Development of a Hydrogen Market in Eastern Germany until 2045

An infrastructure analysis based on regional potentials and demand

On behalf of GASCADE Gastransport GmbH

Final report, February 2022

Institute of Energy Economics at the University of Cologne gGmbH

Alte Wagenfabrik
Vogelsanger Strasse 321a
50827 Cologne
Tel.: +49 (0)221 277 29-100
Fax: +49 (0)221 277 29-400
www.ewi.uni-koeln.com

Authors

Dr. Eren Çam

Jan Kopp

David Schlund

Philipp Theile

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List of Abbreviations

bcm	Billion Cubic Meters
CCS/U	Carbon Capture and Storage/Utilization
CHP	Combined Heat and Power
RES	Renewable Energy Sources
EU ETS	European Emission Trading System
EUTL	European Union Transaction Log
IPCEI	Important Projects of Common European Interest
HCV	Heavy Commercial Vehicles
LCV	Light Commercial Vehicles
NUTS	Nomenclature des Unités Territoriales Statistiques

Executive Summary

Germany is pursuing to achieve climate neutrality by 2045. The phase-out of fossil fuels can be realized by electrification of gas and mineral oil utilization or by substituting them with climate-neutral gases such as hydrogen. The utilization of hydrogen provides technical or economic advantages over pure electrification, especially in sectors that are difficult to electrify, such as the chemical industry, the steel industry or heavy-duty transport. Early entry into the hydrogen market can thus facilitate the transformation of these sectors.

Eastern Germany can become Germany's energy hub

The focus of this study is on the hydrogen market ramp-up in eastern Germany and the resulting requirements for the development of a hydrogen infrastructure. With its important industrial locations and the metropolitan areas of Berlin and Leipzig, eastern Germany has a potentially high demand for hydrogen. At the same time, the regions along the Baltic Sea coast offer high potential for hydrogen production. In addition, eastern Germany is a potential energy hub for Germany with its port of Rostock, connection to the Nord Stream and Nord Stream 2 import pipelines, and gas connections to the Czech Republic and Poland. To balance the regional imbalances of hydrogen production and demand, the development of a hydrogen network seems to be reasonable.

The study analyzes the development of regional hydrogen balances in eastern Germany based on the reference years 2030 and 2045. For this purpose, based on the two scenarios *Electrification* and *Diversification*, regional hydrogen demand of the industry, transport, building and power generation sectors and hydrogen production are determined. Both scenarios build on a study commissioned by the German Federal Ministry for Economic Affairs and Energy ("Long-term scenarios for the transformation of the energy system in Germany"; only available in German) as the primary source. The *Electrification* scenario assumes a high penetration of electricity applications in the system, while the *Diversification* scenario makes greater use of hydrogen applications. In addition, a variant with technology-neutral production, which also considers natural gas-based hydrogen in addition to electricity-based hydrogen production, is studied. Together with analyses of possible import and export needs in eastern Germany, the hydrogen balances provide an indicative picture of future hydrogen transport needs.

A north-south imbalance in hydrogen demand emerges in eastern Germany

The *Electrification* scenario yields a hydrogen surplus of about 3 TWh in 2030 and a deficit of 2 TWh in 2045. In the case of *Diversification*, the hydrogen deficit is 2 TWh in 2030 and up to 54 TWh in 2045. Especially the northern regions emerge as production centers since they have high production potentials with low hydrogen demand from industry and transport. The South, especially the metropolitan areas of Leipzig and Berlin, become import regions, as they have low production potentials while facing high hydrogen demand from the industry, transport, and building sectors. In addition to balancing supply and demand, the future role of eastern Germany as an energy hub is a particular driver of the hydrogen infrastructure. Thus, in 2045, about 48 TWh of transits must be ensured in the *Diversification* scenario. In the *Electrification* scenario, on the other hand, hardly any transits are necessary. Alternatively, climate-neutral hydrogen can be produced from natural gas with subsequent capture of CO_2 emissions, which is a cost-effective option in direct cost comparison. By decoupling natural gas-based hydrogen production from volatile RE-generation, significant generation potentials can be created in eastern Germany, enabling the export of climate-neutral hydrogen to neighboring regions and providing additional back-up capacity to increase the security of hydrogen supply.

Regardless of hydrogen penetration, it makes sense to establish an initial hydrogen grid by 2030 — additional transport capacities will be needed by 2045

As a result, the initial hydrogen grid of the "Important Projects of Common European Interest" (IPCEI) covers a large part of the transport demand until 2030. The grid is extending mainly from north to south and is needed in both scenarios. In 2045, the indicative grids diverge more significantly. Especially in the *Diversification* scenario, additional capacities for hydrogen transport will be necessary. The scenario shows that additional north-south pipelines are repurposed to transport imports and domestic production from the North to industrial sites and metropolitan areas in the South, as well as to meet transit needs to southern Germany. In addition, interconnectors are being provided to the West and East to import hydrogen from northern and eastern European countries. If the production of climate-neutral hydrogen based on imported natural gas is considered, then there is an additional need for transport capacity to all neighboring regions, starting from the production sites on the Baltic Sea coast. Given the assumptions, both scenarios ensure that a possible peak load situation in the hydrogen infrastructure can be covered by existing cavern storage facilities and the import capacity. In the *Electrification* scenario, the required storage volume of 18 TWh exceeds the current hydrogen storage potential of 12 TWh. In the case of *Diversification*, the storage volume of 14 TWh is sufficient to cover the demand of 12 TWh.

High capital intensity and substantial time spans for construction require early focus on transport infrastructure

With the kick-off of the IPCEI, the foundation has thus been laid for providing sufficient infrastructure to supply eastern Germany with hydrogen in 2030. For a climate-neutral Germany in 2045 that relies on hydrogen as an energy carrier, further conversions are needed to meet import and transit requirements. Grid expansion is taking place in an environment of great uncertainty regarding the level of transportation demand and the ability to refinance the grids. At the same time, infrastructure investments are characterized by high capital intensity and long planning periods. To ensure the implementation of these long-term projects, a timely definition of an appropriate investment framework that provides greater certainty for players on the supply, demand and infrastructure sides is important for initiating the market ramp-up.

1 Introduction

Phasing out the use of fossil fuels is one of the greatest challenges the economy and the society is facing in the upcoming decades. In addition to the electrification of technologies and processes, the use of climate-neutral hydrogen[1] is seen as a solution to this problem. Hydrogen can be used in a variety of ways and enables long-term energy storage. Hydrogen can thus be an important element on the path to climate neutrality.

A prerequisite for decarbonization by means of hydrogen is a sufficient climate-neutral supply. Regionally, there are at times large differences with regard to the generation and consumption potentials of hydrogen. The supply is largely determined by the potential of renewable energy sources (RES) to produce electricity-based "green" hydrogen, by the geographical distance to potential export countries, and by the availability of pipeline connections to those export countries. High demands for hydrogen tend to be concentrated in industrial centers and metropolitan areas, which are characterized by high population density and high economic activity. Consequently, there is a spatial gap between production and consumption, which can be closed by building a hydrogen grid as the backbone of gas-based climate-neutral energy supply.

The eastern part of Germany with the federal states of Berlin, Brandenburg, Mecklenburg-Western Pomerania, Saxony, Saxony-Anhalt, and Thuringia is in the process of establishing a hydrogen economy. The existing natural gas transport grid in eastern Germany plays an important role in this, contributing significantly to meeting the current demand for natural gas throughout the entire country. In addition, the transport grid ensures the necessary transit capacities for natural gas from eastern to western and southern Europe and is strongly integrated into the European cross-border natural gas infrastructure.

The existing natural gas transport infrastructure in eastern Germany offers a high potential for the conversion of long-distance gas pipelines to supply a future hydrogen economy. Moreover, due to the connections to eastern and western Europe, eastern Germany can become an essential part of a transnational European hydrogen grid.

The aim of this study is to analyze the hydrogen market ramp-up until the planned achievement of climate neutrality for Germany in 2045, focusing on the investigation of a hydrogen transport infrastructure in the eastern German states with two scenarios. These scenarios differ in the assumed penetration of hydrogen in the conversion and end-use sectors in the examined reference years 2030 and 2045. Furthermore, for the scenario with high market penetration of hydrogen, an additional variant is analyzed, which assumes a technology-neutral production of hydrogen. Here,

[1] In this study, climate-neutral hydrogen is defined as hydrogen that releases none or very little CO_2 emissions during production. This includes green hydrogen from renewable energy, blue hydrogen from the reforming of fossil fuels with subsequent capture and utilization or long-term storage of CO_2 (Carbon Capture and Storage/Utilization (CCS/U)), and turquoise hydrogen produced from methane pyrolysis. Any residual CO_2 emissions are compensated accordingly to achieve climate-neutrality.

in parallel to the production of green hydrogen from RES, the natural gas-based production of blue and turquoise hydrogen is assumed.

