%20Hydrogen%20by%20Repurposing%20Existing%20Gas%20Infrastructure_Overview%20of%20studies.pdf.

Ajanovic, A., Haas, R., 2021. Prospects and impediments for hydrogen and fuel cell vehicles in the transport sector. International Journal of Hydrogen Energy 46, 10049–10058. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360319920310843, doi:`10.1016/j.ijhydene.2020.03.122`.

Andresen, G.B., Rodriguez, R.A., Becker, S., Greiner, M., 2014. The potential for arbitrage of wind and solar surplus power in Denmark. Energy 76, 49–58. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360544214002977, doi:`10.1016/j.energy.2014.03.033`.

Auer, H., Crespo del Granado, P., Oei, P.Y., Hainsch, K., Löffler, K., Burandt, T., Huppmann, D., Grabaak, I., 2020. Development and modelling of different decarbonization scenarios of the European energy system until 2050 as a contribution to achieving the ambitious 1.5°C climate target—establishment of open source/data modelling in the European H2020 project openENTRANCE. e & i Elektrotechnik und Informationstechnik 2020. doi:`https://doi.org/10.1007/s00502-020-00832-7`.

Ausfelder, F., Drake, F.D., Erlach, B., Fischedick, M., Henning, H.M., Kost, C., Münch, W., Pittel, K., Rehtanz, C., Sauer, J., Schätzler, K., Stephanos, C., Themann, M., Umbach, E., Wagemann, K., Wagner, H.J., Wagner, U., 2017. Sektorkopplung - Untersuchungen und Überlegungen zur Entwicklung eines integrierten Energiesystems. Schriftenreihe Energiesysteme der Zukunft, München. URL: http://energiesysteme-zukunft.de/fileadmin/user_upload/Publikationen/pdf/ESYS_Analyse_Sektorkopplung.pdf.

Aziz, M., Wijayanta, A.T., Nandiyanto, A.B.D., 2020. Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization. Energies 13, 3062. URL: https://www.mdpi.com/1996-1073/13/12/3062, doi:`10.3390/en13123062`. number: 12 Publisher: Multidisciplinary Digital Publishing Institute.

Baccianti, C., 2022. Delivering RePowerEU: A solidaritybased proposal for financing additional green investment needs. Technical Report. Agora Energiewende. Berlin. URL: https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_09_KlimaInvest2030/A-EW_260_KlimaInvest_III_WEB.pdf.

Bard, J., Gerhardt, N., Selzam, P., Beil, M., Wiemer, M., Buddensiek, M., 2022. The Limitations of Hydrogen Blending in the European Gas Grid. Technical Report. Fraunhofer IEE. URL: https://www.iee.fraunhofer.de/content/dam/iee/energiesystemtechnik/en/documents/Studies-Reports/FINAL_FraunhoferIEE_ShortStudy_H2_Blending_EU_ECF_Jan22.pdf.

BP, 2022. Statistical Review of World Energy 2022. Technical Report 71. London. URL: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html.

Brauers, H., Braunger, I., Jewell, J., 2021. Liquefied natural gas expansion plans in Germany: The risk of gas lock-in under energy transitions. Energy Research & Social Science 76, 102059. URL: https://linkinghub.elsevier.com/retrieve/pii/S2214629621001523, doi:`10.1016/j.erss.2021.102059`.

Bruegel, 2022. Can Europe survive painlessly without Russian gas? URL: https://www.bruegel.org/blog-post/can-europe-survive-painlessly-without-russian-gas.

Burandt, T., Löffler, K., Hainsch, K., 2018. GENeSYS-MOD v2.0 - Enhancing the Global Energy System Model. Model Improvements, Framework Changes, and European Data Set. Technical Report. DIW Data Doc., 95 (2018).

Burandt, T., Xiong, B., Löffler, K., Oei, P.Y., 2019. Decarbonizing China's energy system – Modeling the transformation of the electricity, transportation, heat, and industrial sectors. Applied Energy 255, 113820. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261919315077, doi:`10.1016/j.apenergy.2019.113820`.

