Graphical Abstract

Hydrogen supply chain scenarios for the decarbonisation of a German multi-modal energy system*,

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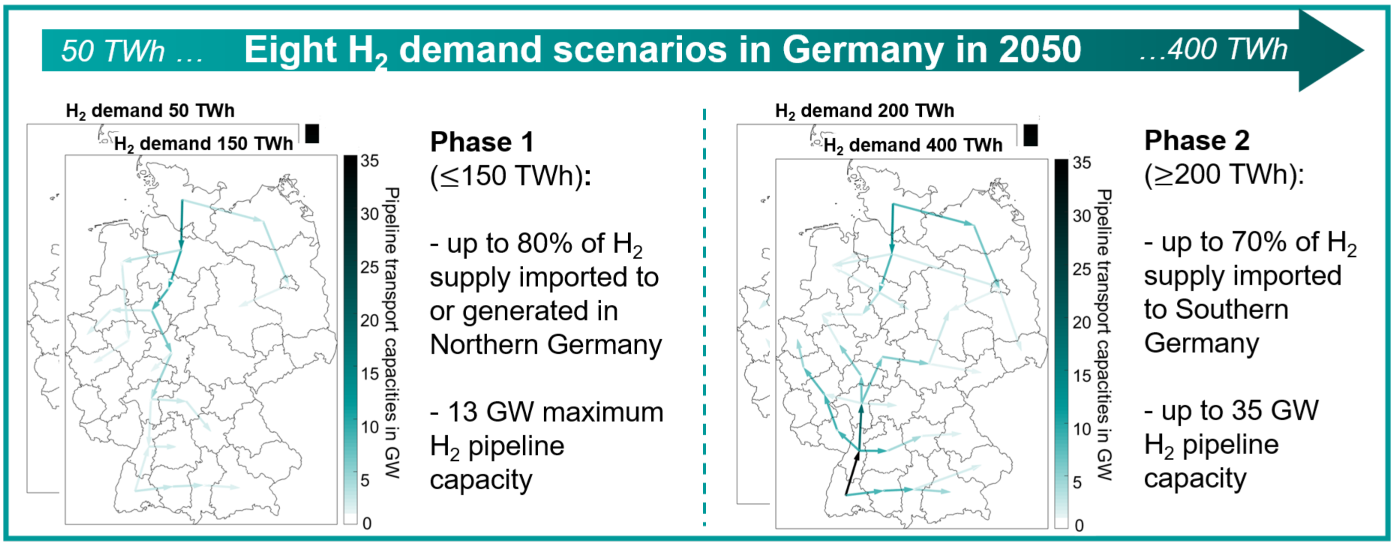

Highlights

Hydrogen supply chain scenarios for the decarbonisation of a German multi-modal energy system

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- Multi-modal hydrogen supply chain modelling under varying demand scenarios for 2050

- 80 % of hydrogen imports and generation available in north Germany (base scenario)

- 46 % of existing inter-regional gas grid connections with potential to be reassigned

- 73 GW pipeline and 11 GW trailer capacity built in base scenario for German supply

- Two no-regret pipeline routes are identified starting in Schleswig-Holstein

Hydrogen supply chain scenarios for the decarbonisation of a German multi-modal energy system

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Abstract

Analysing hydrogen supply chains is of utmost importance to adequately understand future energy systems with a high degree of sector coupling. Here, a multi-modal energy system model is set up as linear programme incorporating electricity, natural gas as well as hydrogen transportation options for Germany in 2050. Further, different hydrogen import routes and optimised inland electrolysis are included. In a sensitivity analysis, hydrogen demands are varied to cover uncertainties and to provide scenarios for future requirements of a hydrogen supply and transportation infrastructure. 80 % of the overall hydrogen demand of 150 TWh/a emerge in northern Germany due to optimised electrolyser locations and imports, which subsequently need to be transported southwards. Therefore, a central hydrogen pipeline connection from Schleswig-Holstein to the region of Darmstadt evolves already for moderate demands and appears to be a no-regret investment. Furthermore, a natural gas pipeline reassignment potential of 46 % is identified.

Keywords: energy system modeling, natural gas infrastructure, sector coupling, hydrogen pipeline, hydrogen trailer

1. Introduction

It has only been recently that some of the biggest economic zones of the planet have given pledges and target years for becoming climate-neutral, among them China, the European Union and Japan [1]. The German government resharpened the climate goals at the beginning of May 2021 announcing to reach net-zero emissions by 2045 [2]. Already prior to that, the EU Hydrogen Strategy [3] and the German National Hydrogen Strategy [4] were published. These promote the application of hydrogen (H_2) across the sectors electricity, heat, transport and industry to advance the transformation towards a carbon-neutral energy system. One reason for that is that H_2 can be stored in large quantities and thus helps to integrate intermittent renewable energy sources (RES) within its versatile field of application. For instance, green hydrogen produced from renewable sources can be used to decarbonise industries such as steel and ammonia production as well as the transportation sector by directly using H_2 in fuel cell electric vehicles (FCEVs) or processed as synthetic fuel in internal combustion engines for heavy duty road transport, ships or trains.

Since the prospective H_2 generation and usage locations can differ from each other, a well-designed H_2 transport infrastructure will be needed to fully foster the potentials outlined above. Yet, there is no public H_2 pipeline infrastructure in Germany to date. There is, however, a first memorandum of understanding for a connection planned to be established in the northwest of Germany by the end of 2022 [5]. It aims to take advantage of the well-developed natural gas infrastructure in Germany to quickly establish the pipeline-bound H_2 transport connection at low cost via repurposing existing pipelines while at the same time building only few new dedicated sections. This reassignment potential of the existing natural gas grid is acknowledged not only in industry, but also in politics and research (e. g. [4, 6–8]).

The relevance of existing gas transport infrastructure is, inter alia, shown in the difficulties of the last years in trying to extend the electricity grid in Germany to make it fit to accommodate the volatile RES wind and sun. First, there are the costs and reservations from the public regarding the required extension of the electricity grid as well as the difficulties of long-term storage of electricity. Second, a standard pipeline can transfer up to ten times as much energy at a significantly lower investment cost compared to a 380 kV twin overhead power line [9]. Additionally, Germany exhibits the fourth largest gas storage capacities globally that can supply the German demand for about 80 days [10]. Approximately 60 % of all gas storage sites are salt caverns [10], which are considered as also being suitable for H_2 utilisation [11, 12]. Contrary to that, H_2 feed-in restrictions considering the gas grid pose the risk of not being able to fully exploit the potential of wind electrolysis [13]. This emphasises the role but also the challenges of existing natural gas infrastructure in a future multi-modal energy system that in-

[⋆⋆] DOI to formal publication: https://doi.org/10.1016/j.ijhydene.2021.09.041
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creasingly relies on H_2 and derived renewable gases. A holistic approach on modelling energy transport considering electricity, natural gas and H_2 is necessary to sufficiently take all these interactions into account and ensure a cost-optimal hydrogen supply infrastructure for Germany.

1.1. State of research

Several authors analysed and optimised future hydrogen transportation options by applying different methods. In an investigation focused on US states, which includes the options of pipeline transportation as well as gaseous hydrogen (GH_2) and liquid H_2 trailers, Yang and Ogden made a first effort to find the lowest-cost H_2 delivery mode [14]. They found that for densely populated areas with a large hydrogen demand, pipeline transportation is most cost-efficient, whereas for moderate or low demands liquid H_2 trailers or GH_2 trailers are more economical. Ball et al. made an early approach of setting up an energy system optimisation model for the assessment of a German transport system based on H_2 with the target year 2030 [15]. Some of their findings are that introducing H_2 leads to a remarkable reduction in carbon dioxide (CO_2) emissions from early phases on and that in densely populated areas it leads to minimised infrastructure costs. In [16], an analysis of H_2 pipeline infrastructure in Germany with the target year 2050 is carried out by Baufumé et al. based on a geographic information system, where fuel stations serve as demand sinks and transmission and distribution is investigated on level 3 according to the Nomenclature des Unités Territoriale Statistiques (NUTS) scheme developed by the EU. In that model, an approach to use predefined routes for a possible grid infrastructure to avoid for the pipelines to cross forbidden or implausible areas is implemented. Krieg [17] attempts a comprehensive forecast for a H_2 pipeline grid in Germany to supply a future FCEV demand. Therein, it is investigated which routes of existing infrastructure like rail lines, freeways and the natural gas pipeline routes are most suitable as orientation for a H_2 grid. Robinius built up on that work using the rail and natural gas networks as orientation [18]. He further investigated different market designs for the utilisation of H_2 in the transport sector to subsequently evaluate them in a multi-modal energy system model of the German electricity and gas sectors, including H_2 pipelines.

For Great Britain, the decarbonisation of the transport sector focusing on the interplay of electricity and H_2 networks to reach an optimal design of an integrated energy system is investigated by Samsatli et al. using a mixed-integer linear programme [19]. New H_2 pipelines are assumed to be built next to existing ones to be able to neglect rights of way costs. The problems of limited temporal resolution and sectoral scope of that study are partially resolved in [20], where the focus is on the role of renewable H_2 and storage for the heating sector in Great Britain. It is found that repurposing the natural gas grid to hydrogen utilisation only has little positive influence on the system costs. This stands in opposition to Cerniauskas et al. [7], who conduct a cost assessment for a perspective repurposing of natural gas pipelines to H_2 usage in Germany. One of their key findings is that pipeline reassignment can reduce H_2 delivery costs by at least 60 %, while around 39 % of the total transmission pipeline length are assumed to have a reassignment potential, based on estimates regarding the existence of parallel pipelines. Backing of the reassignment potential of existing natural gas infrastructure can also be found in the so-called European Hydrogen Backbone, which was published by several European gas transmission system operators [21]. In its recent extension of mid-2021 [8], 69 % of the approximately 40 000 km-long H_2 transmission network is projected to come from repurposed natural gas pipelines by the year 2040.

An economical assessment of power-to-hydrogen and power-to-gas including the option to feed into gas pipelines is performed by Schiebahn et al. [22]. They conclude that it is inefficient to convert H_2 to methane to be able to transport the product through the existing natural gas grid, so H_2 should rather be used directly, which would necessitate a dedicated H_2 infrastructure. Welder et al. design an energy system model that covers the German state of North Rhine-Westfalia in high spatial detail to evaluate five distinct H_2 reconversion options, in which the pathway that features reconversion with combined-cycle gas turbines results to be most cost-effective [23]. Due to its focus, the study has a rather limited technological scope, however, and also does not include natural gas transportation. Another techno-economic model is published and applied by Reuß et al. to analyse a hydrogen supply chain for the German road transport sector [24–26]. The authors consider GH_2 transportation in pipelines and trailers as well as liquid H_2 trailers as well as those transporting liquid organic hydrogen carriers. One conclusion is that pipelines are a cost-effective transportation option in regions with higher hydrogen demand. Also Emonts et al. focus on the German road transport to analyse different pathways for establishing renewable H_2 as fuel [27]. They find the combination of pipeline transportation and underground storage to be most cost-efficient for high-demand scenarios, whereas for low demand liquid hydrogen and liquid organic hydrogen carriers are more favourable options. An in-depth analysis of H_2 trailer transport options at different pressure levels was conducted by Lahnaoui et al. [28]. Their study results in the finding that higher-pressure trailers are more economical for high H_2 demand.

Haumaier et al. perform a potential analysis for power-to-gas technologies in Germany based on a geographic information system considering gas grid restrictions [13]. It is found that the feed-in capacities of the existing pipeline transmission infrastructure in Germany can restrict the located power-to-gas potentials. For that investigation—congruent to the presented paper—the publicly available LKD-EU data set [29] is employed.