The methodology follows a combined use of bottom-up and top-down analyses. These analyses are based on the long-term scenarios for the transformation of the energy system in Germany (Fraunhofer ISI et al., 2021) by distributing the calculated hydrogen quantities from production and demand in the respective reference years to the districts and large cities in eastern Germany. This top-down approach is supported by bottom-up calculations in specific demand areas of the industrial and transport sectors. In addition to the distribution of hydrogen production capacities according to RE potentials in the respective regions of eastern Germany, large-scale hydrogen projects of the "Important Projects of Common European Interest" (IPCEI), such as "doing hydrogen" (Gascade & Ontras, 2021), are considered. These projects map the development of the hydrogen market ramp-up in eastern Germany until 2030.

The spatially resolved hydrogen production and demand volumes per district or city form the baseline for identifying hydrogen surpluses and deficits. These results are used to evaluate the hydrogen infrastructure needs. Depending on regional hydrogen surpluses and deficits, import requirements, and potential hydrogen transit capacity needs, current natural gas pipelines can be identified that would be suitable for conversion to hydrogen. As a result, indicative hydrogen grid maps will be developed that represent a potential future hydrogen transport grid in eastern Germany.

2 Political strategies for the hydrogen market ramp-up

The political focus on the production and use of climate-neutral hydrogen is often defined by official hydrogen strategies issued by national or regional governments. At the federal level in Germany, the National Hydrogen Strategy (NHS) (BMWi, 2020) was published in June 2020. The goal of the strategy is, in the first phase, to foster the market ramp-up of a national green hydrogen economy by 2023. In the second phase, the focus is on the development of an international hydrogen infrastructure with the possibility of cross-border trade. The targeted electrolysis capacity of the NHS is 5 GW by 2030 and 10 GW by 2040 (BMWI, 2020).

In this study, the strategies of the eastern German states of Thuringia (TMUEN, 2021) Saxony-Anhalt (MULE, 2021), Saxony (SMEKUL, 2021) and Berlin-Brandenburg (MWAE, 2021) are considered. The strategies of the states of Saxony-Anhalt, Saxony and Brandenburg are moreover based on the “Joint Key Issues Paper of the Eastern German Coal States on the Development of a Regional Hydrogen Economy” (SMEKUL, MWAE & MULE, 2020) [in German]. The roadmap of the state of Mecklenburg-Western Pomerania is part of the North German Hydrogen Strategy (North-German States, 2019), along with the states of Bremen, Hamburg, Lower Saxony, and Schleswig-Holstein.

2.1 Thuringia

The Thuringian State Hydrogen Strategy (TMUEN, 2021) pursues a governance- and research-centered approach, accompanied by the plan to improve the legal framework at the federal level. The energy, transport, industry (esp. glass and ceramics) and agriculture sectors have been identified as potential application areas for hydrogen. The current consumption centers of these sectors are foreseen to act as early adopters for the utilization of climate-neutral hydrogen. To satisfy demand for green hydrogen in the initial phase, the strategy sets the goal of ensuring significant electrolysis capacity (TMUEN, 2021) by 2030.

Since Thuringia has little hydrogen-processing industry (e.g., chemical industry), both existing and expected medium-term hydrogen consumption is below the national average. Therefore, to generate additional demand for hydrogen (and its derivatives), the strategy plans the medium-term switch of Thuringia's public transport to fuel cells in rail transport and buses in urban and intercity transport.

The Thuringian hydrogen strategy acknowledges several possibilities for transporting hydrogen. In the short-term, for example, it is considered possible to inject hydrogen in natural gas transit pipelines (‘blending’). In the medium-term, there is also the possibility of connecting Thuringia to a national hydrogen grid through a conversion of unused natural gas transport pipelines.

2.2 Saxony-Anhalt

Saxony-Anhalt has the ambitious goal to become a hydrogen model region. Therefore, the hydrogen strategy for Saxony-Anhalt (MULE, 2021) focuses on governance and on the financial support of industrial and research projects and attempts to politically influence federal legislation to improve the legal framework. The transport, industry and power sectors have been identified as potential areas of application. In the power sector, a connected eastern German hydrogen economy, with Saxony-Anhalt as the center, is to be created through targeted funding measures and infrastructural expansion, starting from the central German lignite-mining area.

Thus, by 2030, an electrolysis capacity of 1 GW to produce 5 TWh of green hydrogen is planned to be created in spatial proximity to the existing consumption centers. To ensure climate-neutrality of hydrogen, the increase in electrolysis capacity will be accompanied by an increase in RES of at least 5 GW by 2030. The two elements are linked by expanding the existing hydrogen grids and integrating them into a national hydrogen infrastructure. The expansion of infrastructure and storage capacities will play an important role here. Starting from the Central German Chemical Triangle[2] and existing natural gas cavern storage facilities in Saxony-Anhalt, targeted measures are going to be taken to secure supply of hydrogen for large-scale consumers, on the one hand, and to bridge long-term seasonal fluctuations between production and demand, on the

[2] The Central German Chemical Triangle (Ger. “Mitteldeutsches Chemiedreck”) refers to the industrial region around Halle (Saale), Merseburg and Bitterfeld in Saxony-Anhalt and Leipzig in Saxony. Numerous large chemical and mineral oil processing industries are located here.

other hand. In the short-term, the state of Saxony-Anhalt is also considering blending hydrogen into natural gas networks to support the market ramp-up.

By 2040, the goal of Saxony-Anhalt is to meet hydrogen demand exclusively with green hydrogen at competitive prices. Furthermore, the resulting local hydrogen grid should be integrated in a transnational hydrogen pipeline grid to allow for imports as well. In the medium-term, the use of green hydrogen as a fuel in local public transport is intended to strengthen regional demand.

2.3 Mecklenburg-Western Pomerania

The hydrogen strategy of the state of Mecklenburg-Western Pomerania is part of the joint North German Hydrogen Strategy (North-German States, 2019) of the states of Bremen, Hamburg, Mecklenburg-Western Pomerania, Lower Saxony, and Schleswig-Holstein. The North German Hydrogen Strategy focuses on governance, financial support for hydrogen projects, and political influence at the federal level to improve the legal framework. The sectors of industry, energy and transport have a high priority. At the federal level, the states are striving for a transformation process toward a "level playing field" (North-German States, 2019) for climate-neutral energy sources. Furthermore, bureaucratic hurdles for hydrogen projects should be lowered through technology-neutral tendering for the production of hydrogen and by optimizing commissioning procedures.

The northern German states plan to install at least 500 MW of electrolysis capacity for green hydrogen by 2025 and at least 5 GW by 2030. Hydrogen clusters in the industry and transport sectors should be identified as early adopters, bundling production, distribution and use of hydrogen in the initial phase of the market ramp-up. In the long run, the strategy aims at integrating north Germany into the international hydrogen trade. It is expected that the future hydrogen demand in the regions will exceed the local electrolysis capacity, so that a part of the future demand will have to be covered by imports.

The northern German states are particularly suitable as centers to produce green hydrogen due to their high generation potential for onshore and offshore wind power. Furthermore, the geological conditions are also favorable for the underground storage of hydrogen, as a large part of Germany's cavern storage facilities are in the northern German states. For future hydrogen supply, the northern German states aim to repurpose the gas grid to hydrogen, primarily using the successively decommissioned low-calorific gas grid.

2.3 Saxony

The hydrogen strategy of the state of Saxony (SMEKUL, 2021) pursues two major goals. First, to establish hydrogen as a secondary energy carrier to enable sector coupling, and second, to develop a hydrogen economy along the entire value chain by 2030. Saxony aims to become a technology leader in electrolyser and fuel cell production, which is why the Saxon hydrogen strategy follows an industry- and research-centered approach. The industry-oriented approach manifests in the promotion of emerging industry branches and the support for the decarbonization of existing industrial processes by using hydrogen.

In order to establish a Saxon hydrogen transport infrastructure, the state government plans to connect existing hydrogen centers[3] in northern Saxony. Building on this, a gradual expansion of the hydrogen infrastructure is planned by converting existing gas pipelines (combined with new construction if necessary). In the medium- to long-term, however, it is essential to integrate Saxony into the national and European hydrogen grid, as the limited production and storage capacities of the state make imports from neighboring countries necessary. To facilitate these imports, the state of Saxony supports to establish the EEX energy exchange as a central trading platform for hydrogen and its derivatives.

The Saxon hydrogen strategy forecasts an annual hydrogen demand of 0.8 to 1.6 TWh in 2030. The electrolysis capacity required to cover this demand is estimated at 280 to 570 MW. It should be noted, however, that these figures are only projections and do not reflect capacity targets. In the medium-term, the hydrogen used should be produced exclusively by climate-neutral production technologies. In the short-term, however, the use of turquoise and blue hydrogen is also considered, in line with the legislative framework at the federal level.