Caglayan, D.G., Weber, N., Heinrichs, H.U., Linßen, J., Robinius, M., Kukla, P.A., Stolten, D., 2020. Technical potential of salt caverns for hydrogen storage in Europe. International Journal of Hydrogen Energy 45, 6793–6805. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360319919347299, doi:`10.1016/j.ijhydene.2019.12.161`.

Cerniauskas, S., Jose Chavez Junco, A., Grube, T., Robinius, M., Stolten, D., 2020. Options of natural gas pipeline reassignment for hydrogen: Cost assessment for a Germany case study. International Journal of Hydrogen Energy 45, 12095–12107. URL: https://www.sciencedirect.com/science/article/pii/S0360319920307023, doi:`10.1016/j.ijhydene.2020.02.121`.

Conde, A.S., Rechberger, K., Spanlang, A., Wolfmeir, H., Harris, C., 2021. Decarbonization of the steel industry. A techno-economic analysis. Matériaux & Techniques 109, 305. URL: https://www.mattech-journal.org/articles/mattech/abs/2021/03/mt210047/mt210047.html, doi:`10.1051/mattech/2022002`. number: 3-4 Publisher: EDP Sciences.

Ember, 2022. EU Carbon Price Tracker. URL: https://ember-climate.org/data/data-tools/carbon-price-viewer/.

Espegren, K., Damman, S., Pisciella, P., Graabak, I., Tomasgard, A., 2021. The role of hydrogen in the transition from a petroleum economy to a low-carbon society. International Journal of Hydrogen Energy 46, 23125–23138. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360319921015639, doi:`10.1016/j.ijhydene.2021.04.143`.

European Commission, 2020. A hydrogen strategy for a climate-neutral Europe. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. European Commission. Brussels. URL: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1594897267722&uri=CELEX:52020DC0301.

European Commission, 2022a. Coal regions in transition. URL: https://energy.ec.europa.eu/topics/oil-gas-and-coal/eu-coal-regions/coal-regions-transition_en.

European Commission, 2022b. European Green Deal. URL: https://ec.europa.eu/clima/eu-action/european-green-deal_en.

European Commission, 2022c. REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition. URL: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131.

Eurostat, 2022. Gross and net production of electricity and derived heat by type of plant and operator (NRG_ind_peh). URL: https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_peh/default/table?lang=en.

Fuel Cells and Hydrogen 2 Joint Undertaking., 2020. Hydrogen-powered aviation :a fact based study of hydrogen technology, economics, and climate impact by 2050. Publications Office, LU. URL: https://data.europa.eu/doi/10.2843/766989.

Gabrielli, P., Poluzzi, A., Kramer, G.J., Spiers, C., Mazzotti, M., Gazzani, M., 2020. Seasonal energy storage for zero-emissions multi-energy systems via underground hydrogen storage. Renewable and Sustainable Energy Reviews 121, 109629. URL: https://linkinghub.elsevier.com/retrieve/pii/S1364032119308366, doi:`10.1016/j.rser.2019.109629`.

Galyas, A.B., Kis, L., Tihanyi, L., Szunyog, I., Vadaszi, M., Koncz, A., 2023. Effect of hydrogen blending on the energy capacity of natural gas transmission networks. International Journal of Hydrogen Energy URL: https://www.sciencedirect.com/science/article/pii/S0360319922059146, doi:`10.1016/j.ijhydene.2022.12.198`.

Gerbaulet, C., Lorenz, C., 2017. dynELMOD: A Dynamic Investment and Dispatch Model for the Future European Electricity Market. DIW Berlin, Data Documentation No. 88. DIW Berlin. Berlin, Germany. URL: https://www.diw.de/sixcms/detail.php?id=diw_01.c.558131.de.