A European energy system model including H_2 infrastructure and investigating 38 historical weather years is presented by Caglayan et al. [30]. Key findings are that more renewable energies within a region lead to lower electricity costs, which in turn favours the H_2 production in these regions. A similar approach to the presented paper in terms of multi-modal energy transport infrastructure that includes the electricity, natural gas and H_2 transmission networks was published in [31]. In that joint study of a gas and an electricity-grid transmission system operator, pathways for a German and Dutch energy system that go beyond the currently existing network development plans are presented for the target year 2050. As in the present paper, the development of the power-to-gas technology and the related energy transportation infrastructure is analysed with a 95 % decarbonisation target. Thereby, a simplified representation of actual transmission assets is used based on aggregated energy transmission capacities between regions. A system-cost minimisation is applied and the spatial resolution is largely on NUTS 2 level for Germany (without city states), NUTS 1 level for the Netherlands and country level for the rest of Europe. Nevertheless, the H_2 supply chain does only consider H_2 pipelines for the hydrogen transport.

Finally, an investigation featuring a multi-modal German energy system that also encompasses both electricity and gas transportation is presented by Gils et al. [32]. Its distinguishing characteristics are the wide range of modelled technologies as well as a pathway to climate neutrality until 2050. It does not include H_2 transmission via trailers, however, and the chosen regional resolution of Germany in that study is distinctly lower than in the presented paper (eleven versus 38 regions), which in comparison results in a less detailed representation of inner-German energy flows.

The literature research shows that even though existing studies have investigated on a future H_2 transportation infrastructure in Germany, most of them put a focus on particular aspects of the H_2 supply chain and are thus limited with regards to multimodality. Adversely, investigations that employ a temporally and regionally highly resolved optimisation model are rather rare and either focus on different countries, are less detailed in terms of regionalisation or do not include the option of different H_2 import routes to Germany.

1.2. Original contributions

With this paper, the existing literature is complemented by investigating a future H_2 supply chain in Germany in an hourly and spatially highly resolved multi-modal energy system model. This includes the optimisation of differentiated H_2 import routes, inland electrolysis, storage as well as pipeline and trailer transport options, which have not been considered together in any previous model known to the authors. The central research question of the presented work is how a future H_2 supply chain for a decarbonised Germany 2050 could look like considering different projected H_2 demand volumes. This is addressed by evaluating the energetic H_2 demand in eight different scenarios in the form of a local sensitivity analysis, which is carried out to cover uncertainties about actual future H_2 demands. As part of the applied linear programming approach, transport restrictions for electricity, natural gas and H_2 are implemented. This finally also allows for the identification of potential natural gas pipeline reassignment connections.

The employed energy system model with H_2 supply chain is presented in Section 2. Detailed explanations are given on how the H_2 demand, supply and transport infrastructure is modelled as well as on the performed procedure of the local sensitivity analysis of the H_2 demand. Results of this modelling approach are presented in Section 3, followed by a discussion (Section 4) and the conclusions (Section 5).

2. Material and methods

In this chapter, the multi-modal energy system model is described. The general setup of the model is presented in Section 2.1 along with the applied modelling framework. The overall H_2 supply chain implemented in the multi-modal energy system model used in this study is composed of the elements mentioned in the Sections 2.2 to 2.7 and is illustrated in Figure 1. As depicted, a switch in mode of transportation is possible from pipeline to trailer, but not vice versa. This is because we assume that trailers commonly transport smaller volumes of H_2 (cf. [24]), which would not reach a sufficient utilisation for pipelines if the mode of transport is switched from trailer to pipeline. Further, the distribution of H_2 within one region is assumed via trailer transport and modelled based on an estimated cost factor. This cost estimate is 6.15 €ct/kWh [25].[1] In Section 2.8, the approach of the performed sensitivity analysis of H_2 demand is introduced.

2.1. Energy system model

The employed energy system model is formulated as a linear programme using the modelling framework Energy System Development Plan (ESDP), which is described in [33] and applied in an updated version in [34]. The developed model of Germany is adopted from Kolster et al. [35] for the electricity and heat sector and extended from the year 2030 to the year 2050. Both models share the same base assumptions on techno-economic parameters for electricity and heat generation. The model developed for the present analysis, however, is the first in ESDP to feature a hydrogen supply chain including pipelines and trailers as well as a natural gas infrastructure representation. These are introduced and presented in the following sections.

The model is formulated using GAMS 30.3.0 Minor Release from March 6, 2020 and solved using the CPLEX optimisation package 12.12.0.0. The optimisation aims at minimising the total system costs while balancing demand and supply for each hour of the year. CO_2 emissions can be restricted for different years. Additionally, several constraints are formulated based on the modelled scenarios, which depend on techno-economic parameters, which are managed using a PostgreSQL and PostGIS data base. The regionalisation approach is based on the EU's NUTS classification system which is orientated at administrative boundaries [36]. The NUTS 2 level is chosen for the focus region Germany, which corresponds to 38 government districts. In addition, 13 countries that have a grid-bound energy exchange with Germany (electricity and/or gas) are represented on country level.[2] As sole exception the Russian energy system is not modelled explicitly and the distance for the gas transport to the state of Mecklenburg-Western Pomerania is set

[1]The cost of 6.15 €ct/kWh is taken from the most cost-efficient pathway for a 50 % H_2 market penetration scenario given in [25] and is the sum of the conversion processes 'Compressor', 'Distribution' and 'Station'.

[2]These countries are: Austria, Belgium, Czech Republic, Denmark, France, Luxembourg, the Netherlands, Norway, Poland and Switzerland. Sweden and the United Kingdom are only connected via electricity grid, Russia only via gas pipeline.

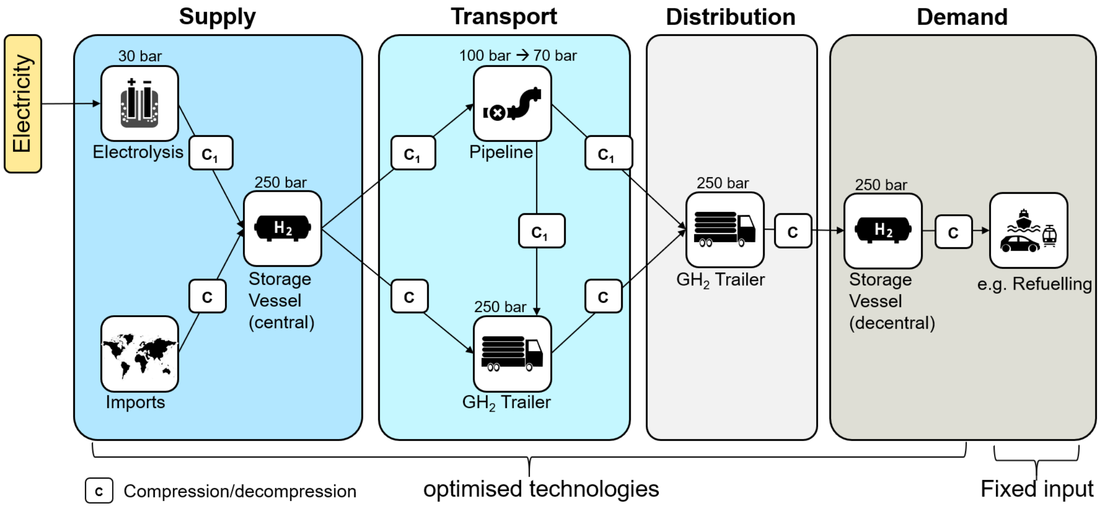

Figure 1: Hydrogen supply chain including all modelled technologies, conversion processes and pressure levels. Pressure differences from one process to the following are just indicative in the model, as they imply the need for compression which is entailed with costs and losses according to Table 7. The respective compression units are marked with "c_1" in the diagram.

to 1224 km corresponding to the actual length of the only existing connection, which is the Nord Stream pipeline [37].[3] Apart from this special case, distances between regions are modelled as centroid-to-centroid connections.

All relevant technologies from the electricity and heat sector implemented in the model for Germany are listed in Table D.8 with their corresponding capacities and energies respectively. For the transmission of electricity, net transfer capacities (NTCs) are calculated. The alternating current (AC) electricity grid is modelled with publicly available data from the transmission system operators from the years 2016/17. Additionally, all network development measures for high voltage direct current (HVDC) lines projected to be built by the year 2030 in [38] are implemented in the model. Electricity import and export capacities are based on [38] and [39].

2.2. *Hydrogen demand*

In 2019 about 55 TWh of H_2 were consumed in Germany evenly distributed between the chemical and petrochemical industry [4]. To further decarbonise all sectors, future applications of H_2 in the industry, heat, transport and power sector is discussed. Driven by the EU and the German National Hydrogen Strategy, the future demand is commonly projected to grow in all sectors but with diverging quantified volumes reaching up to a total of 400 TWh in Germany [40]. This uncertainty can pose an obstacle today for planning and developing the necessary H_2 infrastructure. To overcome this, we model varying H_2 demand volumes and assess the required H_2 infrastructure for each scenario as described in Section 3.1.

Analysing the H_2 transportation capacities requires a regionalisation of the total H_2 demand. Since we assume the transport sector to constitute a major share of the H_2 demand in 2050, we use it to distribute the total demand among the 38 NUTS 2 regions of Germany. This is done on the basis of market penetration rates published by Cerniauskas et al. [41] for a medium H_2 penetration scenario for the transport sector as shown in Table 1. In addition to the original source, H_2-driven domestic shipping is considered with a market penetration of 75 %.

In the transport sector, population and vehicle density are strong indicators for the refuelling demand of passenger cars and buses. Following the methods presented by Cerniauskas et al. [41] and Rahmouni et al. [42] those indicators are used to allocate the passenger hydrogen demand. For the road freight transport it is assumed that most refuelling activities are concentrated in regions with a high road freight traffic performance measured in tonne-kilometres. International road freight transport is thereby included. Furthermore, future H_2 demand of trains is allocated to the NUTS 2 regions only by diesel-train refuelling stations since it is not expected that trains already running on electrified railways are switched to H_2-based drive trains. Finally, since inland waterway vessels refuel at departure and arrival destinations, inland ports weighted by their annual freight handling are used to distribute potential H_2 refuelling demand of domestic vessels. International shipping and aviation are not considered for the demand distribution within this study. Figure 2 shows the resulting normalised H_2 demand distribution, which is assumed for all scenarios based on the market penetration rates presented in Table 1. The overall hydrogen demand in this scenario adds up to about 150 TWh, which is referred to as the base scenario in the following. Further, the temporal distribution of this demand is based on hourly road traffic volumes in Germany from the year 2011 [43].

2.3. *Hydrogen supply*

In order to supply the future H_2 demand, different import routes as well as inland production with water electrolysis, utilising a proton-permeable polymer-electrolyte membrane, are

[3]Only the capacity of the Nord Stream pipeline is modelled, not that of Nord Stream 2.

Table 1: Assumed hydrogen penetration rates for different markets in Germany in the year 2050 derived from the medium scenario in [41].