2.4 Berlin-Brandenburg

The hydrogen strategy of the Berlin-Brandenburg capital region (MWAE, 2021) is based on a digital survey of stakeholders in the local hydrogen industry. Based on the survey and the evaluation of further studies, seven activities along the value chain are identified, for which a total of 62 measures are being developed. The strategy focuses in particular on the establishment of a digital H_2-marketplace that intends to coordinate local players, skills and synergies.

In addition to the industrial sector, hydrogen should be used in the mobility sector, for power generation and, to a certain extent, to provide heat in the building sector. In the medium to long-term hydrogen should be transported by a dedicated hydrogen grid. This is created by converting existing gas pipelines and, starting from connecting industrial clusters, is successively integrated into a European hydrogen infrastructure. In the short-term, blending of hydrogen into the natural gas grid should be further tested and increasingly used during the market ramp-up phase. To this end, measures are planned by distribution grid operators to increase the hydrogen blending limit to 20 percent by volume. Long-distance gas grid operators are already testing to blend hydrogen into the gas network at two feed-in stations. The state of Brandenburg is supporting these measures by funding of research projects on network expansion, conversion and gas separation.

[3] Hydrogen centers in Saxony are Leipzig, Chemnitz, Dresden, the county of Meißen, Freiberg, Lusatia and Görlitz.

The strategy projects a hydrogen demand in Berlin-Brandenburg of 22.5 TWh in 2040. Due to the limited availability of RES to produce green hydrogen, no potential for hydrogen exports from the region is anticipated. In the medium-term, only green hydrogen will be used in the region, but in the short-term turquoise and blue hydrogen can also play a role to balance demand and supply. In particular, methane pyrolysis is seen by the strategy as a way to produce hydrogen in a climate-neutral way.

2.5 Bordering federal states and countries

The development of the hydrogen infrastructure in the eastern German states is also dependent on the plans of the neighboring federal states and countries. In the following, the strategies of the western federal states, the Scandinavian countries in the North, as well as the European Union and of the countries Czech Republic and Poland are outlined. The focus is set on infrastructure development and the import strategies.

The plans for the development of a hydrogen transport infrastructure in the western German states are primarily focusing on the conversion of natural gas pipelines. The hydrogen strategy of the state of North Rhine-Westphalia, for example, assumes a distribution of 90 % repurposed and 10 % newly built pipelines in the final hydrogen grid (MWIDE NRW, 2020). The blending of hydrogen into natural gas pipelines is also considered as an option. In the long-term, all western states admit the necessity of hydrogen imports to cover the energy demand. The Netherlands and Norway are foremost being considered as trading partners. The southern German states also plan to import hydrogen within Germany from the northern states (MUKE BW, 2020; StmWi BY, 2020).

Out of the eastern countries of Poland and the Czech Republic, only the latter has published a comprehensive strategy to date. It states that both conversions and new constructions of gas pipelines are under consideration. The government expects blending to take place in the future, especially along the main natural gas transit routes. The Czech Republic plans to import hydrogen from the Mediterranean and northern European countries to meet domestic demand (Ministry of Industry and Trade of the Czech Republic, 2021).

Poland has presented ambitious plans for expanding its national hydrogen economy. Wind offshore and electrolysis capacities in particular should be expanded for production. As a result, a large part of the national energy demand is planned to be covered by self-production. The hydrogen should be transported by blending and via newly built pipelines (Polish Ministry of Climate and Environment, 2021).

The northern European countries Norway, Sweden and Finland only marginally consider the development of a large-scale hydrogen infrastructure in their strategies. Norway sees itself as a potential exporter of hydrogen and is pushing for market-driven natural gas-based generation (NMPE and NMCE, 2021). Finland does not plan to build the first hydrogen pipelines until 2030 (Business Finland, 2020), and Sweden has not published a strategy at the time of writing.

In the European Union's hydrogen strategy, blending of existing natural gas pipelines is perceived as the most cost-effective alternative to building a hydrogen infrastructure. Blending is seen as a way to strengthen decentralized production sites. To ensure that blending does not pose an obstacle to cross-border trade due to incompatibilities, the EU plans to define a comprehensive regulatory framework for this purpose. In addition to production within the EU, hydrogen imports from non-EU countries, such as north Africa, are also being considered (EU, 2020).

3 Scenarios

The analysis of hydrogen demand and production is based on two scenarios that assume different energy system developments. As shown in Figure 1, both paths take the achievement of climate neutrality by 2045 into account and are based on the primary reference Fraunhofer ISI et al., 2021 for assumptions and results. The study in this reference describes a pathway in which climate neutrality is achieved in 2050. Since this is a target scenario, the study results for the year 2050 are assumed to be equal with the target of climate neutrality in 2045. In the analysis of this study, the sector-specific assumptions and development paths of the energy system are taken from the primary source and distributed to the individual regions using a hybrid bottom-up and top-down approach. In addition, the results are supplemented by further analyses on current planned and operating hydrogen project.

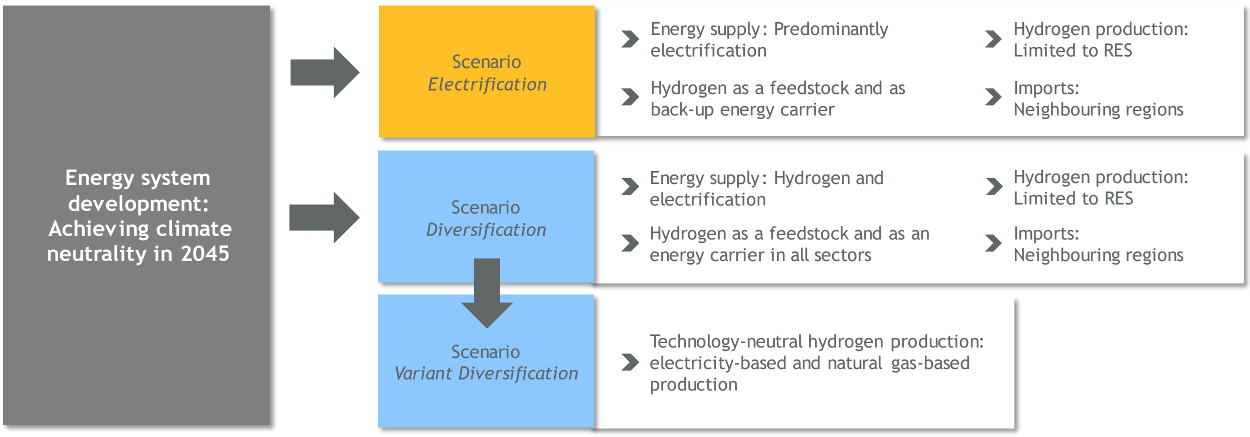


Figure 1: Overview of the defined scenarios

Source: Own illustration

The approach ensures a high level of consistency in the cross-sector results and at the same time maps the status quo of existing hydrogen project pipeline. In the following, both scenarios are outlined, and the most essential assumptions are presented. A detailed description of the numerical sector-specific assumptions is provided in chapter 4.

3.1 Electrification

The first scenario follows the approach of a predominant electrification of final energy consumption.[4] Hydrogen is mainly consumed by processes that cannot be technically electrified, such as the use of hydrogen as a feedstock in the chemical industry, mineral oil refineries or steel production. In smaller amounts, the gas is used to provide process heat. In addition, hydrogen is a form of energy storage for back-up power generation during periods when electricity generation from RES exceeds electricity demand. In the transport sector, hydrogen is used to a very limited extent. Hydrogen is not used in the building sector in this scenario.

Hydrogen is only produced from electricity-based RES, i.e., fossil-based processes such as natural gas reforming or pyrolysis are not considered. Imports originate from other European and neighboring countries. The provision of the necessary electricity generation, as well as determining the cost-efficient imports to eastern Germany, are part of the optimization of European electricity markets undertaken in the primary reference. Due to the currently emerging slower hydrogen market ramp-up in eastern Europe compared to northern and western countries, the assumption is made that imports from eastern regions will not be available in 2030.

3.2 Diversification

In the second scenario, the decarbonization of the power and the end-use sectors is realized by means of hydrogen in addition to electrification.[5] The approach has the advantage that the dependence on electricity as the dominant energy source can be reduced in peak load situations. Moreover, by repurposing natural gas pipelines and storage facilities, it is possible to utilize existing infrastructure with large storage and transport capacities. In addition to the use as a feedstock, the energetic use of hydrogen in the sectors is thus also being increased, leading to a significantly higher demand for hydrogen. In the industrial sector, this primarily concerns the use of hydrogen to provide process heat, as well as the heating of buildings with boilers. The transport sector is also experiencing greater penetration, with hydrogen being used in trains and buses in addition to cars, trucks, airplanes, and ships. In the energy system, hydrogen continues to be a pillar of seasonal energy storage and ensures back-up generation capacity in the power sector.

The assumptions for hydrogen production are analogous to the previous scenario. Hydrogen production and trade flows are optimized in electricity market modeling of the primary source and adopted in this analysis.