German National Government, 2022. Weniger Gasverbrauch im Ernstfall. URL: https://www.bundesregierung.de/breg-de/themen/klimaschutz/gasersatz-reserve-2048304.

Giehl, J., Hollnagel, J., Müller-Kirchenbauer, J., 2023. Assessment of using hydrogen in gas distribution grids. International Journal of Hydrogen Energy URL: https://www.sciencedirect.com/science/article/pii/S0360319923000617, doi:`10.1016/j.ijhydene.2023.01.060`.

Guidehouse, 2020. European Hydrogen Backbone - How a dedicated hydrogen infrastructure can be created. Technical Report. URL: https://www.newenergycoalition.org/custom/uploads/2020/10/European-Hydrogen-Backbone-Report.pdf.

Hainsch, K., Löffler, K., Burandt, T., Auer, H., Crespo del Granado, P., Pisciella, P., Zwickl-Bernhard, S., 2022. Energy transition scenarios: What policies, societal attitudes, and technology developments will realize the EU Green Deal? Energy 239, 122067. URL: https://www.sciencedirect.com/science/article/pii/S036054422102315X, doi:`10.1016/j.energy.2021.122067`.

Hauenstein, C., Hainsch, K., Herpich, P., Hirschhausen, C.R.v., Holz, F., Kemfert, C., Kendziorski, M., Oei, P.Y., Rieve, C., 2022. Stromversorgung auch ohne russische Energielieferungen und trotz Atomausstiegs sicher – Kohleausstieg 2030 bleibt machbar. DIW aktuell. DIW Berlin. Berlin. URL: https://www.diw.de/documents/publikationen/73/diw_01.c.839634.de/diw_aktuell_84.pdf.

Hoelzen, J., Silberhorn, D., Zill, T., Bensmann, B., Hanke-Rauschenbach, R., 2022. Hydrogen-powered aviation and its reliance on green hydrogen infrastructure – Review and research gaps. International Journal of Hydrogen Energy 47, 3108–3130. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360319921043184, doi:`10.1016/j.ijhydene.2021.10.239`.

Holz, F., Sogalla, R., von Hirschhausen, C., Kemfert, C., 2022. Energieversorgung in Deutschland auch ohne Erdgas aus Russland gesichert. Technical Report 83. Deutsches Institut für Wirtschaftsforschung (DIW Berlin). Berlin. URL: https://www.diw.de/documents/publikationen/73/diw_01.c.838841.de/diw_aktuell_83.pdf.

Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolis, J., Bazillian, M., Roehrl, A., 2011. OSeMOSYS: The Open Source Energy Modeling System: An introduction to its ethos, structure and development. Energy Policy 39, 5850–5870. URL: http://www.sciencedirect.com/science/article/pii/S0301421511004897, doi:`10.1016/j.enpol.2011.06.033`.

IEA, 2019. Electricity Information 2019: Overview. URL: https://webstore.iea.org/electricity-information-2019-overview.

IEA, 2019. The Future of Hydrogen: Seizing today's opportunities. Report prepared by the IEA for the G20, Japan. International Energy Agency. Paris. URL: https://webstore.iea.org/download/direct/2803?fileName=The_Future_of_Hydrogen.pdf.

Judd, R., Pinchbeck, D., 2016. Hydrogen admixture to the natural gas grid, pp. 165–192. doi:`10.1016/B978-1-78242-364-5.00008-7`.

Kemfert, C., Präger, F., Braunger, I., Hoffart, F.M., Brauers, H., 2022. The expansion of natural gas infrastructure puts energy transitions at risk. Nature Energy URL: https://www.nature.com/articles/s41560-022-01060-3, doi:`10.1038/s41560-022-01060-3`.

Lan, R., Irvine, J.T.S., Tao, S., 2012. Ammonia and related chemicals as potential indirect hydrogen storage materials. International Journal of Hydrogen Energy 37, 1482–1494. URL: https://www.sciencedirect.com/science/article/pii/S0360319911022968, doi:`10.1016/j.ijhydene.2011.10.004`.