Passenger vehicles	Buses	Trucks	Rail transport	Shipping
50 %	60 %	50 %	75 %	75 %

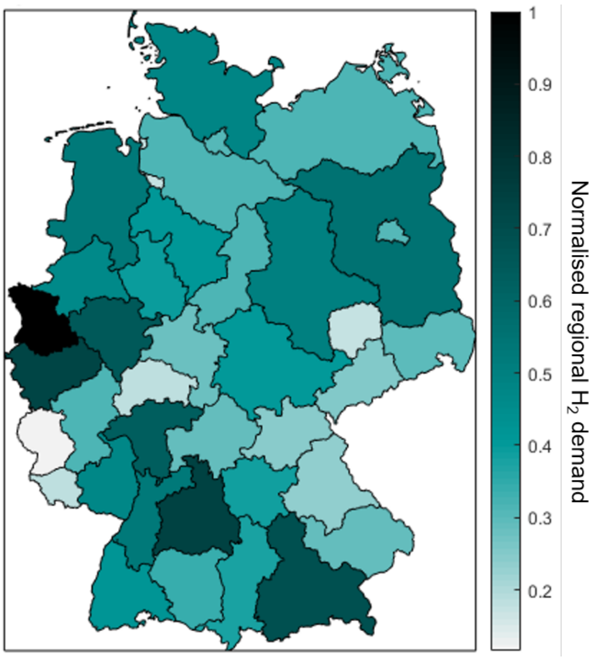

Figure 2: Regionalised hydrogen demand based on market penetration rates as listed in Table 1. The values are normalised to the highest demand within a single region.

considered within the model. While international sites with high wind or solar potential are suitable for low-cost H_2 production, transportation from these regions to Germany can come along with relatively high costs [44, 45]. In this paper, imports are modelled in competition to producing H_2 in Germany facing adverse site-specific conditions such as higher electricity costs and less full load hours (FLH) of the electrolysers [44, 45]. We only consider imports from international sites already discussed in literature and politics. The model incorporates different H_2 import routes as shown in Figure 3. All assumptions refer to the import at the German border. The routes differ in terms of cost assumptions, maximum available H_2 supply volume to Germany and NUTS 2 import region.

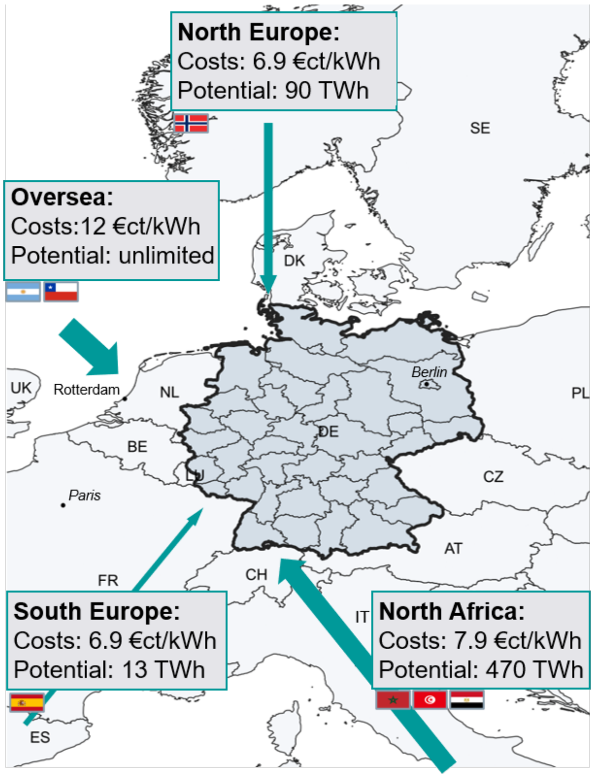

Figure 3: Modelled hydrogen import routes with assumed import costs and maximum assumed import potential based on [44–46]. The national flags indicate the specific countries named in literature for cost and volume assumptions. Unlimited imports are assumed from overseas.

In northern Germany, H_2 imports from Norway via Denmark using a new H_2 pipeline are assumed based on [45]. Moreover, since the harbour of Rotterdam plays a major role in energy imports (coal and oil) for the European Union already today, its future potential as central hub for H_2 imports is discussed increasingly. Reassigned natural gas pipelines or newly built H_2 pipelines can transport H_2 to Germany. The assumed import costs are based on the production in high potential wind regions in South Chile and Argentina, shipping of liquid H_2 towards Rotterdam and gaseous transport via pipelines towards Germany [44, 45]. These imports are modelled to arrive directly in the western regions of Germany or via Belgium along already existing natural gas pipeline routes. The import volume is not restricted, assuming that further worldwide locations could also supply H_2. Furthermore, imports in the southwest of Germany via France are considered. The cost assumptions are based on H_2 produced from solar power in Spain transported by newly-built H_2 pipelines [45]. Furthermore, we limit the imports from Southern Europe to the combined potential from Spain and France. Finally, Northern Africa with its high potential for solar power is considered as promising region to produce large amounts of green H_2. The model incorporates its H_2 imports via pipelines over Italy and Switzerland or via Spain and France towards the region of Freiburg in the south of Germany based on [45, 46]. Finally, the import potential is restricted to 470 TWh according to the projected potential from Morocco in [45]. Nevertheless, in [46] a similar import potential via pipeline of 400 TWh from Northern Africa is calculated as combined potential from Morocco and Tunisia.

The technology-specific costs for H_2 production in Germany in 2050 are set according to Table 2. As indicated in there, the electricity consumption for this technology is supplied by the optimised hourly electricity mix within the region of installation. It consists mainly of renewable energies, but the output of the electrolysis cannot be considered as completely green H_2 since the electricity mix in 2050 within the 95 %-decarbonised model can still feature a small amount of natural gas burned in gas power plants. The electrolysis capacity is optimised in each NUTS 2 region within Germany based on the regional electricity costs, the potential FLH and the infrastructure costs for transporting H_2 towards the demand centres. Thereby, the scarce resource of intermittent renewable electricity still needs to meet other electricity demands such as for households, industry, traffic and power-to-heat applications. Furthermore, electricity transmission is limited by NTCs. H_2 exports and transits are not considered within this analysis.

Table 2: Assumed techno-economic parameters for water electrolysis in 2050 based on [47]; full load hours and electricity costs are calculated endogenously within the model. The operation and maintenance (OM) costs are defined as share of the initial investment costs.

Efficiency	**Lifetime**	**Investment costs**	**OM costs**
74 %	20 a*	450 €/kW	1.5 %/a

* This corresponds to 5000 full load hours per year.

2.4. Natural gas pipelines

The basis of the natural gas and therefore also the derived H_2 pipeline infrastructure builds a data set developed within the 'LKD-EU' project [29], which is referred to as LKD-EU data set in the following. At the time the present study was developed, it was the most extensive openly accessible data set on pipeline infrastructure for Germany known to the authors.[4] Due to the lack of capacity data[5] and to develop a consistent representation of gas transportation capacities, new capacities are assigned to all pipelines within the data set. To do so, pipeline classes and diameters, which are given for most entries, are used to calculate transportation capacities according to the values given in Table 3. For each respective class a transportation capacity is assigned to each pipeline based on the given diameter in the data set by linear interpolation between the upper and lower bounds defined in Table 3. The energy transportation capacities shown in Table 3 are estimates originally derived from Kunz et al. [49]. According to that report, the values can be regarded as an upper boundary of the actual transportation capacities. They are calculated with the assumptions of a maximum mass flow speed of 10 m/s, a net calorific value of 49.725 MJ/kg and ideal gas conditions.

Table 3: Pipeline classification used to assign capacities to natural gas pipelines in the LKD-EU data set from [29] (table adopted from [13] and [49]).

Class	**Diameter in** mm	**Transport capacity in** MW
A	$1000 \leqslant x \leqslant 1400$	$27\,125 \leqslant x \leqslant 53\,125$
B	$700 \leqslant x < 1000$	$3333 \leqslant x \leqslant 27\,125$
C	$500 \leqslant x < 700$	$1708 \leqslant x \leqslant 8375$
D	$350 \leqslant x < 500$	$833 \leqslant x \leqslant 41$
E	$200 \leqslant x < 350$	$167 \leqslant x \leqslant 833$
F	$100 \leqslant x < 200$	$167 \leqslant x \leqslant 667$
G	$10 \leqslant x < 100$	167

In a next step, all pipelines connecting the same two regions are aggregated to one inter-regional transmission capacity. All inner-regional pipelines which do not cross an administrative NUTS 2 border are neglected. Since there is no information on the direction of the gas flows included in the LKD-EU data set, this approach yields an undirected grid representation with the same transportation capacity for both directions. To obtain a directed gas grid representation, the year 2020 is parametrised according to known power plant capacities [50, 51]; natural gas import and export volumes as well as natural gas demands per NUTS 2 region of the year 2015 [29, 49]. While the inter-regional gas transportation capacities are optimised, a physical representation of gas flows is not considered. This optimisation run allows to identify the most probable gas flow directions between all regions. The resulting representation for the natural gas transmission grid on NUTS 2 level for Germany is shown in Figure B.10. The additionally depicted cross-border capacities to grid neighbours are an aggregation of values derived from [52]. Different natural gas import routes are considered in the model from the Netherlands (directly or via Belgium), Russia (directly or via Poland or the Czech Republic) and Norway (directly or via Denmark) according to the cross-border capacities of the existing natural gas grid.

[4] At the time of publishing this study, the SciGRID_gas data set is already available. It contains a comprehensive collection of available gas grid data sets for Europe and also incorporates the LKD-EU data set [48].

[5] In the LKD-EU data set, transport capacities are only assigned to about 13 % of the listed pipelines. 1809 entries are listed for pipelines in the data set [29], 238 have an assigned transport capacity in GWh/d, the others are 0 or left blank.

2.5. Hydrogen pipelines

Based on the representation derived for the natural gas grid as presented in Section 2.4, the optimiser can build up inter-regional H_2 transmission capacities. Since the energy system is modelled as linear programme, a minimum pipeline capacity restriction cannot be defined model-endogenously. This would turn the problem into a mixed-integer programme which would necessitate a far higher amount of computational resources. Consequently, very low capacity pipelines can be built up by the optimiser. This is resolved by manually removing all inter-regional pipeline connections that are below a minimal threshold of 750 MW in a post-processing. This value is 90 % of the minimum inter-regional capacity in the gas grid data set [29] in NUTS 2 aggregation. The transported volumes of the removed pipelines are concurrently shifted to trailer transportation.

For building up a H_2 pipeline, the optimiser assumes linearly increasing investment costs with increasing transport distance and capacity. The calculation of these costs is based on the non-linear equation Eq. (1) as derived from Krieg [17] and also used in Reuß et al. [24]. This Eq. (1) uses the pipeline diameter d to estimate the investment costs per meter. An average diameter of 753 mm is applied here for newly constructed H_2 pipelines based on the average diameter of the aggregated natural gas grid capacities derived from the LKD-EU data set.

$$\begin{aligned}&\mathrm{Invest}_{\mathrm{Pipeline,EUR/m}} = \\ &0.0022\,€/(\mathrm{mm}^2\mathrm{m})\cdot d^2 + 0.86\,€/(\mathrm{mm\,m})\cdot d + 247.50\,€/\mathrm{m}\end{aligned} \tag{1}$$

As described above, the costs also depend linearly on the capacity. Hence, an average pipeline capacity of 5 GW is assumed based on an interpolation of the average diameter using Table 3. The assumptions on technological and economic parameters for building pipelines are summarised in Table 4.

Table 4: Assumed techno-economic parameters for hydrogen pipelines in 2050 based on [17], [24] and [25].

Inlet pressure	Outlet pressure	Lifetime	Investment costs	OM costs
100 bar	70 bar	40 a	2143 €/m*	5 €/m/a

* This cost assumption is based on Eq. (1) with an average pipeline diameter of 753 mm and a corresponding 5 GW average pipeline capacity.