Due to an expected high hydrogen import demand in the *Diversification* scenario, another variant is considered that represents a technology-neutral production of climate-neutral hydrogen. The variant is based on the assumption that, in addition to electricity-based hydrogen production, natural gas-based production methods with carbon capture to supply hydrogen are also possible,

[4] Based on the scenario "TN Strom" in Fraunhofer ISI et al. (2021).
[5] Based on the scenario "TN-H2-G" in Fraunhofer ISI et al. (2021).

with the resulting CO_2 emissions either being stored underground (reforming of natural gas with storage or utilization of CO_2 emissions (CCS/U)) or stored in the form of solid carbon (natural gas pyrolysis). The natural gas required for this is primarily imported from Russia via the Nord Stream and Nord Stream 2 pipelines in eastern Germany, as it is expected that the supply option will also be available in the long-term at low cost with high security of supply. While in the previous two scenarios the results originate from a modeling and optimization of European electricity markets in the primary source, this variant is limited to the discussion of potentials and implications that a technology-neutral production could mean for the hydrogen infrastructure and supply.

4 Calculation of regional hydrogen balances

The aim of the methodology is to determine regional hydrogen balances, on which a suitable indicative hydrogen grid will be derived. For this purpose, a hybrid approach of a top-down allocation of the results from the primary source (Fraunhofer ISI et al., 2021), as well as bottom-up analyses is chosen. Using the primary reference has the advantage that energy demand and supply have been optimized and are therefore consistent. Figure 2 illustrates the methodology of the analysis.

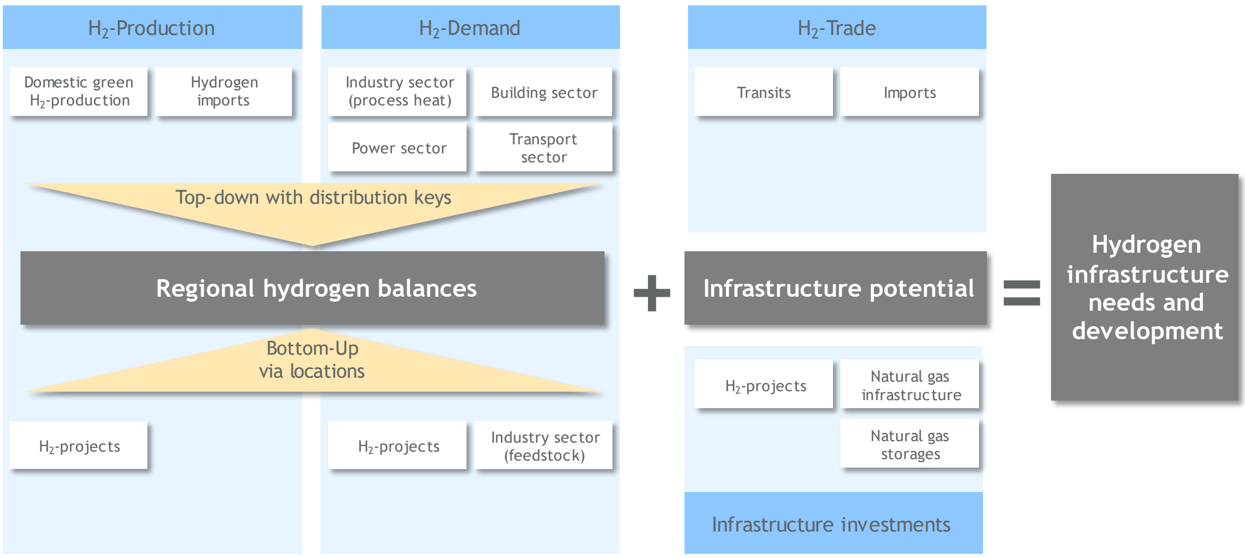


Figure 2: Overview of the calculation methodology

Source: Own illustration

Domestic hydrogen production and sectoral hydrogen demands of the primary source are allocated among regions using distribution keys. The use of hydrogen as a feedstock is derived using a bottom-up approach. Furthermore, recently announced projects for large-scale production and use of hydrogen are considered. The approach is explained in detail in the following sections.

4.1 Industry sector

The current demand for hydrogen in industry is estimated at around 55 TWh per year, mainly from the use as a feedstock in mineral oil refineries, ammonia production, and the chemical industry. Primary steel production will emerge as an additional large consumer in the future. Furthermore, hydrogen can replace today's fossil fuels (mainly coal and gas) in the provision of process heat, whereby the process heat can also be generated by electrification. Accordingly, the analysis of industrial hydrogen demand is performed separately for the use of hydrogen as a feedstock and as an energy carrier.

The assessment of feedstock hydrogen demand follows a bottom-up analysis in which historical production volumes are determined on a site-by-site basis for ammonia, methanol, and primary steel production plant locations, as well as for mineral oil refineries. For the projection of future hydrogen demand, assumptions are made regarding the development of production volumes, the penetration of climate-neutral hydrogen in the respective process, and the specific hydrogen demand per unit produced. The parameters are then used to calculate the future demand for climate-neutral hydrogen of the individual plants. The industry-specific assumptions are shown in Table 1. Since electrification is not an alternative to the material use of hydrogen, the assumptions for both scenarios are identical.

Table 1: Assumptions for the bottom-up analysis of feedstock hydrogen demand in industry

Source: Fraunhofer ISI et al. (2021), EWI (2021), own Assumptions

Industrial sector	Production development [% p.a.]	Specific hydrogen demand [TWh_{H2}/mio t]	Penetration of climate-neutral hydrogen [%]	
			2030	2045
Ammonia	-0.34	5.93	10	100
Mineral oil refineries	-1.00	0.13	10	100
Methanol	-0.49	6.64	10	100
Primary steel	-2.07	2.28	16	100

The provision of process heat in the industrial sector currently accounts for around 77 % of industrial energy demand (BMWi, 2021). A large part of this energy comes from fossil fuels, such as coal and natural gas. In the future, the energy demand for the generation of process heat can be covered either by electricity from RES or by climate-neutral produced hydrogen. Due to the high heterogeneity of the different processes, determining the energetic hydrogen demand of the industrial sectors is much more complex and can only be realized with a detailed bottom-up analysis of all sectors, temperature levels and plant specifics. For simplification, the energetic hydrogen demand is therefore distributed top-down to the regions. For this purpose, the energetic hydrogen demand of the whole industrial sector, determined in the primary source, is distributed over the CO_2 intensity of the plants included in the European Emissions Trading Scheme (EU ETS).

The approach implies that all CO_2 emissions outside of process emissions are attributable to the provision of process heat. The plant-specific share of emissions with respect to the total emissions of the industrial subsectors ferrous/non-ferrous metal processing, cement, glass, paper, ceramics, and ceramic products is used as the distribution key. The emission data are taken from the European Union Transaction Log (EUTL) of 2019.[6]

In addition to the top-down and bottom-up analysis of industrial hydrogen demand, projects under IPCEI Hydrogen are considered and added to the regional hydrogen balances (considered projects in Table A1 in Appendix **A.1**). This allows taking into account the status quo of market ramp-up in addition to the modeled cost-optimal development of the energy system based on the primary source.

4.2 Transport sector

The hydrogen demand in the transport sector is determined along the four modes of transport: road, rail, waterborne, and airborne. The total final energy demand for Germany is derived from the primary reference. The assumptions on the hydrogen penetration rate within the transport modes are based on dena (2021) (see Table 2). Finally, the hydrogen demand is distributed among the regions of eastern Germany based on the current regional breakdown of the respective transport modes.

Table 2: Assumptions on the penetration of climate-neutral hydrogen in the transport sector

Source: Fraunhofer ISI et al. (2021), dena (2021), Own Assumptions

Scenario	Year	Hydrogen penetration rate in %			
		Road	Rail	Waterborne	Airborne
Electrification	2030	0	0	0	0
	2045	10	0	5	8
Diversification	2030	0	0	0	0
	2045	49	5	5	8

The domestic hydrogen demand and the number of vehicles of a vehicle class (passenger cars, light commercial vehicles (LCV) and trucks) in road transport are taken from the primary source (Fraunhofer ISI et al., 2021). According to this, no additional hydrogen demand arises in road transport in 2030, whereupon 10 % of the final energy demand in the *Electrification* scenario and 49 % in the *Diversification* scenario are met with hydrogen in 2045. The distribution key is based on the vehicles registered with the Federal Motor Transport Authority in the two classes of cars

[6] Due to the global COVID-19 pandemic that broke out in early 2020 and the associated measures, 2020 is not suitable as a reference year. Therefore, 2019 is used as a representative year in the analysis.

and trucks within the individual regions (KBA, 2021). The share of Germany's hydrogen demand is calculated as the proportion of registered vehicles of a vehicle class within a region in reference to the total number of vehicles of this vehicle class. The weighting of the individual vehicle classes among each other takes place based on their average mileage per year and an expected average hydrogen consumption (Helgeson et al., 2020). Passenger car registrations are used as an approximation to distribute the demand for LCV vehicles. Regionalization based on registrations only indirectly reflects actual fuel consumption in the regions. For trucks in particular, fuel consumption could be more likely to occur at refueling stations along highways rather than in the region of registration.