Liu, W., Zuo, H., Wang, J., Xue, Q., Ren, B., Yang, F., 2021. The production and application of hydrogen in steel industry. International Journal of Hydrogen Energy 46, 10548–10569. URL: https://www.sciencedirect.com/science/article/pii/S0360319920347376, doi:`10.1016/j.ijhydene.2020.12.123`.

Löffler, K., Hainsch, K., Burandt, T., Oei, P.Y., Kemfert, C., Von Hirschhausen, C., 2017. Designing a Model for the Global Energy System—GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS). Energies 10, 1468. URL: https://www.mdpi.com/1996-1073/10/10/1468, doi:`10.3390/en10101468`.

Mahajan, D., Tan, K., Venkatesh, T., Kileti, P., Clayton, C.R., 2022. Hydrogen Blending in Gas Pipeline Networks—A Review. Energies 15, 3582. URL: https://www.mdpi.com/1996-1073/15/10/3582, doi:`10.3390/en15103582`. number: 10 Publisher: Multidisciplinary Digital Publishing Institute.

McKinlay, C.J., Turnock, S.R., Hudson, D.A., 2021. Route to zero emission shipping: Hydrogen, ammonia or methanol? International Journal of Hydrogen Energy 46, 28282–28297. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360319921022175, doi:`10.1016/j.ijhydene.2021.06.066`.

Niermann, M., Timmerberg, S., Dinh, S., Kaltschmitt, M., 2021. Liquid Organic Hydrogen Carriers and alternatives for international transport of renewable hydrogen. Renewable and Sustainable Energy Reviews 135, 110171. doi:`10.1016/j.rser.2020.110171`.

OECD, 2022. Energy prices are spiking. URL: https://www.oecd.org/coronavirus/en/data-insights/energy-prices-are-spiking.

Ragwitz, M., Müller-Kirchenbauer, J., Klaaßen, B., Graf, M., Hermann, U., Nolden, C., Evers, M., Akça, O., Jiang, D., Hurtig, K., 2022. Europäische Gasversorgungssicherheit aus technischer und wirtschaftlicher Perspektive vor dem Hintergrund unterbrochener Versorgung aus Russland. Im Auftrag des Akademienprojektes Energiesysteme der Zukunft“ (ESYS). Technical Report. Cottbus. URL: https://www.ieg.fraunhofer.de/content/dam/ieg/deutsch/dokumente/pressemitteilungen/Gutachten_Gasversorgungssicherheit_bei_unterbrochener_Versorgung_aus_Russland___Fraunhofer_TUBerlin___14072022.pdf.

Rasmussen, M.G., Andresen, G.B., Greiner, M., 2012. Storage and balancing synergies in a fully or highly renewable pan-European power system. Energy Policy 51, 642–651. URL: https://linkinghub.elsevier.com/retrieve/pii/S0301421512007677, doi:`10.1016/j.enpol.2012.09.009`.

Rechberger, K., Spanlang, A., Sasiain Conde, A., Wolfmeir, H., Harris, C., 2020. Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking. steel research international 91, 2000110. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/srin.202000110, doi:`10.1002/srin.202000110`. _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/srin.202000110.

Reuß, M., Grube, T., Robinius, M., Preuster, P., Wasserscheid, P., Stolten, D., 2017. Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. Applied Energy 200, 290–302. URL: https://www.sciencedirect.com/science/article/pii/S0306261917305457, doi:`10.1016/j.apenergy.2017.05.050`.

Ruhnau, O., Stiewe, C., Muessel, J., Hirth, L., 2022. Gas demand in times of crisis. The response of German households and industry to the 2021/22 energy crisis. Technical Report. Berlin. URL: http://hdl.handle.net/10419/261082.