2.6. Hydrogen trailer

As alternative to the pipeline-bound transportation of H_2, the possibility for GH_2 trailer transportation is implemented into the model. Techno-economic assumptions are taken from [24] and [25] as listed in Table 5.

Table 5: Assumed techno-economic parameters for transmission of hydrogen by truck/trailer combination based on [24] and [25].

	Truck	GH_2 trailer
$\mathrm{Invest}_{\mathrm{EUR}}$	160 000 €	660 000 €
lifetime	8 a	12 a
utilisation	2000 h/a	
$\mathrm{OM}_{\mathrm{annum}}$	12 %	2 %
fuel demand	27.6 L/100 km	—
fuel price	1 €/L	—
driver cost	35 €/h	—
speed*	70 km/h	
transport capacity	one GH_2 trailer	1100 kg
transport pressure	—	250 bar

* Other than in [24], an average truck speed of 70 km/h is assumed, because trucks are only modelled for hydrogen transmission, not for distribution.

2.7. Hydrogen storage and compression

H_2 can be stored, for instance, in salt caverns or in pressure vessels [53]. The model considers only vessels at a pressure level of 250 bar [24, 54], which can be installed in each region either centrally or decentrally within the demand location. They are assumed to be located in the vicinity of the electrolysis plants (cf. Section 2.3) or the end-user site, e. g. a refuelling station, and thus need no further transportation infrastructure. Table 6 shows the corresponding assumed techno-economic parameters. No differentiation is thereby made between central and decentral storage vessels.

Table 6: Assumed techno-economic parameters for hydrogen storage vessels in 2050 based on [24]. The operation and maintenance (OM) costs are defined as share of the initial investment costs.

Pressure	Lifetime	Investment costs	OM costs	Self-discharge
250 bar	20 a	15 €/kWh*	2 %/a	0 %/h

* assumed lower calorific value of hydrogen of 33.33 $\mathrm{kWh/kg_{H_2}}$

To reach the needed pressure levels in each conversion step, (de)compression is assumed as indicated with a "c" in Figure 1. For the explicitly modelled compressor units "c_1" between electrolysis and storage as well as between storage and pipeline, pipeline and GH_2 transport and distribution trailer, the cost assumptions are given in Table 7. The listed losses are due to leakage and arise per compression process. Additional compression costs to make up for pressure drops along a pipeline segment are included in the pipeline cost equation Eq. (1) [17]. Compression costs for imports are assumed to be included in the import prices, re-compression costs between two assets with the same H_2 pressure level, e. g. storage to trailer, are not considered. Further, the compression costs for trailer distribution and at the demand location are assumed to be part of the distribution cost estimate as described in the beginning of Chapter 2.

2.8. Sensitivity analysis for hydrogen demand

Knowledge about future H_2 demands is important for planning a hydrogen supply infrastructure. Since this is a highly

Table 7: Assumed techno-economic parameters for compressor units "c_1" (cf. Figure 1) in the year 2050 based on [24, 44]. The same assumptions are used for reversed inlet and outlet pressures. The operation and maintenance (OM) costs are defined as share of the initial investment costs.

Inlet pressure	**Outlet pressure**	**Life-time**	**Investment costs**	**OM costs**	**Losses**
30...70 bar	250 bar	15 a	730 €/kW	4 %/a	0.5 %

uncertain parameter, a local sensitivity analysis varying the annual H_2 demand of Germany from 50 TWh to 400 TWh is conducted to investigate the impact of different exogenously given demands on the supply and transportation infrastructure. The H_2 demand thereby is the only input parameter being varied. This analysis focuses mainly on the optimised output of the H_2 supply chain: The H_2 transportation capacities for pipeline and GH_2 trailer transmission, the H_2 import volumes and routes, the storage vessels as well as the electrolyser locations in Germany. In addition to the optimised H_2 supply chain investments and operation, all scenarios optimise the RES capacity and operation for the target year 2050 (cf. Table D.8), the hourly electricity imports and exports, batteries as well as sector-coupling technologies such as heat pumps and heat storage technologies. Additional H_2 demand can occur in the optimisation in gas power plants or for heating technologies within the model. However, these options are not used by the optimiser, so this is not further mentioned in the following.

3. Results

The results from the optimisation of the linear programme and its corresponding assumptions as described in the previous Chapter 2 are presented below. A map of Germany showing its NUTS 2 regions and their hereafter utilised names can be found in Figure A.9 in the appendix.

3.1. Scenarios

All scenarios from the local sensitivity analysis (cf. Section 2.8) share the same set of base assumptions. A weighted average cost of capital of 7 % and a 95 % CO_2 emission reduction for the target year 2050 compared to 1990 is assumed, which corresponds to an upper limit of 52.6 million t. To ensure a high security of H_2 supply, a strategy of diversification is considered. Therefore, each import route needs to be developed within the model to a specified minimum of at least 5 % from the total H_2 demand in the base scenario.[6] This is specifically important for the most expensive imports from overseas to the western regions of Germany. We assume that a central European hub such as Rotterdam will be established for the European H_2 supply. The distribution of the H_2 demand to the NUTS 2 regions is assumed as described in Section 2.2 and to stay the same throughout all scenarios. The normalised distribution is however scaled by the total hydrogen demand within each scenario. To provide a broader understanding of the results, the installed capacities for electricity and heat generation in the base scenario are listed in Table D.8. The total electricity consumption in the base scenario including losses and endogenously optimised technologies such as heat pumps and electrolysers is 969 TWh and the space and process heat demand is assumed to be 1072 TWh.

[6]As mentioned before, the base scenario is defined as the scenario with 150 TWh hydrogen demand.

3.2. Hydrogen supply

Figure 4 shows the optimised H_2 supply volumes for the import route and the inland production in the base scenario. It can be seen that all import routes are exploited supplying about 84 % of the demand. In Germany, 9.2 GW of electrolyser capacity contributing 24.6 TWh of H_2 are installed mainly in the north of Germany within the regions of Schleswig-Holstein and Mecklenburg-Western Pomerania (cf. Figure C.11). The main share of foreign H_2 supply arrives from Norway via Denmark in the region of Schleswig-Holstein with a volume of 90 TWh accounting for up to 60 % of the total H_2 supply. Therefore, almost 80 % of the overall H_2 demand of Germany in this scenario is imported to or generated in Northern Germany. Finally, the slightly more expensive imports from Northern Africa add up to only 14.7 TWh for the case of a German H_2 demand of 150 TWh.

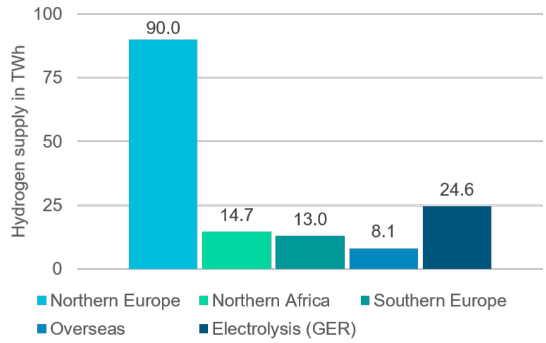

Figure 4: Hydrogen energy supply by origin in the base scenario (hydrogen demand of 150 TWh).

The results of the demand variation as indicated in Figure 5 reveal that an increasing H_2 demand changes the H_2 supply structure mainly based on assumed import prices and upper import limits as described in Section 2.3. First, it shows that import volumes from overseas and Southern Europe remain very low; the former due to high prices, the latter due to limited supply potentials. Second, two phases can be identified. The first phase (1) for demands of up to 150 TWh and the second phase (2) from 200 TWh to 400 TWh. In phase 1 starting at a H_2 demand of 50 TWh, the model shows a balanced supply from all available options. Increasing demands in Germany are supplied by ramping up the import volumes primarily from Northern Europe. As the maximum import volume of 90 TWh from Norway is exploited in the base scenario in Germany, phase 2 is initiated at an H_2 demand of 200 TWh. This phase is characterised by increasing import volumes from Northern Africa up to a level of 260 TWh. Furthermore, both phases also differ in the installation rate of electrolysers in Germany represented by the slope of the dark blue line in Figure 5. While 1.5 GW capacity of new electrolysers are installed for every additional 50 TWh of H_2 demand in phase 1, this rate drops down to 0.32 GW on average in phase 2. For phase 1 this corresponds approximately to 1 GW electrolyser capacity per 10 million passenger fuel cell electric vehicles.

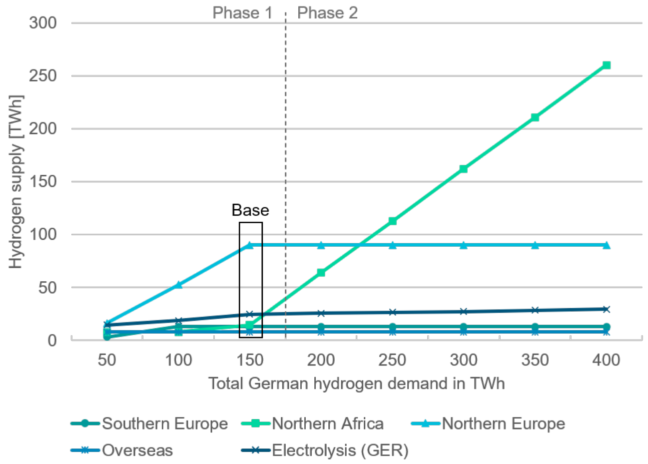

Figure 5: Hydrogen energy supply for varying hydrogen demands.

To supply each German region in the base scenario, a total of 11 GW GH_2 trailer capacity and 73 GW pipeline capacity are installed within the model. Temporally differentiating supply and demand patterns are balanced by 37 GWh of predominantly decentral GH_2 storage vessels. These energy storages contribute with 5 % to the total energy storage capacity within the multi-modal energy system, including heat, battery and pumped hydro storage units.

Figure 6 shows the supplied H_2 energy within each German region differentiated by mode of transportation (pipeline or trailer) and origin (imported or locally generated by electrolysis). Further, it shows the aggregated exported H_2 from each region to another inner-German region. The major share of imports from abroad lands in Schleswig-Holstein in the north of Germany and Freiburg in the south. Smaller shares are imported directly to regions at the western borders to France, Belgium and the Netherlands. Especially regions along the main north-to-south pipeline connection (cf. Figure 2.5) such as Schleswig-Holstein, Lueneburg and Kassel pass through up to 100 TWh of H_2 towards the south, thus making up a major share of transmission infrastructure investments. These regions are also mainly supplied via pipeline. Lueneburg is an exception as it is supplied by trailer and uses the pipeline primarily to transmit the energy further south. Furthermore, Figure 6 shows that regions with H_2 supplies below 4.9 TWh/a are only connected via trailer, for instance Dresden and Lower Bavaria.