In rail transport, hydrogen demand is determined for the scenarios based on the final energy demand from Fraunhofer ISI et al. (2021) using assumptions on hydrogen penetration (dena, 2021). In 2030, there is no hydrogen demand in rail transport, as routes on which trains previously ran on diesel are either electrified or the trains are converted to synthetic fuels. The same applies to the year 2045 in the *Electrification* scenario. Only in the year 2045 of the *Diversification* scenario the trains on the non-electrified lines are operated with hydrogen, such that 5 % of the final energy demand in rail transport is covered by hydrogen. The distribution key to the eastern German districts is determined from the ratio of the length of non-electrified lines in the districts and large cities and the total length of the German non-electrified line network (DB, 2021).

Waterborne transport still predominantly uses marine diesel in 2030, subsequently there is no hydrogen demand in any of the scenarios. Due to a lack of alternatives, hydrogen is used as a fuel in both inland and maritime shipping in 2045 in both scenarios. This accounts for 5 % of the total final energy demand, while the remaining demand is met by synthetic fuels or alternative fuels (e.g., methanol, ammonia). The distribution key of these hydrogen volumes is derived from historical freight movements of German inland and seaports (Eurostat, 2021a; Eurostat, 2021b). Among the most important eastern German seaports are Rostock and Sassnitz, and among the inland ports are Magdeburg and Berlin. The respective share of those ports in the export of goods in Germany is used as an approximation of the distribution of the hydrogen demand of inland or maritime shipping respectively. However, neither the length of the traveled routes nor passenger movements are considered, which can lead to deviations from the real distribution of fuel consumption.

Analogous to waterborne transport, no hydrogen demand arises in airborne transport in 2030. Only in 2045 hydrogen is used with 8 % of the final energy demand in both scenarios since synthetic fuels are the only fuel alternative according to the current state of knowledge. The distribution among the eastern German districts and major cities is based on air traffic data from German airports in 2019 (ADV, 2019). The share of the individual eastern German airports in the total hydrogen demand is calculated via the number of short-, medium-, and long-haul flights of the airports' passenger and cargo traffic. The share of an airport in the total German hydrogen consumption is calculated via the average route length and the fuel consumption of a traffic unit, i.e., 100 kg of freight or 1 passenger of 1.83 l of kerosene per traffic unit (BDL, 2020). The role of the new Berlin airport BER is not yet included in the historical data. The assumptions of its future traffic volume are based on current studies (BER, 2021). This does not consider reciprocal effects with the traffic volumes of the other eastern German airports, resulting in their hydrogen demand to be potentially overestimated.

4.3 Building sector

In the reference scenarios of the primary source, the building sector has no hydrogen demand in 2030. Only in the *Diversification* scenario the heat demand of the building sector is partially covered by hydrogen, resulting in the demand of 35 TWh in 2045. This hydrogen demand is distributed among the districts and large cities based on population, such that a higher hydrogen demand arises especially in large cities (Eurostat, 2021c). Population is a key determinant of heat demand, so using it to distribute hydrogen demand in the building sector is deemed sufficient. However, this does not consider the building and heating equipment stock, potentially leading to an over- or underestimation of the heat demand in eastern Germany or in individual regions.

The additional demand of the IPCEI in the building sector, i.e., the construction of a hydrogen CHP plant, is added to the hydrogen demand of the respective region and is thus included in the hydrogen balances.

4.4 Power sector

In the power sector, additional hydrogen demand can arise from the generation of electricity from hydrogen if, for example, electricity storage facilities are not sufficient to balance electricity consumption and generation from RES. In the scenarios, this is only the case in 2045, as natural gas is still used as a fuel in 2030. The hydrogen demand of the power sector is calculated from the electricity generation of hydrogen power plants taken from the primary source and distributed to eastern Germany. The conversion efficiency of hydrogen power plants is assumed to be 48 %.

For the distribution of the hydrogen demand quantities, the assumption is made that the hydrogen power plants are built at locations of today's gas power plants. Since these sites are equipped with the necessary peripheral facilities and are already located at the interface between the electricity and gas grids, they represent suitable locations for hydrogen power plants. The hydrogen demand is distributed based on the current installed capacity of the gas-fired power plants (BNetzA, 2021). Of the total 25 GW of installed gas-fired power plant capacity, around 3 GW is located in eastern Germany.

4.5 Production

The hydrogen demand is complemented by domestic production of green hydrogen in Fraunhofer ISI et al. (2021). In the *Electrification* scenario, production amounts to about 0.2 TWh in 2030 and about 36 TWh in 2045, while in the *Diversification* scenario it amounts to 0.4 TWh in 2030 and 62 TWh in 2045. This hydrogen production for Germany is distributed among the eastern German districts and large cities based on the RES potentials (FfE, 2020). The RES potentials consider onshore wind power, rooftop photovoltaics, and ground-mounted photovoltaics potentials. The distribution is based on the energy output potential. However, no dispatch optimization is performed, so this distribution serves only as an approximation of actual hydrogen production.

Moreover, the hydrogen production capacities of IPCEI are utilized to distribute the hydrogen quantities. The output capacities of the projects currently in planning already exceed the projected hydrogen volumes of both scenarios for 2030. Therefore, only the generation volumes of the IPCEI are considered for 2030 and distributed to the districts and major cities based on the project locations.[7]

The following assumptions are made for the *Diversification* scenario variant, which assumes technology-neutral production: In 2030, a maximum of 50 % of the annual natural gas import capacity of the Nord Stream Pipeline (corresponding to 27.5 bcm/a) is used for the production of hydrogen, with a maximum of 75 % of this being used to produce hydrogen. In 2050, the full import capacity (corresponding to 55 bcm/a) can be used to produce climate-neutral hydrogen. Residual capacities, especially of the Nord Stream 2 pipeline, can be used, for example, to import and redistribute natural gas to other countries to produce climate-neutral hydrogen. The conversion efficiency of natural gas to hydrogen is assumed to be 60 % (based on the lower heating value).

4.6 Infrastructure

For the development of a hydrogen infrastructure, conversion of existing natural gas pipelines is an option since their utilization rate will be reduced in the long-term due to the decline in the use of fossil fuels. Establishing a suitable hydrogen infrastructure requires, in addition to a reliable forecast of hydrogen supply and demand, detailed information on the natural gas network, natural gas demand and the temporal profile of all parameters mentioned. Since such high-resolution data are difficult to determine at the present time, a heuristic approach is chosen for the estimation of a future hydrogen grid in eastern Germany. The approach intends to provide an initial indication of the long-term use of existing natural gas pipelines. For this purpose, capacity, and topology information on the existing natural gas network in eastern Germany is researched and obtained from existing sources (EWI internal gas network database; Kunz et al., 2017). For the calculation of the annual hydrogen transport capacity based on today's natural gas transport capacities, the simplifying assumption is made that hydrogen pipelines in 2030 will initially only be operated at a maximum pressure of 30 bar, which corresponds to the output pressure of commercially available electrolysers. In the long-term, the pressure of hydrogen transport pipelines will be increased by the installation of compressors, so that a higher energy quantity can be transported, which is assumed to be up to 75 % of the current transport capacity (in terms of energy) of natural gas pipelines.

[7] Import flows and transit requirements are taken from Fraunhofer et al. (2021). Due to the consideration of IPCEI Hydrogen, there are deviations from the import requirements determined in the primary source. Therefore, the import and transit flows of the primary source are scaled to the analysis results of this study.

To determine a hydrogen infrastructure, sources and sinks are connected using existing natural gas pipelines, considering hydrogen import points and transit needs, in such a way that imbalances can be resolved while maintaining natural gas transport via major transit pipelines in 2030. New construction of hydrogen pipelines is only considered in exceptional cases. An initial hydrogen grid is derived for the year 2030 from the planned IPCEI, which serves as a basis across both scenarios as well as the variant in the *Diversification* scenario.