Sachverständigenrat für Umweltfragen, 2021. Wasserstoff im Klimaschutz: Klasse statt Masse. Stellungnahme, Sachverständigenrat für Umweltfragen (SRU), Berlin. URL: https://www.umweltrat.de/SharedDocs/Downloads/DE/04_Stellungnahmen/2020_2024/2021_06_stellungnahme_wasserstoff_im_klimaschutz.pdf;jsessionid=3612595FE2707DF1BC7E9C21406E6BC0.intranet231?___blob=publicationFile&v=3.

Sadeghi, S., Ghandehariun, S., Rosen, M.A., 2020. Comparative economic and life cycle assessment of solar-based hydrogen production for oil and gas industries. Energy 208, 118347. URL: https://www.sciencedirect.com/science/article/pii/S0360544220314547, doi:`10.1016/j.energy.2020.118347`.

Schlachtberger, D., Brown, T., Schramm, S., Greiner, M., 2017. The benefits of cooperation in a highly renewable European electricity network. Energy 134, 469–481. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360544217309969, doi:`10.1016/j.energy.2017.06.004`.

Siemens Energy, 2021. Hydrogen infrastructure – the pillar of energy transition. The practical conversion of long-distance gas networks to hydrogen operation. Technical Report. Germany. URL: https://assets.siemens-energy.com/siemens/assets/api/uuid:3d4339dc-434e-4692-81a0-a55adbcaa92e/200915-whitepaper-h2-infrastructure-en.pdf?ste_sid=e2bdb1d4e9eea340c5d7b1cb6d93195c.

Ueckerdt, F., Bauer, C., Dirnaichner, A., Everall, J., Sacchi, R., Luderer, G., 2021. Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nature Climate Change 11, 384–393. URL: http://www.nature.com/articles/s41558-021-01032-7, doi:`10.1038/s41558-021-01032-7`.

Van Hoecke, L., Laffineur, L., Campe, R., Perreault, P., Verbruggen, S.W., Lenaerts, S., 2021. Challenges in the use of hydrogen for maritime applications. Energy & Environmental Science 14, 815–843. URL: http://xlink.rsc.org/?DOI=D0EE01545H, doi:`10.1039/D0EE01545H`.

Victoria, M., Zhu, K., Brown, T., Andresen, G.B., Greiner, M., 2019. The role of storage technologies throughout the decarbonisation of the sector-coupled European energy system. Energy Conversion and Management 201, 111977. URL: https://linkinghub.elsevier.com/retrieve/pii/S0196890419309835, doi:`10.1016/j.enconman.2019.111977`.

Vidas, L., Castro, R., Pires, A., 2022. A Review of the Impact of Hydrogen Integration in Natural Gas Distribution Networks and Electric Smart Grids. Energies 15, 3160. doi:`10.3390/en15093160`.

Vogl, V., Åhman, M., Nilsson, L.J., 2018. Assessment of hydrogen direct reduction for fossil-free steelmaking. Journal of Cleaner Production 203, 736–745. URL: http://www.sciencedirect.com/science/article/pii/S0959652618326301, doi:`10.1016/j.jclepro.2018.08.279`.

Wolf, A., Zander, N., 2021. Green Hydrogen in Europe: Do Strategies Meet Expectations? Intereconomics 56, 316–323. URL: https://doi.org/10.1007/s10272-021-1008-3, doi:`10.1007/s10272-021-1008-3`.

Zhang, H., Li, J., Su, Y., Wang, P., Yu, B., 2021. Effects of hydrogen blending on hydraulic and thermal characteristics of natural gas pipeline and pipe network. Oil & Gas Science and Technology – Revue d'IFP Energies nouvelles 76, 70. URL: https://ogst.ifpenergiesnouvelles.fr/articles/ogst/abs/2021/01/ogst210179/ogst210179.html, doi:`10.2516/ogst/2021052`. publisher: EDP Sciences.