3.3. *Hydrogen pipeline network*

The centralised supply structure, which relies heavily on imported H_2 as described in the previous Section 3.2, requires a

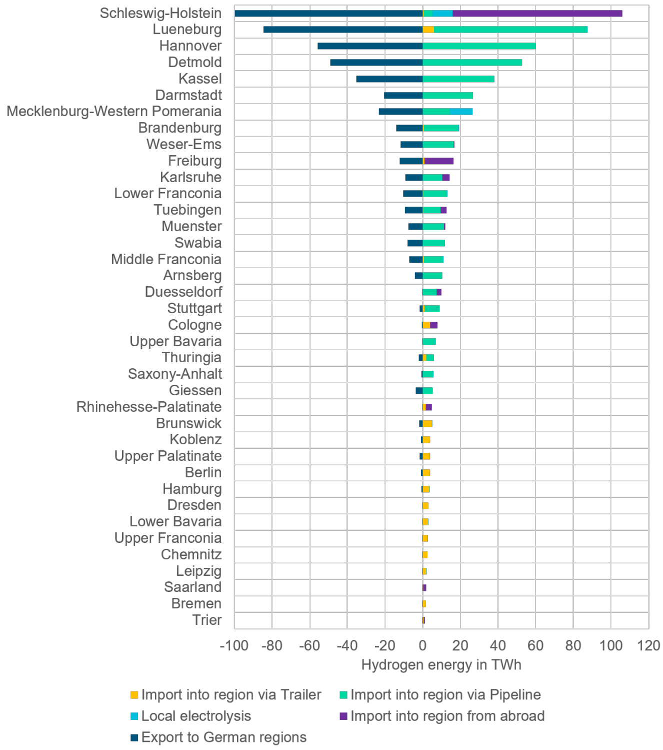

Figure 6: Regional hydrogen energy supply differentiated by mode. Exports describe the hydrogen which is exported into another German region. Imports indicate the imported hydrogen energy from abroad to the border region or from another inner-German region.

transportation infrastructure to supply all demand regions in Germany. Therefore, the model builds up pipeline and trailer capacities. Figure 7 shows the optimised transportation capacities for H_2 pipelines between the 38 German regions for the eight defined demand scenarios. While the colours indicate the installed inter-regional pipeline capacity, the arrows indicate the predominant H_2 flow directions. Regions without a pipeline connection are supplied by trailers. An exception to this are the regions of Trier and Saarland in the southwest of Germany which are directly supplied by imports via Belgium and France within all scenarios (cf. Figure 6).

In the base scenario, a well-established pipeline network transports the imported H_2 from Northern Europe as well as the H_2 produced in Northern Germany to the south. A maximum capacity of 13 GW is required for the first inter-regional pipeline connection from Schleswig-Holstein to Lueneburg. The capacity of the last segment of the major north-to-south connection ending in Karlsruhe is 1 GW. A second pipeline connection with a similar capacity supplies the region of Karlsruhe from the south. Southern imports mainly arrive in Freiburg transporting H_2 predominantly to the major demand region of Upper Bavaria.

Furthermore, the demand sensitivity analysis shows that the optimised pipeline network correlates with the underlying supply structure. The resulting optimised H_2 network in the scenarios can also be categorised in phase 1 and phase 2 as described in Section 3.2. The base scenario thereby shows a fully developed network structure in phase 1. Figure 7 additionally reveals that a central pipeline connecting the north, herein the region of Schleswig-Holstein, and the south, namely the region of Darmstadt, is already established at a H_2 demand of 50 TWh. This connection with several exit points along the way is expanded until a demand of 150 TWh is reached.

A first pipeline connection transporting only H_2 from electrolysis starting in Mecklenburg-Western Pomerania and leading to Brandenburg/Berlin is established in the 50 TWh scenario. This connection is expanded to a capacity of 3 GW at the end of phase 1. Simultaneously, a second pipeline connection is built to transport electrolysis H_2 and imported H_2 from Schleswig-Holstein to the regions in the east of Germany.

In phase 2 the increasing H_2 demand within all regions requires more imports from the south. This results in a less developed north-to-south pipeline network since the available supply volume from the north can only satisfy the increasing demand in the northern regions. South-to-north connections are established instead.

At 200 TWh a south-to-west pipeline connection is built up supplying major demand regions in the west. Thereby, no exit points are built along this connection up to the region of Cologne. The region of Koblenz, for instance, which lies along this south-to-west connection, is supplied entirely by trailers (cf. Figure 6). From a total demand in Germany of 250 TWh on, this region is connected to the pipeline network from Darmstadt. The maximum inter-regional capacity of 35 GW occurs at a demand of 400 TWh between Freiburg and Karlsruhe.

3.4. Gas grid utilisation

To reduce the costs of H_2 transportation, existing natural gas pipelines could be reassigned to transport H_2. We identify inter-regional connections where a pipeline reassignment would be applicable without interfering with the remaining required gas transportation capacities.

Since Germany plays an important role today as gas transit country [49], gas exports mainly to France, Austria, Switzerland, the Czech Republic and the Netherlands need to be considered for a natural gas grid utilisation analysis. With the assumption of gas transits through Germany decreasing to 25 % of the volumes in 2017 (in line with the overall European gas demand reduction in the 'Optimised Gas' scenario in [55]), the endogenously determined German gas demand in the model decreases to 143 TWh.[7]

Figure 8 shows the maximum occurring load factor of each inter-regional connection assuming a demand reduction in neighbouring countries to 25 % compared to 2017. Since most inter-regional connections in our model are built up with more than one pipeline in reality [29], we base the identification of potential reassignments on a maximum load factor[8] of about 0.5. While red lines indicate inter-regional connections with a maximum occurring load factor greater than 0.5, green lines indicate connections which could potentially be reassigned. Grey lines are connections where a reassignment seems feasible, but further investigations are required.

Overall, it shows that about 46 % of all inter-regional connections in the natural gas grid are never utilised more than 50 %. Furthermore, the average utilisation of the entire natural gas network lies at about 29 %. With reduced imports especially from Russia compared to today's volumes, Figure 8 shows that the maximum occurring load factor of the large inter-regional capacities within the northeast of Germany are below 50 %. In contrast to that, the lower capacities of the highly connected network in the western regions of Germany are still highly utilised. Potential reassignments are exemplarily discussed at the end of Section 4.

4. Discussion

As the results indicate, the H_2 supply for Germany will depend on imports. This holds true if supply chains from international high potential renewable locations, e. g. in Europe or Northern Africa, can be established to costs equal or below 7.9 €ct/kWh of H_2 (cf. Figure 3). Within the optimisation a H_2 supply from Norway as the first major import route is built up. Even though this could already change with slightly different import cost assumptions, this import route still seems to be highly relevant and reasonable for first major pipeline connections. This can be argued due to lower regulatory and political challenges as this route crosses fewer countries and territories compared to the one from Northern Africa.

For the inland electrolysis the results indicate a higher installation rate in phase 1 compared to phase 2 (cf. Figure 5 for the definition of these phases). This can have several reasons:

- First, electrolysers are already installed in the most cost-efficient locations in the northern regions of Germany. The two regions with the major share of electrolyser capacity, Schleswig-Holstein and Mecklenburg-Western Pomerania, have the greatest combined wind and solar capacities and therefore on average the lowest electricity costs. Compared to these regions, the optimisation output reveals 16.5 % higher electricity costs on average, for instance in Weser-Ems, a region showing a high potential for electrolysis in other studies such as from Haumaier et al. [13] or Metzger et al. [56]. Additionally, further utilisation of installed electrolysers would only be possible at higher electricity prices, which results in levelised H_2 costs greater than the assumed import prices of 7.9 €ct/kWh from Northern Africa. This statement is also supported by the expansion of newly installed capacities in phase 2 only in the region of Brandenburg operating for just 2617 FLH compared to 3346 FLH in Schleswig-Holstein. Furthermore, the levelised cost of installations in the south of Germany seem not to be competitive with the H_2 import prices.
- Second, in phase 2 the pipeline infrastructure from north to south is less developed and more regions are supplied

[7] The imported natural gas is used to power 35 GW of gas power plants for heat and electricity generation as a result of the optimisation.

[8] The maximum load factor is defined as the maximum occurring gas flow within one hour over the year divided by the pipeline capacity.

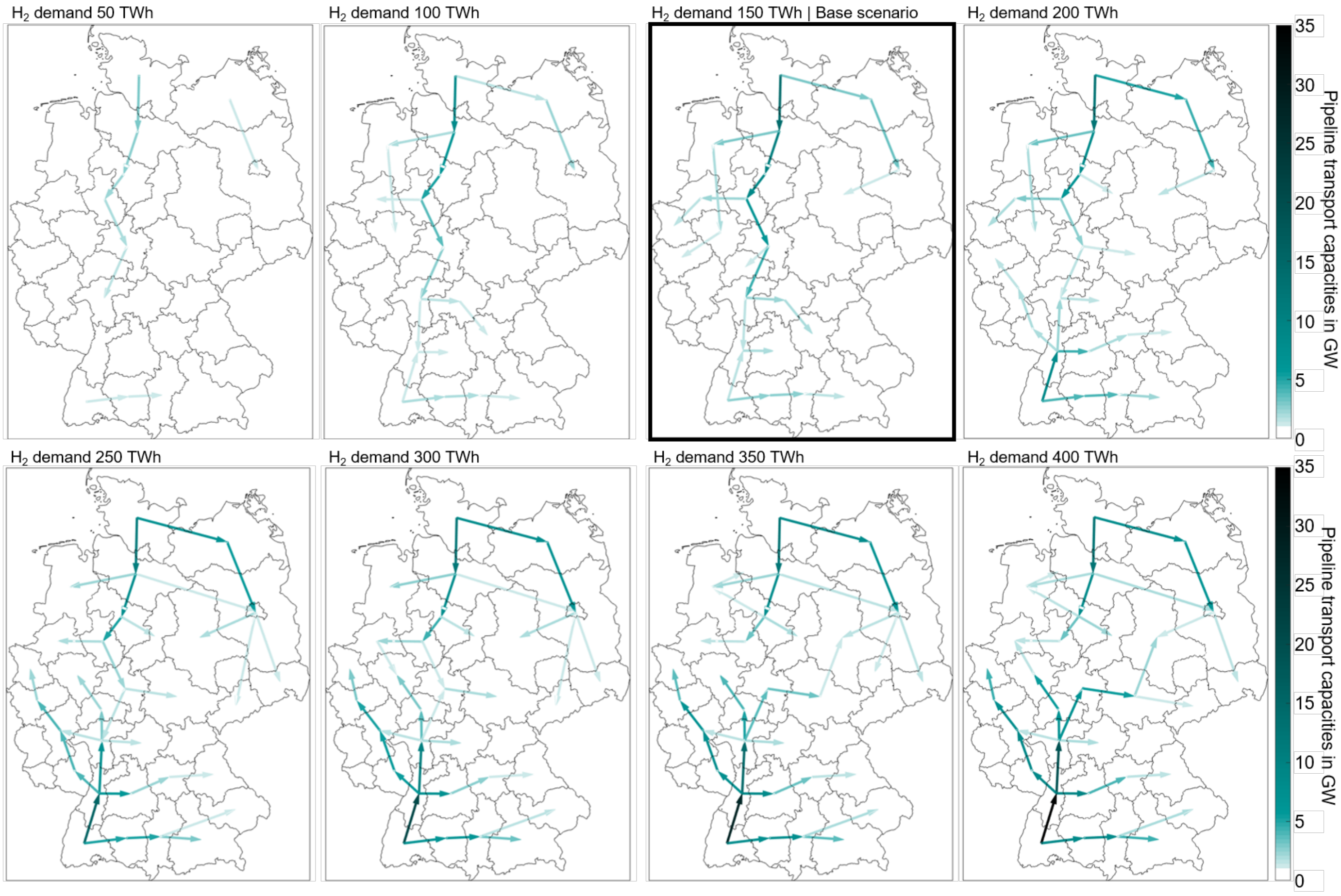

Figure 7: Inter-regional hydrogen pipeline transportation capacities for varying total hydrogen demands in Germany.