For the conversion of today's natural gas storage facilities into future hydrogen storages, cavern storage sites in eastern Germany are considered, as pore storages are hardly suitable for storing hydrogen according to the current state of knowledge. For the withdrawal capacity of repurposed cavern storages, the assumption is made that the withdrawal capacity of hydrogen caverns is 70 % of today's natural gas withdrawal capacity. Per assumption, the storage capacity of repurposed cavern storage is 33 % of the existing natural gas storage capacity (own assumption based on INES (2021)). The hydrogen storage demand is taken from the primary source and scaled according to the share of eastern German cavern storages in the total German cavern storage capacity.[8]

5 Results

In the following chapter, the results from the analyses are presented and discussed. First, the total balance of hydrogen demand, production and imports of eastern Germany is introduced per sector and for the two scenarios. Then, the spatial distribution of the balances among the individual rural and urban districts is presented, which provides direct information about the need for infrastructure. Proposals for a possible hydrogen grid in the individual years and scenarios are provided in the following chapter, and an exemplary capacity balance for a peak load situation in 2045 is analyzed. In the last part, a variation of the production side in the scenario *Diversification* is carried out, which considers a technology-neutral production of climate-neutral hydrogen. For this, the implications on the hydrogen grid, imports and possible transits are shown and discussed.

5.1 Hydrogen balance

Figure 3 below illustrates the overall results of the calculated hydrogen volumes from production and demand within the *Electrification* and *Diversification* scenarios for the years 2030 and 2045.[9]

[8] Data source for cavern storage: GIE (2021).

[9] See also Table **A.2** in Appendix A.2.

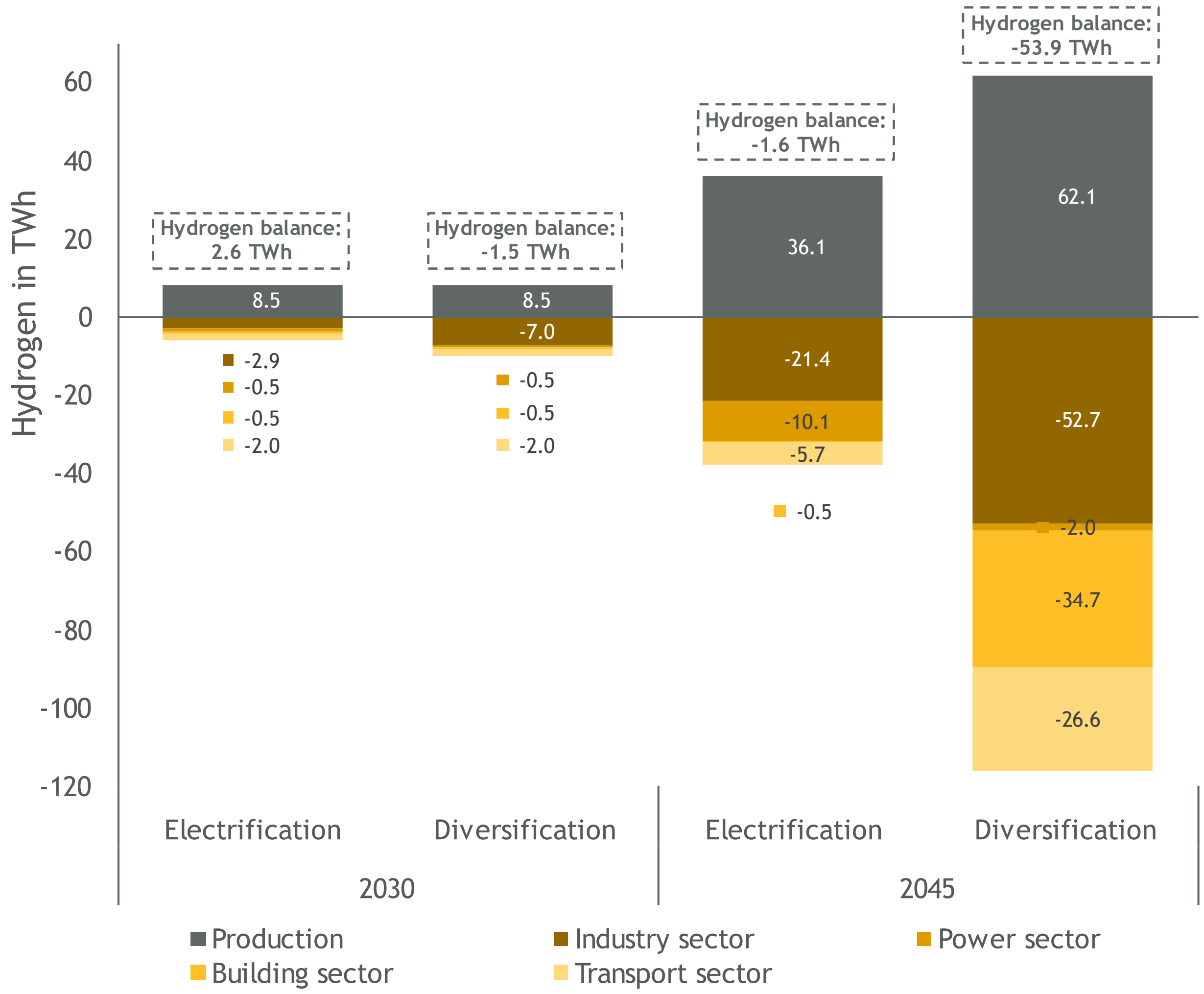


Figure 3: Sectoral hydrogen demand in the *Electrification* and *Diversification* scenarios for the years 2030 and 2045

Source: Own illustration

In both scenarios, significant hydrogen demand is already expected in 2030, almost entirely attributable to the industrial sector. Planned IPCEI Hydrogen projects, such as "doing hydrogen", also create demand in other sectors. Due to high planned electrolysis capacities in the projects, eastern Germany can almost cover its demand in 2030 in the *Diversification* scenario. In the *Electrification* scenario, exports of slightly less than 3 TWh are possible, given that all assumed projects are realized. By 2045, a significant increase in hydrogen demand is expected in all sectors, except for the building sector in the *Electrification* scenario. The highest hydrogen demand arises in the industrial sector in both scenarios (21 TWh and 53 TWh, respectively). The difference in demand is thereby entirely attributable to the increased use of hydrogen for providing process heat in the *Diversification* scenario. The remaining hydrogen demand in the industrial sector is from feedstock demand and therefore not substitutable by electrification. In the transport sector, the annual hydrogen demand is just under 6 TWh and 27 TWh, respectively. The discrepancy results mainly from heavy-duty transport. In the power sector, hydrogen-fueled power plants fulfill an important back-up function. The resulting demand is 10 TWh in the

Electrification scenario and 2 TWh in the *Diversification* scenario. In the *Electrification* scenario, the balance of demand and production in eastern Germany is almost even, while imports of 54 TWh are necessary in the *Diversification* scenario. These mainly come from northern and eastern Europe as well as the Baltic States (Fraunhofer ISI et al., 2021).

5.2 Regional distribution

The results of the hydrogen balances in the *Electrification* and *Diversification* scenarios for 2030 and 2045 are broken down regionally and visualized in map visualizations for all 77 districts and large cities in eastern Germany, as shown in Figure 4. The regions are colored depending on the result of the calculated hydrogen quantities. Regions with a production surplus are colored blue, while regions with a production deficit are shown in red. White colored regions indicate (nearly) balanced districts and large cities (deviation of supply and demand below 0.1 TWh). Furthermore, the maps show locations of energy-intensive industries of ammonia, glass, methanol, paper, steel, cement production, and mineral oil refineries.