Öhman, A., Karakaya, E., Urban, F., 2022. Enabling the transition to a fossil-free steel sector: The conditions for technology transfer for hydrogen-based steelmaking in Europe. Energy Research & Social Science 84, 102384. URL: https://www.sciencedirect.com/science/article/pii/S2214629621004722, doi:`10.1016/j.erss.2021.102384`.

Appendices

Appendix A. Model Description

GENeSYS-MOD is a cost-optimizing linear program, focusing on long-term pathways for the different sectors of the energy system, specifically targeting emission targets, integration of renewables, and sector-coupling. The model minimizes the objective function, which comprises total system costs (encompassing all costs occurring over the modeled time period) Löffler et al. (2017); Howells et al. (2011).

The GENeSYS-MOD framework consists of multiple blocks of functionality, that ultimately originate from the OSeMOSYS framework. Figure A.1 shows the underlying block structure of GENeSYS-MOD v2.9, with the additions made in the current model version (namely the option to compute variable years instead of the fixed 5-year periods, as well as an employment analysis module, in addition to the regional data set and the inclusion of axis-tracking PV).

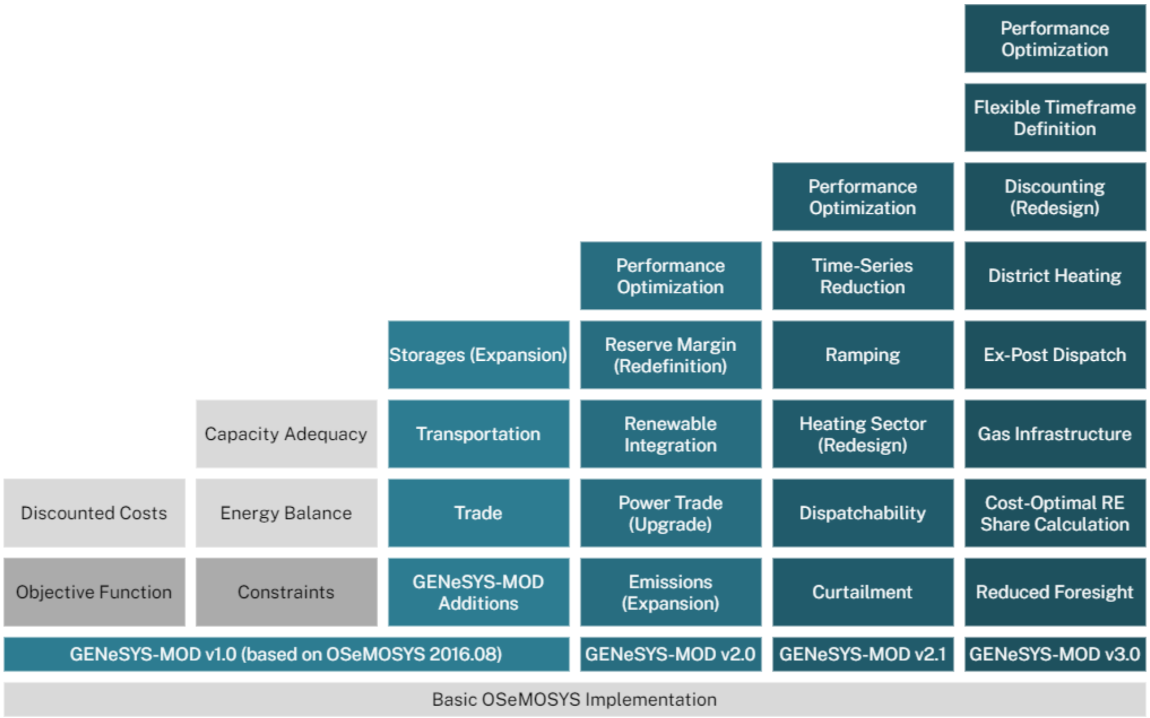

Figure A.1: Model structure of the GENeSYS-MOD implementation used in this study.