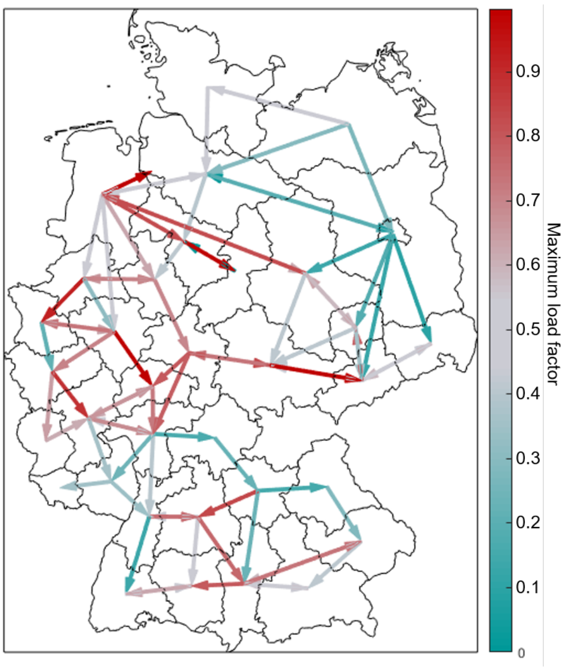

Figure 8: Natural gas grid utilisation in the base scenario. Green arrows indicate potential reassignment connections, red arrows indicate that no reassignment can be suggested from this analysis. A gas demand reduction in neighbouring countries for the year 2050 to 25 % compared to 2017 [55] is assumed. Further, 143 TWh natural gas demand in Germany from optimisation.

by imports from the south. The limited north-to-south connections restrict further sales of inland-produced H_2 to southern regions and can therefore reduce the competitiveness of produced H_2 in northern Germany. From this observation we interpret that a H_2 supply infrastructure from north to south favours the installation of electrolysers in Germany due to the access to a larger market area.

The optimised pipeline networks indicate that connecting major demand centres such as Cologne and Duesseldorf in the west as well as Upper Bavaria in the southeast via pipeline to central import or production regions (cf. Figure 7) is more cost-efficient than e. g. decentral H_2 production or the supply via trailers (cf. Figure 6). A further analysis shows that this holds true even for import prices of 12 €ct/kWh. From this it can be derived that a fully connected pipeline network is most cost-efficient within the multi-modal German energy system as modelled for the year 2050. Since a linear approach including a post-processing (cf. Section 2.5) is used to evaluate the share of trailer and pipeline capacity, it is to mention that 6 GW of installed pipeline capacities are shifted to trailers within that post-processing. This is about 7 % of the total H_2 transportation capacity within the model. While this post-processing directly effects the presented statements about the regional H_2 supply mode for regions with low H_2 supplies below 4.9 TWh (cf. Section 3.2), it is argued that it increases the plausibility and economic feasibility of the remaining identified pipeline connections. Furthermore, the regional supply assessment (cf. Figure 6) can give an indication on which regions in Germany are most important for implementing a H_2 economy. Those are the regions with the highest overall H_2 energy supply and exports, such as Schleswig-Holstein, Lueneburg, Hannover, Detmold and Kassel. Even if the order can change with an increasing H_2 demand and thus with an increasing supply from the south via Freiburg, these regions still keep the importance already identified in the base scenario. Nevertheless, an economic impact of or requirements for infrastructural investments per region cannot be directly derived from Figure 6. This is inter alia due to the fact that the geometric size varies from region to region, which could result in different required pipeline lengths and different H_2 distribution grid investments. Further, the size of a region correlates with the transport distance for H_2 within the model, because of the utilised simplification of centroid-to-centroid connections. This can favour the usage of trailers as mode of transportation, which occurs for the small regions of Berlin, Bremen and Hamburg. Especially since the geographical centres of Brandenburg and Berlin are just about 3.2 km apart, the supply via trailer to Berlin is strongly affected by the chosen regions within the model. In contrast to that, the results for these highly populated areas still seem reasonable in terms of whether a region is connected via a large transmission pipeline. This is because large pipeline transportation infrastructures would most probably occur only outside of cities and a distribution via trailer or smaller underground distribution pipelines would be more realistic.

Inferring from the local sensitivity analysis, a pipeline connection from import entry regions in Northern Germany with potential inland electrolyser locations can be considered as no-regret investment. The optimisation already shows the macroeconomic benefit of this infrastructure in the 50 TWh scenario. In line with the National Hydrogen Strategy this enables and increases the market for H_2 production sites in Northern Germany. Nevertheless, these findings refer only to the assumed H_2 demand distribution and a green H_2 supply of the assumed demand. A further no-regret connection can be identified from Schleswig-Holstein via Mecklenburg-Western Pomerania to Brandenburg/Berlin. This already shows to be a central backbone for supplying regions in the northeast of Germany at a H_2 demand of 100 TWh. Furthermore, especially the natural gas pipeline network in these northeast regions has the potential to be reassigned to transport H_2.

Within a European context an intensified network structure in the west connecting industry clusters in the Netherlands and Germany could increasingly dominate the picture as shown in the European Hydrogen Backbone [8, 21]. Although our results do not show that, an intensified H_2 pipeline network in the western regions including a cross-border connection to the Netherlands could still be beneficial already in early stages of a H_2 economy. This is due to the two circumstances that no industry clusters are considered in our model, and the allocation of the demand centres is based on the transportation sector alone. With our results reflecting the approach of a multi-modal energy system optimised for the target year 2050 we contribute to the discussion with a variety of demand scenarios and indicate that even industry clusters in the west could benefit from a centralised H_2 supply from Northern Europe and Northern Africa due to significantly lower costs compared to imports at the harbour of Rotterdam.

Finally, reassigned natural gas pipelines could reduce the transport costs of H_2. Even though this analysis is not supposed to suggest real pipeline reassignments, it gives a first impression whether pipelines along major future H_2 corridors still have a crucial importance for methane transportation in Germany in 2050. Further, natural and green gas import origins could be different in the year 2050 than assumed. What is shown by the analysis, however, is that the asset utilisation in general decreases to 34 % leaving room for reassignments.

A 40 GW inter-regional connection consisting of several non-parallel pipelines mainly transporting imported Norwegian natural gas via Denmark from Schleswig-Holstein further south today is only utilised up to 50 % in 2050 (Figure 8). In addition, Figure 7 concurrently emphasises the importance of a H_2 pipeline with a capacity of 13 GW being built between the same regions throughout all scenarios. Therefore, this connection can be an ideal candidate for a pipeline reassignment to minimise the transportation costs of H_2. In a recently published pre-feasibility study a similar corridor is investigated by the responsible transmission system operators for gas to connect Denmark and the Hamburg region with a H_2 pipeline [57]. Further along this route, the optimisation shows that reassigned pipelines could transport the H_2 at least up to the region of Detmold, where the pipeline density significantly increases. Further reassignments in this western area are not identifiable from this study. This can be in contrast to studies with a more detailed representation of the natural gas network with the reason being that our approach neglects pipelines that lie only within one NUTS 2 region, since only the inter-regional transportation capacities between two NUTS 2 regions are considered. The sensitivity analysis shows that with increasing hydrogen demand above 150 TWh, the importance of the H_2 connection in the southwest from Freiburg to Karlsruhe grows significantly. When building a pipeline in this hilly region, the Black Forest Natural Park poses restrictions on possible routes. With the applied approach to suggest building pipelines along existing natural gas pipelines, this connection would be allocated in the west of the Black Forest along the river Rhine and the border to France. This is where the major European Trans Europa Naturgas Pipeline (TENP) is situated consisting of multiple pipelines [29]. Figure 8 indicates that the natural gas transport along this route could decrease significantly to a maximum annual utilisation rate of about 20 %, which therefore makes it another candidate pipeline for reassignment. Nevertheless, it is to be emphasised that the required hydrogen capacity for the 400 TWh scenario could exceed the existing natural gas transportation capacities by up to a factor of six. After all, the assumptions about the European natural gas demand—in this case especially for Italy and Switzerland—are crucial parameters to be reconsidered for evaluating the robustness of this reassignment suggestion in future work.

5. Conclusion

With the future importance of H_2 as energy carrier within the next decades in Germany, large investments are required to build up a sufficient H_2 infrastructure. To deal with the uncertainty of the future demand of H_2 in the planning process, we use a multi-modal energy system model and apply a local sensitivity analysis varying this demand. This allows us to identify major hydrogen supply routes as well as a dedicated hydrogen pipeline network for the year 2050. Therefore, we contribute to the discussion by showing a variety of scenarios and building up a comprehensive hydrogen supply chain as part of the multi-modal model including detailed H_2 import routes. We find that connecting major demand and supply centres via pipeline is already macroeconomically beneficial at low H_2 demands of 50 TWh/a. Further, our analysis shows the importance of considering detailed H_2 import routes to identify suitable pipeline connections. A central north-to-south connection through Germany is shown to be a no-regret option (operated in one or the other direction). A second no-regret connection is found to link Schleswig-Holstein with the regions in the northeast of Germany such as Brandenburg and Berlin.

Abbreviations

CO_2	carbon dioxide
ENTSO-E	European Network of Transmission System Operators for Electricity
ENTSOG	European Network of Transmission System Operators for Gas
ESDP	Energy System Development Plan
FCEV	fuel cell electric vehicle
FLH	full load hour
GH_2	gaseous hydrogen
H_2	hydrogen
HVDC	high voltage direct current
NTC	net transfer capacity
NUTS	Nomenclature des Unités Territoriale Statistiques
OM	operation and maintenance
PV	photovoltaic
RES	renewable energy source

Data availability

Information on the technologies implemented in the model and their respective installed capacities including data sources is given in Appendix D.

CRediT author statement

The presented research is based on the master thesis of JS under the supervision of DH and SN.

Dominik Husarek: Conceptualisation, Methodology, Validation, Investigation, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Visualisation, Supervision, Project administration;

Jens Schmugge: Conceptualisation, Methodology, Software, Validation, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualisation;

Stefan Niessen: Writing - Review & Editing, Supervision

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge funding by the German Federal Ministry of Education and Research (BMBF) within the Kopernikus Project ENSURE 'New ENergy grid StructURes for the German Energiewende' [grant number 03SFK1A0-2].

Appendix A. Naming convention for regions in Germany

Figure A.9 shows the regions and their names to which is extensively referred to in Section 3.

Appendix B. Gas grid capacities

Figure B.10 shows the inter-regional transmission capacities for natural gas implemented in the energy system model including assumed gas flow directions.

Appendix C. Electrolyser capacity distribution

Figure C.11 shows the optimised electrolyser capacities in each NUTS 2 region in Germany for the base scenario.

Appendix D. Installed capacities of technologies

Table D.8 lists relevant technologies from the electricity sector integrated in the model for Germany with their installed capacities. Whenever the word *optimised* appears, it indicates that the corresponding value is not exogenously specified, but calculated endogenously by the solving algorithm. These optimised values are shown for the base scenario. For gas power plants we assume values from the German NEP 2030 (2019) [38] as upper boundaries for 2050, while biomass and pump storage are fixed to the values presented in that report. Waste and run-of-river power plants are implemented with today's capacities for the year 2050 [50].

Figure A.9: Naming convention for the NUTS 2 regions of Germany used within this study.