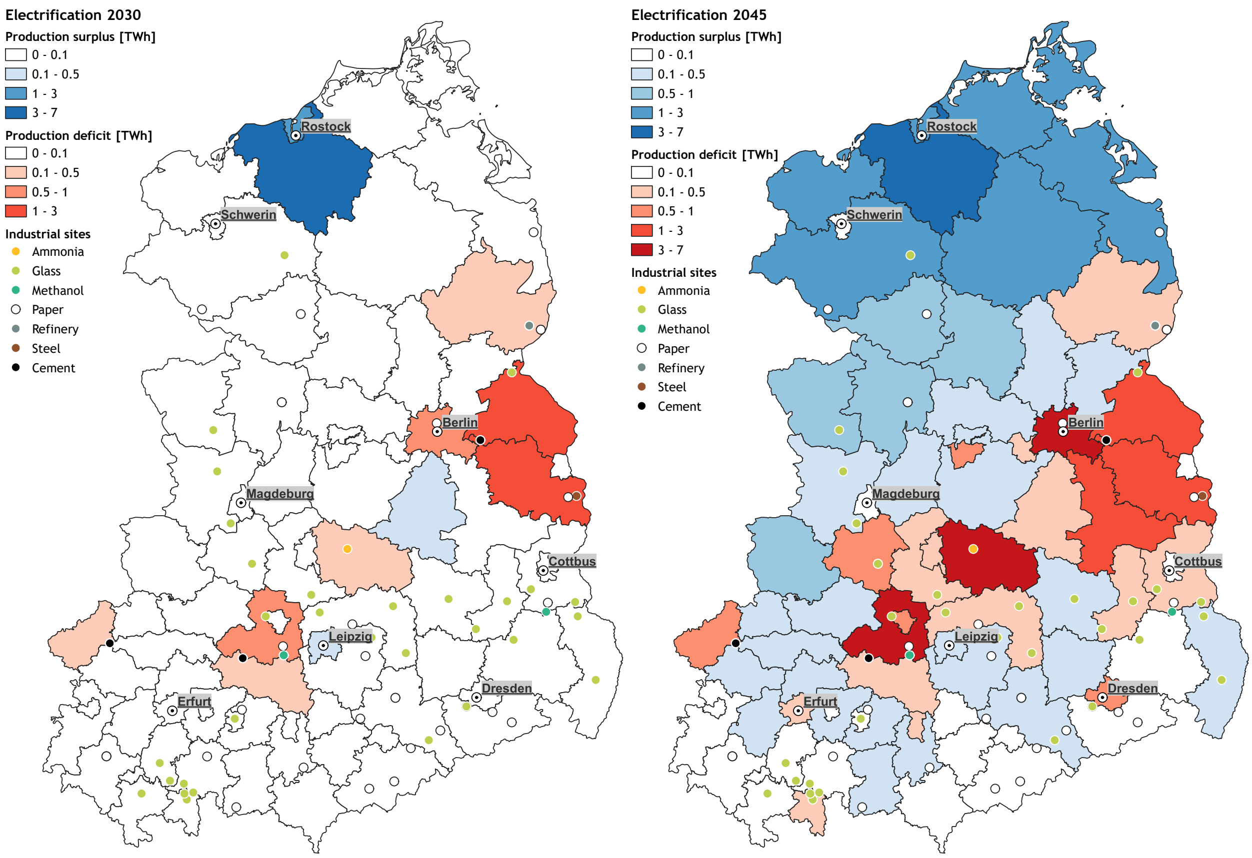


Figure 4: Hydrogen balances in the *Electrification* scenario for 2030 (left) and 2045 (right)

Source: Own illustration

In the *Electrification* scenario, the total hydrogen demand in 2030 is about 6 TWh, which is mainly driven by large-scale projects of industrial companies in the Berlin area and in the Central German

Chemical Triangle. This is complemented by a total hydrogen production of about 9 TWh. Due to favorable RES potentials, production is concentrated in the North of eastern Germany (Mecklenburg-Western Pomerania) and close to consumption at industrial sites in the Central German Chemical Triangle. In balance, this scenario results in a hydrogen surplus of almost 3 TWh for eastern Germany. The region would thus become a net exporter of hydrogen in 2030. Spatially, this results in districts and large cities with production surpluses and deficits. The districts with the largest production surpluses are the district of Rostock (5 TWh) and the adjacent city of the same name (2 TWh), as there is hardly any demand for hydrogen in 2030 and at the same time a total production of 8 TWh results from IPCEI Hydrogen projects. In contrast, districts such as Märkisch-Oderland (2 TWh) and Oder-Spree (1 TWh) have the largest production deficits. In these regions significantly higher hydrogen demand arises than can be produced within the districts due to projects such as "doing hydrogen - CEMEX Rüdersdorf" and "DRIBE2 - Arcelor Mittal Eisenhüttenstadt". The balance map shows that, due to surpluses in the North and deficits in the Center and South of eastern Germany, there tends to be a north-south imbalance.

For the same scenario in 2045, the associated balance map on the right-hand side of Figure 4 shows a significant change in eastern Germany. Total hydrogen demand increases substantially to 38 TWh between 2030 and 2045 due to significantly higher demand from the industrial, power and transport sectors. Total hydrogen production also increases significantly, reaching 36 TWh by 2045. The resulting hydrogen balance results in an import demand of about 2 TWh in the *Electrification* scenario in 2045. Imports originate to a large extent from the Baltic States, northern and eastern Europe, with transit demand to other regions being very low at around 1 TWh. Due to the hardly changed demand for hydrogen until 2045, the region of Rostock still has the largest production surplus with 5 TWh. In addition, the neighboring district Mecklenburgische Seenplatte has the second largest production surplus (2 TWh) due to high hydrogen production without significant demand. In 2045, the significant increase in demand creates the largest production deficit in the district of Saale (-5 TWh), driven by methanol production (4 TWh) and mineral oil processing (1 TWh). The district of Wittenberg has the second largest production deficit (-5 TWh), which is largely due to ammonia production (almost 6 TWh) in the industrial sector. Likewise, Berlin has a significant production deficit of -4 TWh, which is mainly due to the increased use of hydrogen in the power and transport sectors. Due to production surpluses in the North and production deficits in the Center and South of eastern Germany, the geographical separation between production and demand remains and the north-south imbalance is reinforced.

The *Diversification* scenario in 2030 has a total hydrogen demand of 10 TWh, almost 70 % higher than the *Electrification* scenario (see Figure 5). The increase is mainly due to the stronger use of hydrogen to generate process heat (4 TWh) in the industry. This is met by an unchanged total hydrogen production of 9 TWh. Due to the identical production capacities and locations in the two scenarios for 2030, the spatial concentration of production remains unchanged compared to the *Electrification* scenario. As a result, eastern Germany imports just under 2 TWh of hydrogen from other regions in 2030 in this scenario. Imports initially come from northern Europe (about 2 TWh) and reach eastern Germany via the Northwest. In addition, via a terminal in the port of Rostock (see chapter 5.3), there is the possibility of imports from overseas that can be injected directly into the hydrogen grid to be established there. Pipeline imports from other regions are considered to be not very realistic in 2030, since either long-distance pipelines (e.g., north Africa) must be built or repurposed, or the exporting countries must first push ahead with decarbonization of their national energy system (e.g., eastern European countries). The balance map in Figure 5 shows that those districts with the largest production surpluses remain unchanged in the *Diversification* scenario compared to the *Electrification* scenario. On the production deficit side, the significant increase in demand for hydrogen indicates that more districts and cities face production deficits. The largest production deficit continues to be the Märkisch-Oderland district, which increases to approximately 3 TWh due to greater use of hydrogen-based process heat. The formation of a north-south imbalance can also be seen here.

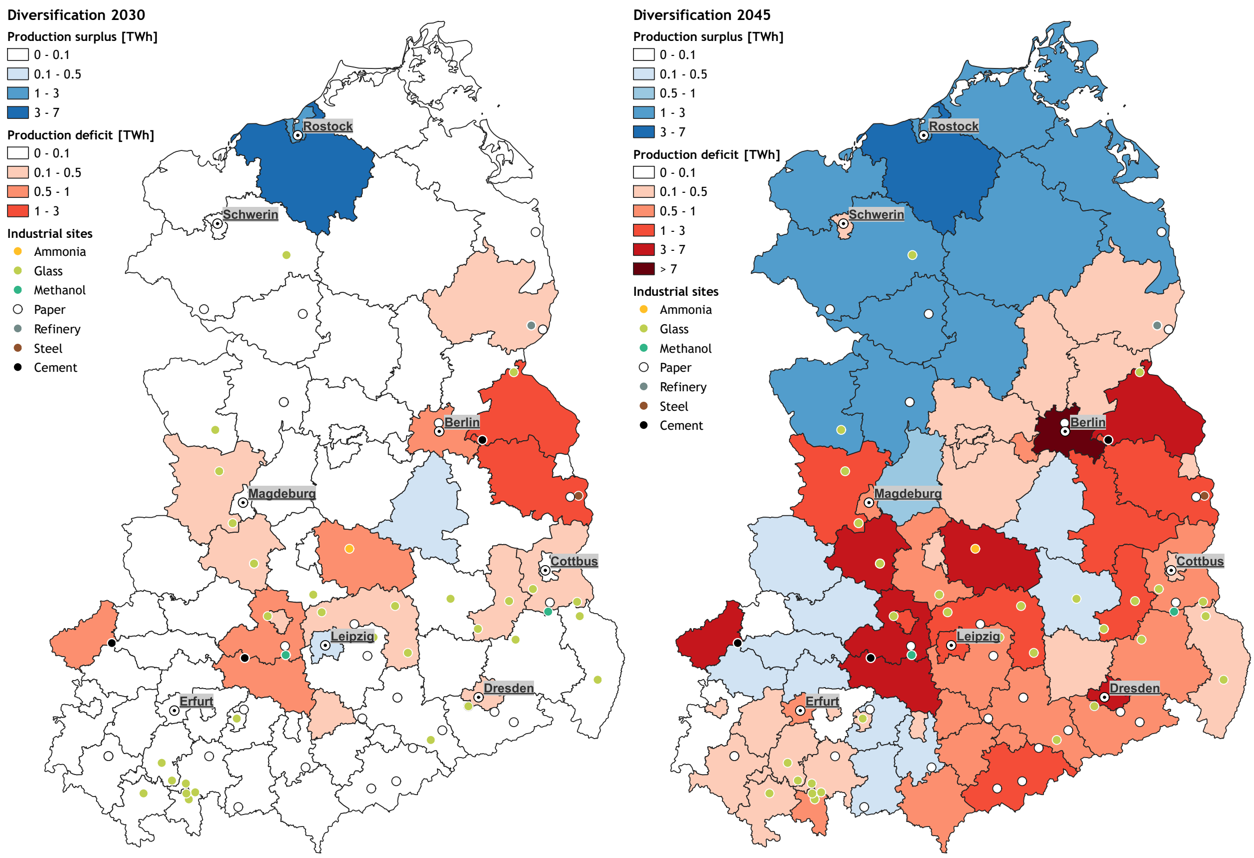


Figure 5: Hydrogen balances in the *Diversification* scenario for 2030 (left) and 2045 (right)