(Final) Energy demands and weather time series are given exogenously for each modeled time slice, with the model computing the optimal flows of energy, and resulting needs for capacity additions and storages.[3] Additional demands through sector-coupling are derived endogenously. Constraints, such as energy balances (ensuring all demand is met), maximum capacity additions (e.g. to limit the usable potential of renewables), RES feed-in (e.g. to ensure grid stability), emission budgets (given either yearly or as a total budget over the modeled horizon) are given to ensure proper functionality of the model and yield realistic results.

The GENeSYS-MOD v2.9 model version used in this paper uses the time clustering algorithm described in Gerbaulet and Lorenz (2017) and Burandt et al. (2019), with every 73rd hour chosen, resulting in 120 time steps per year, representing 6 days with full hourly resolution and yearly characteristics. The years 2017-2050 are modeled in the following sequence: 2017, 2022, 2025, 2030, 2035, 2040, 2045, 2050. All input data is consistent with this time resolution, with all demand and feed-in data being given as full hourly time series. Since GENeSYS-MOD does not feature any stochastic features, all modeled time steps are known to the model at all times. There is no uncertainty about e.g. RES feed-in.

The model allows for investment into all technologies and acts purely economical when computing the resulting pathways (while staying true to the given constraints). It usually assumes the role of a social planner with perfect foresight, optimizing the total welfare through cost minimization. In this paper, an add-on allowing for myopic foresight using multiple computational stages, is introduced. All fiscal units are handled in 2015 terms (with amounts in other years being discounted towards the base year).

For more information on the mathematical side of the model, as well as all changes between model versions, please consult Howells et al. (2011); Löffler et al. (2017); Burandt et al. (2018, 2019).

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[3] GENeSYS-MOD offers various storage options: Lithium-ion and redox-flow batteries, pumped hydro storages, compressed air electricity storages, gas (hydrogen and methane) storages, and heat storages.

Appendix B. Results

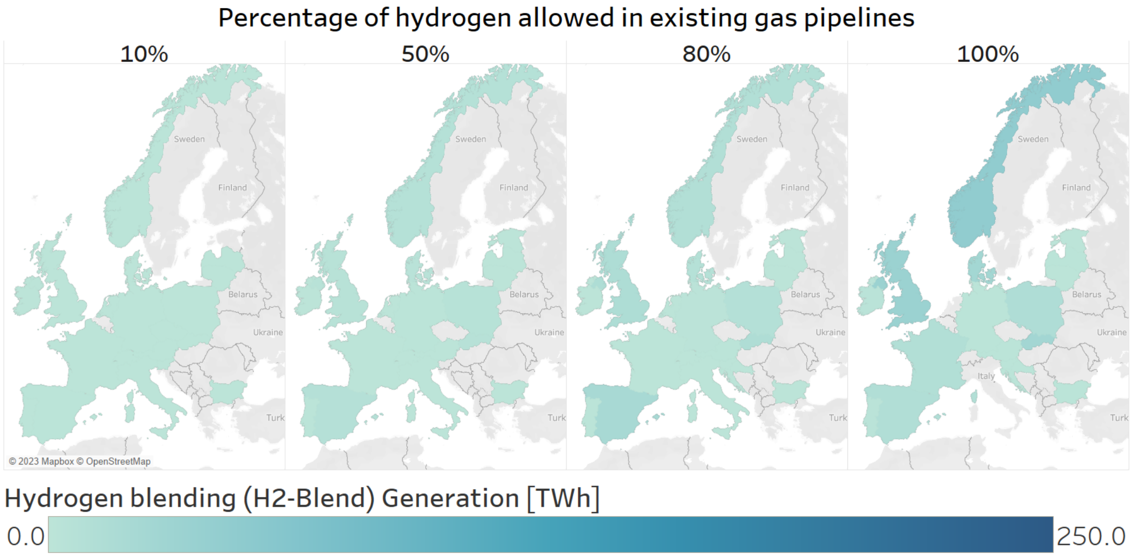

Figure B.2: Use of hydrogen blending at selected blending shares.