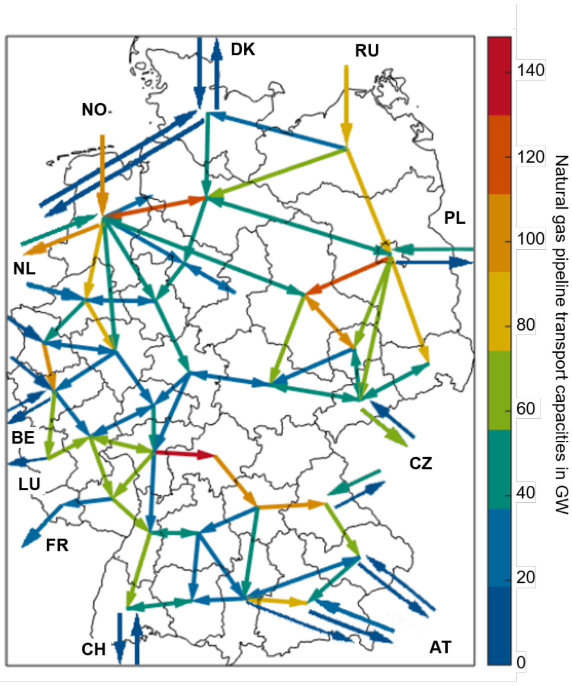

Figure B.10: Aggregated inter-regional natural gas grid capacities based on [29, 52]. Country codes: AT – Austria, BE – Belgium, CH – Switzerland, CZ – Czech Republic, DK – Denmark, FR – France, LU – Luxembourg, NL – Netherlands, NO – Norway, PL – Poland, RU – Russia.

Table D.8: Installed capacities in Germany by technology for the year 2050.

Technology	Installed capacity	Source
Battery central	13.6 GW	*optimised*
Battery decentral	10.1 GW	*optimised*
Biomass	6 GW	[38]
Combined heat and power (CHP)	8.3 GW	*optimised*
Electrolysis	9.2 GW	*optimised*
Gas blast furnace	1.429 GW	[51]
Gas (combined cycle)	15.58 GW*	[38]
Gas (single cycle)	9.51 GW*	[38]
Gas (steam turbine)	0.58 GW*	[38]
Hard coal	0 GW	—
Heat pump (home)	40 GW	*optimised*
Lignite	0 GW	—
Nuclear	0 GW	—
PV	300 GW	*optimised*
Power-to-gas	0.6 GW	*optimised*
Power-to-heat (central)	140 GW	*optimised*
Pump storage	11.6 GW / 89.3 GWh	[38]
Run of river	3.696 GW	[50]
Storage hydro	0.298 GW**	[50], [58]
Waste (electricity)	0.874 GW***	[50]
Waste (heat)	0.874 GW***	[50]
Wind offshore	17 GW	*optimised*
Wind onshore	165.4 GW	*optimised*

* This technology is optimised with an upper boundary set as indicated in the table.
** An own estimate for the upper boundary of the energy capacity of 1.5 TWh/a is set, which is completely exploited by the optimiser.
*** Assumption: Half of the total installed capacity is used for electricity, the other for heat.

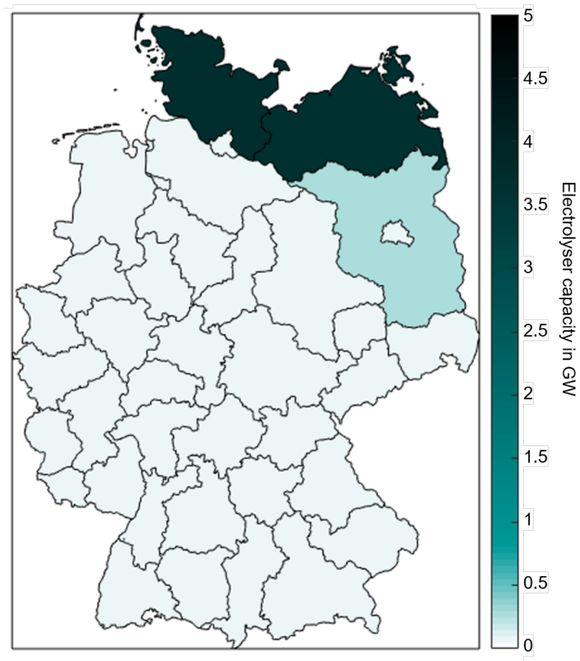

Figure C.11: Optimised electrolyser capacities in the base scenario (hydrogen demand of 150 TWh).

References

[1] Climate Watch Net-Zero Tracker (2021).
URL https://www.climatewatchdata.org/net-zero-tracker

[2] I. Gerretsen, Germany raises ambition to net zero by 2045 after landmark court ruling, Climate Home News (2021-05-05).
URL https://www.climatechangenews.com/2021/05/05/germany-raises-ambition-net-zero-2045-landmark-court-ruling/

[3] European Commission, A hydrogen strategy for a climate-neutral Europe, Tech. Rep. COM(2020) 301 final, European Commission, Brussels (2020-07-08).
URL https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf

[4] BMWi, The National Hydrogen Strategy, Tech. rep., Federal Ministry for Economics Affairs and Energy, Berlin (2020-06).
URL https://www.bmbf.de/files/bmwi_Nationale%20Wasserstoffstrategie_Eng_s01.pdf

[5] OGE, GET H2 Nukleus: first publicly accessible hydrogen network will allow wide-ranging CO2 reductions (2020-03-17).
URL https://oge.net/en/press-releases/2020/get-h2-nukleus-first-publicly-accessible-hydrogen-network-will-allow-wide-ranging-co2-reductions

[6] P. Adam, S. Engelshove, F. Heunemann, T. Tiemann, C. von dem Bussche, Hydrogen infrastructure – the pillar of the energy transition. The pratical conversion of long-distance gas networks to hydrogen operation. Whitepaper (2020).
URL https://assets.siemens-energy.com/siemens/assets/api/uuid:3d4339dc-434e-4692-81a0-a55adbcaa92e/200915-whitepaper-h2-infrastructure-en.pdf

[7] S. Cerniauskas, A. Jose Chavez Junco, T. Grube, M. Robinius, D. Stolten, Options of natural gas pipeline reassignment for hydrogen: Cost assessment for a Germany case study, International Journal of Hydrogen Energy 45 (21) (2020) 12095–12107. doi:10.1016/j.ijhydene.2020.02.121.

[8] J. Jens, A. Wang, K. van der Leun, D. Peters, M. Buseman, Extending the European Hydrogen Backbone. a European hydrogen infrastructure vision covering 21 countries, Tech. rep., European Hydrogen Backbone Initiative (2021-04).
URL https://gasforclimate2050.eu/publications/

[9] C. Findlay, What's your purpose? Reusing gas infrastructure for hydrogen transportation (2020).
URL https://www.siemens-energy.com/global/en/news/magazine/2020/repurposing-natural-gas-infrastructure-for-hydrogen.html

[10] BMWi, Gas (2021).
URL https://www.bmwi.de/Redaktion/DE/Textsammlungen/Energie/gas.html

[11] A. Ozarslan, Large-scale hydrogen energy storage in salt caverns, International Journal of Hydrogen Energy 37 (19) (2012) 14265–14277. doi:10.1016/j.ijhydene.2012.07.111.

[12] J. Michalski, U. Bünger, F. Crotogino, S. Donadei, G.-S. Schneider, T. Pregger, K.-K. Cao, D. Heide, Hydrogen generation by electrolysis and storage in salt caverns: Potentials, economics and systems aspects with regard to the German energy transition, International Journal of Hydrogen Energy 42 (19) (2017) 13427–13443. doi:10.1016/j.ijhydene.2017.02.102.

[13] J. Haumaier, P. Hauser, H. Hobbie, D. Möst, Grünes Gas für die Gaswirtschaft – Regionale Power-to-Gas-Potentiale aus Onshore-Windenergie in Deutschland, Zeitschrift für Energiewirtschaft 44 (2) (2020) 61–83. doi:10.1007/s12398-020-00274-w.

[14] C. Yang, J. Ogden, Determining the lowest-cost hydrogen delivery mode, International Journal of Hydrogen Energy 32 (2) (2007) 268–286. doi:10.1016/j.ijhydene.2006.05.009.

[15] M. Ball, M. Wietschel, O. Rentz, Integration of a hydrogen economy into the German energy system: an optimising modelling approach, International Journal of Hydrogen Energy 32 (10-11) (2007) 1355–1368. doi:10.1016/j.ijhydene.2006.10.016.

[16] S. Baufumé, F. Grüger, T. Grube, D. Krieg, J. Linssen, M. Weber, J.-F. Hake, D. Stolten, GIS-based scenario calculations for a nationwide German hydrogen pipeline infrastructure, International Journal of Hydrogen Energy 38 (10) (2013) 3813–3829. doi:10.1016/j.ijhydene.2012.12.147.

[17] D. Krieg, Konzept und Kosten eines Pipelinesystems zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff, Vol. 144 of Schriften des Forschungszentrums Jülich, Reihe Energie & Umwelt / Energy & Environment, Forschungszentrum Jülich GmbH Zentralbibliothek, Verlag, Jülich, 2012.
URL http://hdl.handle.net/2128/4608

[18] M. Robinius, Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff, Vol. 300 of Schriften des Forschungszentrums Jülich, Reihe Energie & Umwelt / Energy & Environment, Forschungszentrum Jülich GmbH Zentralbibliothek, Verlag, Aachen, 2015.
URL https://publications.rwth-aachen.de/record/565873

[19] S. Samsatli, I. Staffell, N. J. Samsatli, Optimal design and operation of integrated wind-hydrogen-electricity networks for decarbonising the domestic transport sector in Great Britain, International Journal of Hydrogen Energy 41 (1) (2016) 447–475. doi:10.1016/j.ijhydene.2015.10.032.

[20] S. Samsatli, N. J. Samsatli, The role of renewable hydrogen and interseasonal storage in decarbonising heat – comprehensive optimisation of future renewable energy value chains, Applied Energy 233-234 (2019) 854–893. doi:10.1016/j.apenergy.2018.09.159.

[21] A. Wang, K. van der Leun, D. Peters, M. Buseman, European Hydrogen Backbone. How a dedicated hydrogen infrastructure can be created, Tech. rep., European Hydrogen Backbone Initiative (2020-07).
URL https://gasforclimate2050.eu/sdm_downloads/european-hydrogen-backbone/

[22] S. Schiebahn, T. Grube, M. Robinius, V. Tietze, B. Kumar, D. Stolten, Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany, International Journal of Hydrogen Energy 40 (12) (2015) 4285–4294. doi:10.1016/j.ijhydene.2015.01.123.

[23] L. Welder, P. Stenzel, N. Ebersbach, P. Markewitz, M. Robinius, B. Emonts, D. Stolten, Design and evaluation of hydrogen electricity reconversion pathways in national energy systems using spatially and temporally resolved energy system optimization, International Journal of Hydrogen Energy 44 (19) (2019) 9594–9607. doi:10.1016/j.ijhydene.2018.11.194.

[24] M. Reuß, T. Grube, M. Robinius, P. Preuster, P. Wasserscheid, D. Stolten, Seasonal storage and alternative carriers: A flexible hydrogen supply chain model, Applied Energy 200 (2017) 290–302. doi:10.1016/j.apenergy.2017.05.050.

[25] M. Reuß, T. Grube, M. Robinius, D. Stolten, A hydrogen supply chain with spatial resolution: Comparative analysis of infrastructure technologies in Germany, Applied Energy 247 (2019) 438–453. doi:10.1016/j.apenergy.2019.04.064.

[26] M. E. Reuß, Techno-ökonomische Analyse alternativer Wasserstoffinfrastruktur, Vol. 467 of Schriften des Forschungszentrums Jülich Reihe Energie & Umwelt / Energy & Environment, Forschungszentrum Jülich GmbH Zentralbibliothek, Verlag, Jülich, 2019.
URL http://hdl.handle.net/2128/22674

[27] B. Emonts, M. Reuß, P. Stenzel, L. Welder, F. Knicker, T. Grube, K. Görner, M. Robinius, D. Stolten, Flexible sector coupling with hydrogen: A climate-friendly fuel supply for road transport, International Journal of Hydrogen Energy 44 (26) (2019) 12918–12930. doi:10.1016/j.ijhydene.2019.03.183.

[28] A. Lahnaoui, C. Wulf, H. Heinrichs, D. Dalmazzone, Optimizing hydrogen transportation system for mobility via compressed hydrogen trucks, International Journal of Hydrogen Energy 44 (35) (2019) 19302–19312. doi:10.1016/j.ijhydene.2018.10.234.

[29] F. Kunz, J. Weibezahn, P. Hauser, S. Heidari, W.-P. Schill, B. Felten, M. Kendziorski, M. Zech, J. Zepter, C. von Hirschhausen, D. Möst, C. Weber, Reference data set: Electricity, heat, and gas sector data for modeling the German system. (Version 1.0.0) [Data set]. Zenodo [dataset] (2017). doi:10.5281/zenodo.1044463.

[30] D. G. Caglayan, H. U. Heinrichs, M. Robinius, D. Stolten, Robust design of a future 100% renewable European energy supply system with hydrogen infrastructure, International Journal of Hydrogen Energy 46 (57) (2021) 29376–29390. doi:10.1016/j.ijhydene.2020.12.197.

[31] DBI Gas- und Umwelttechnik GmbH, Institute of Energy and Climate Research (IEK), IAEW at RWTH Aachen University, Gasunie, TenneT, Phase II – Pathways to 2050. A joint follow-up study by Gasunie and TenneT of the Infrastructure Outlook 2050, Tech. rep., Gasunie and TenneT (2020).
URL https://www.tennet.eu/fileadmin/user_upload/Company/News/German/Hoerchens/2020/200204_Phase_II_Project_report.pdf

[32] H. C. Gils, H. Gardian, J. Schmugge, Interaction of hydrogen infrastructures with other sector coupling options towards a zero-emission energy system in Germany, Renewable Energy 180 (2021) 140–156. doi:10.1016/j.renene.2021.08.016.

[33] S. Raths, S. Koopmann, C. Müller, A.-K. Meinerzhagen, T. Falke, M. Cramer, T. Kulms, D. Beulertz, H. Barrios, A. Schnettler, M. Tackenberg, F. Steinke, P. Wolfrum, M. Metzger, B. Schlageter, W. Kusian, A. Schmidt, The Energy System Development Plan (ESDP), in: International ETG Congress 2015 – Die Energiewende – Blueprints for the new energy age, ETG-Fachbericht, VDE Verlag GmbH, Bonn, 2015, p. 8.

[34] C. Müller, A. Hoffrichter, L. Wyrwoll, C. Schmitt, M. Trageser, T. Kulms, D. Beulertz, M. Metzger, M. Duckheim, M. Huber, M. Küppers, D. Most, S. Paulus, H. J. Heger, A. Schnettler, Modeling framework for planning and operation of multi-modal energy systems in the case of Germany, Applied Energy 250 (2019) 1132–1146. doi:10.1016/j.apenergy.2019.05.094.

[35] T. Kolster, R. Krebs, S. Niessen, M. Duckheim, The contribution of distributed flexibility potentials to corrective transmission system operation for strongly renewable energy systems, Applied Energy 279 (2020) 115870. doi:10.1016/j.apenergy.2020.115870.

[36] Eurostat, NUTS - nomenclature of territorial units for statistics. Background (2021).
URL https://ec.europa.eu/eurostat/web/nuts/background

[37] Nord Stream AG, The Project. The Pipeline (2021).
URL https://www.nord-stream.com/the-project/pipeline/

[38] BNetzA, Bedarfsermittlung 2019-2030. Bestätigung Netzentwicklungsplans Strom für das Zieljahr 2030, Tech. rep., Bundesnetzagentur, Bonn (2019-12).
URL https://www.netzentwicklungsplan.de/sites/default/files/paragraphs-files/NEP2019-2030_Bestaetigung.pdf

[39] ENTSO-E, Ten Year Net Development Plan 2018 (2019).
URL https://tyndp.entsoe.eu/tyndp2018/

[40] M. Robinius, P. Markewitz, P. Lopion, F. Kullmann, P.-M. Heuser,

K. Syranidis, S. Cerniauskas, T. Schöb, M. Reuß, D. S. Ryberg, L. Kotzur, D. G. Caglayan, L. Welder, J. Linßen, T. Grube, H. Heinrichs, P. Stenzel, D. Stolten, Wege für die Energiewende. Kosteneffiziente und klimagerechte Transformationsstrategien für das deutsche Energiesystem bis zum Jahr 2050, Vol. 499 of Schriften des Forschungszentrums Jülich, Reihe Energie & Umwelt / Energy & Environment, Forschungszentrum Jülich GmbH Zentralbibliothek, Verlag, 2020.
URL https://www.fz-juelich.de/iek/iek-3/EN/_Documents/Downloads/transformationStrategies2050_studyfinalreport_2019-10-31.pdf.pdf;jsessionid=59A7B7C0A91792DD4CB6AA1C27263F73?__blob=publicationFile

[41] S. Cerniauskas, T. Grube, A. Praktiknjo, D. Stolten, M. Robinius, Future hydrogen markets for transportation and industry: The impact of CO_2 taxes, Energies 12 (24) (2019) 4707. doi:10.3390/en12244707.

[42] S. Rahmouni, N. Settou, B. Negrou, A. Gouareh, GIS-based method for future prospect of hydrogen demand in the Algerian road transport sector, International Journal of Hydrogen Energy 41 (4) (2016) 2128–2143. doi:10.1016/j.ijhydene.2015.11.156.

[43] A. Fitschen, H. Nordmann, Verkehrsentwicklung auf Bundesfernstraßen 2011. Traffic development on federal trunk roads in 2011, Tech. Rep. 231, Bundesanstalt für Straßenwesen, Bergisch Gladbach (2013-11-14).
URL https://bast.opus.hbz-nrw.de/frontdoor/index/index/searchtype/authorsearch/author/Arnd+Fitschen/rows/10/start/6/sortfield/title/sortorder/desc/docId/675

[44] P. Runge, C. Sölch, J. Albert, P. Wasserscheid, G. Zöttl, V. Grimm, Economic comparison of electric fuels produced at excellent locations for renewable energies: A scenario for 2035, SSRN Electronic Journal (2020). doi:10.2139/ssrn.3623514.

[45] G. Brändle, M. Schönfisch, S. Schulte, Estimating long-term global supply costs for low-carbon hydrogen, Tech. Rep. 20/04, Institute of Energy Economics at the University of Cologne, Cologne (2020-11).
URL https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2020/11/EWI_WP_20-04_Estimating_long-term_global_supply_costs_for_low-carbon_Schoenfisch_Braendle_Schulte.pdf

[46] N. Gerhardt, J. Bard, R. Schmitz, M. Beil, M. Pfennig, T. Kneiske, Wasserstoff im zukünftigen Energiesystem: Fokus Gebäudewärme. Studie zum Einsatz von H_2 im zukünftigen Energiesystem unter besonderer Berücksichtigung der Gebäudewämeversorgung, Tech. rep., Fraunhofer-Institut für Energiewirtschaft und Energiesystemtechnik, Hannover (2020-05).
URL https://www.iee.fraunhofer.de/content/dam/iee/energiesystemtechnik/de/Dokumente/Studien-Reports/FraunhoferIEE_Kurzstudie_H2_Gebaeudewaerme_Final_20200529.pdf

[47] IEA, The future of hydrogen. IEA G20 hydrogen report: Assumptions annex, Tech. rep., International Energy Agency (2018-12).
URL https://www.iea.org/reports/the-future-of-hydrogen/data-and-assumptions

[48] W. Medjroubi, J. Diettrich, A. Pluta, J. Dasenbrock, SciGRID_gas project homepage (2021).
URL http://gas.scigrid.de/

[49] F. Kunz, M. Kendziorski, W.-P. Schill, J. Weibezahn, J. Zepter, C. R. von Hirschhausen, P. Hauser, M. Zech, D. Möst, S. Heidari, B. Felten, C. Weber, Electricity, heat, and gas sector data for modeling the German system, Tech. Rep. 92, Deutsches Institut für Wirtschaftsforschung and Technische Universität Berlin and Technische Universität Dresden and Universität Duisburg-Essen, Berlin and Dresden and Essen (2017-12).
URL https://www.econstor.eu/handle/10419/173388

[50] BNetzA, Bundesnetzagentur – Kraftwerksliste. (01/04/2020) [dataset] (2020).
URL https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Versorgungssicherheit/Erzeugungskapazitaeten/Kraftwerksliste/kraftwerksliste-node.html

[51] UBA, Datenbank “Kraftwerke in Deutschland”. version: 29/04/2020 [dataset] (2020).
URL https://www.umweltbundesamt.de/dokument/datenbank-kraftwerke-in-deutschland

[52] ENTSOG, The European natural gas network 2019. Capacities at cross-border points on the primary market (2019).
URL https://entsog.eu/sites/default/files/2020-01/ENTSOG_CAP_2019_A0_1189x841_FULL_401.pdf

[53] IEA, The future of hydrogen. Seizing today’s opportunities. Report prepared by the IEA for the G20, Japan, Tech. rep., International Energy Agency, Japan (2019-06).
URL https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf

[54] F. Stöckl, W.-P. Schill, A. Zerrahn, Optimal supply chains and power sector benefits of green hydrogen, Scientific reports 11 (1) (2021) 14191. doi:10.1038/s41598-021-92511-6.

[55] W. Terlouw, D. Peters, J. van Tilburg, M. Schimmel, T. Berg, J. Cihlar, G. U. R. Mir, M. Spöttle, M. Staats, A. V. Lejaretta, M. Buseman, M. Schenkel, I. van Hoorn, C. Wassmer, E. Kamensek, T. Fichter, Gas for Climate. The optimal role for gas in a net-zero emissions energy system, Tech. Rep. 203997, Navigant and Gas for Climate consortium, Utrecht (2019-03-18).
URL https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-The-optimal-role-for-gas-in-a-net-zero-emissions-energy-system-March-2019.pdf

[56] M. Metzger, M. Duckheim, M. Franken, H. J. Heger, M. Huber, M. Knittel, T. Kolster, M. Kueppers, C. Meier, D. Most, S. Paulus, L. Wyrwoll, A. Moser, S. Niessen, Pathways toward a decarbonized future—impact on security of supply and system stability in a sustainable German energy system, Energies 14 (3) (2021) 560. doi:10.3390/en14030560.

[57] M. Grunwald, L. Hansen, Pre-feasibility study for a Danish-German hydrogen network, Tech. rep., Gasunie and Energinet (2021-04).
URL https://www.gasunie.de/uploads/fckconnector/8813f5f0-bd85-5fde-9e84-4509ec7a3a2c

[58] P. Anderer, U. Dumont, E. Massmann, R. Keuneke, Wasserkraftnutzung in Deutschland. Wasserrechtliche Aspekte, ökologisches Modernisierungspotenzial und Fördermöglichkeiten, Tech. Rep. 22/2012, Umweltbundesamt, Dessau-Roßlau (2012-05).
URL https://www.umweltbundesamt.de/publikationen/wasserkraftnutzung-in-deutschland