Source: Own illustration

In 2045, the balance map on the right-hand side of Figure 5 shows a significant increase in regions with production surpluses and deficits in eastern Germany. Total hydrogen demand increases by 106 TWh between 2030 and 2045, reaching a total of 116 TWh. Higher demand in the industrial, building and transport sectors are especially responsible for the increase. By contrast, demand in the power sector grows only very slightly (1 TWh) by 2045. At the same time, total hydrogen production rises notably by around 54 TWh, reaching up to 62 TWh by 2045. The production is mainly located in the North of eastern Germany. The resulting hydrogen balance in the *Diversification* scenario for the year 2045 is negative with a significant production deficit of

54 TWh in total. In this scenario, eastern Germany is thus dependent on significant imports of hydrogen and can only cover 54 % of its own demand through local production. The import flows are taken from the primary source (Fraunhofer ISI et al., 2021) and originate about 30 % from northern Europe and 70 % from eastern Europe and the Baltic states.

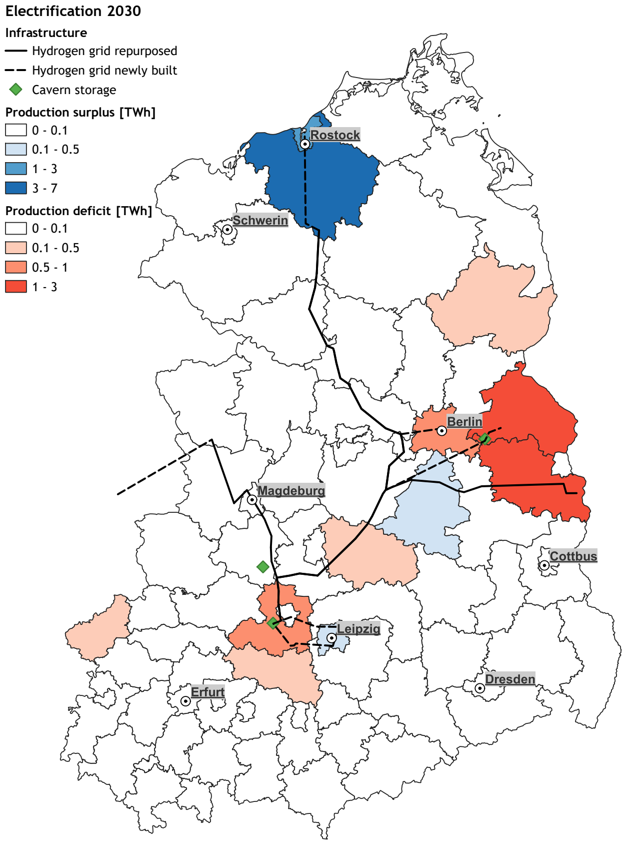
Furthermore, significant transits through eastern to southern Germany are necessary, amounting to up to 55 TWh in 2045. The districts and cities with the largest production surpluses in 2045 remain unchanged compared to the *Electrification* scenario. The Rostock district results in the largest production surplus (4 TWh). This decreases slightly compared to the *Electrification* scenario, since here, in addition to constant production of 5 TWh, demand in the building and transport sectors increases to about 1 TWh. In the Mecklenburgische Seenplatte district, the second largest production surplus remains at 3 TWh. The largest production deficit is found in Berlin (-12 TWh), resulting largely from increased hydrogen demand in the building sector (8 TWh) and the transport sector (4 TWh) in combination with low production (1 TWh). Other large production deficits occur in the Märkisch-Oderland and Eichsfeld districts (both -6 TWh) due to high demand for hydrogen to provide process heat (7 and 6 TWh, respectively).

5.3 Infrastructure

Based on the results of the regional hydrogen balances and considering the need for hydrogen transits, a hydrogen grid is derived that connects sources with sinks and is largely developed by repurposed natural gas pipelines. The grid maps thereby correspond to a first indication for the discussion of a hydrogen infrastructure in eastern Germany. Both scenarios build on the initially planned IPCEI Hydrogen network in 2030.

The maps in Figure 6 illustrate a possible hydrogen grid expansion in 2030 and 2045 in the *Electrification* scenario. In addition, natural gas cavern storages are shown that lie spatially close to the proposed hydrogen grid and serve as the basis for the storage potential analysis in the later part of this chapter. The proposed hydrogen grid in 2030 is largely based on the planned initial hydrogen grid in the IPCEI. It connects the region around Rostock with the consumption centers of Berlin, adjacent regions, and the Central German Chemical Triangle. Moreover, there is an interconnector between the eastern German grid and the planned grid expansions in the western German states.

In 2045, few additional repurposed pipelines are necessary, as demand is mainly driven by large industrial consumers whose clusters have already been connected in the initial phase. Expansions in the North of eastern Germany will allow additional producer regions to be connected. In addition, imports from other regions, as well as transits to western Germany, will be necessary in 2045. To enable these, pipeline repurposing in the direction of the Czech Republic in the southeast (imports: < 1 TWh), as well as in the direction of western Germany (transits: < 1 TWh) are possible. Thus, more natural gas cavern storages can be repurposed to store hydrogen.



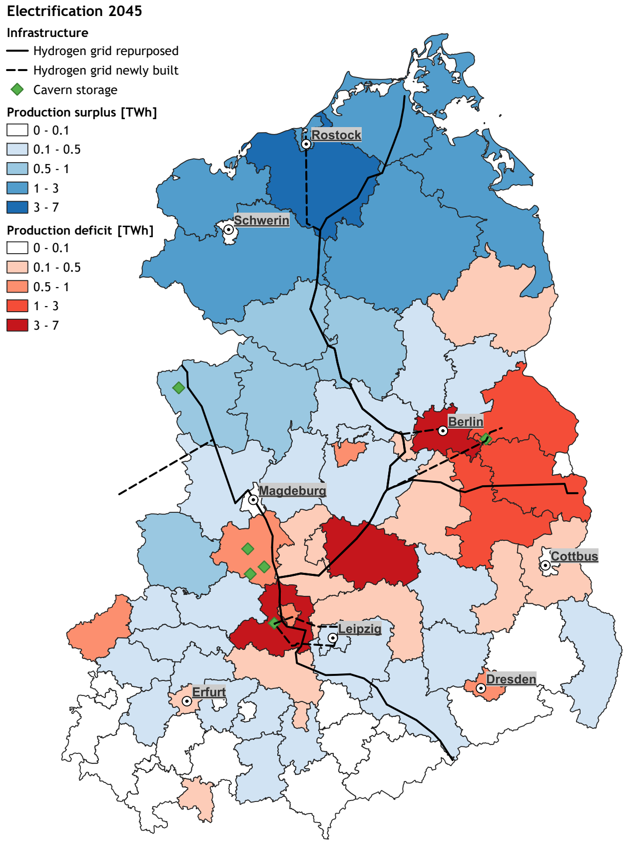


Figure 6: Potential hydrogen grid in the *Electrification* scenario for 2030 (left) and 2045 (right)

Source: Own illustration

In 2030, the proposed hydrogen grid in the *Diversification* scenario is identical to the previous scenario, as shown in Figure 7. The interconnector to western Germany is more important in the *Diversification* scenario because eastern Germany relies on imports of about 2 TWh. The higher hydrogen demand in the *Diversification* scenario has a significant impact on the proposed hydrogen grid in 2045. Due to large imbalances between coastal and inland regions, north-south connections gain importance, leading to further repurposing of pipelines.

In this scenario, eastern Germany imports about 30 TWh of hydrogen from northern Europe, which can be routed through connections in the Northwest and central Germany. Further imports originate from eastern European countries and the Baltic states in the amount of about 73 TWh, which by assumption are fed into the eastern German grid via repurposing cross-border pipelines located in the East of Berlin near Mallnow. Furthermore, transits of around 48 TWh to southern Germany are necessary. Here, it was assumed that the transits would be routed via the southeastern border with the Czech Republic and from there back to Germany. Alternatively, it would be possible to repurpose natural gas pipelines that run directly to southern Germany via Thuringia. The proposed hydrogen grid for 2045 connects the major sources, sinks, and import points. There are other lower imbalances in some regions that are not directly connected to the hydrogen grid. The extent to which these smaller imbalances can be addressed by alternative measures, such as decentralized production or use of alternative technologies, is not part of this study. Nevertheless, it is possible that further pipelines repurposing and new constructions may be required.

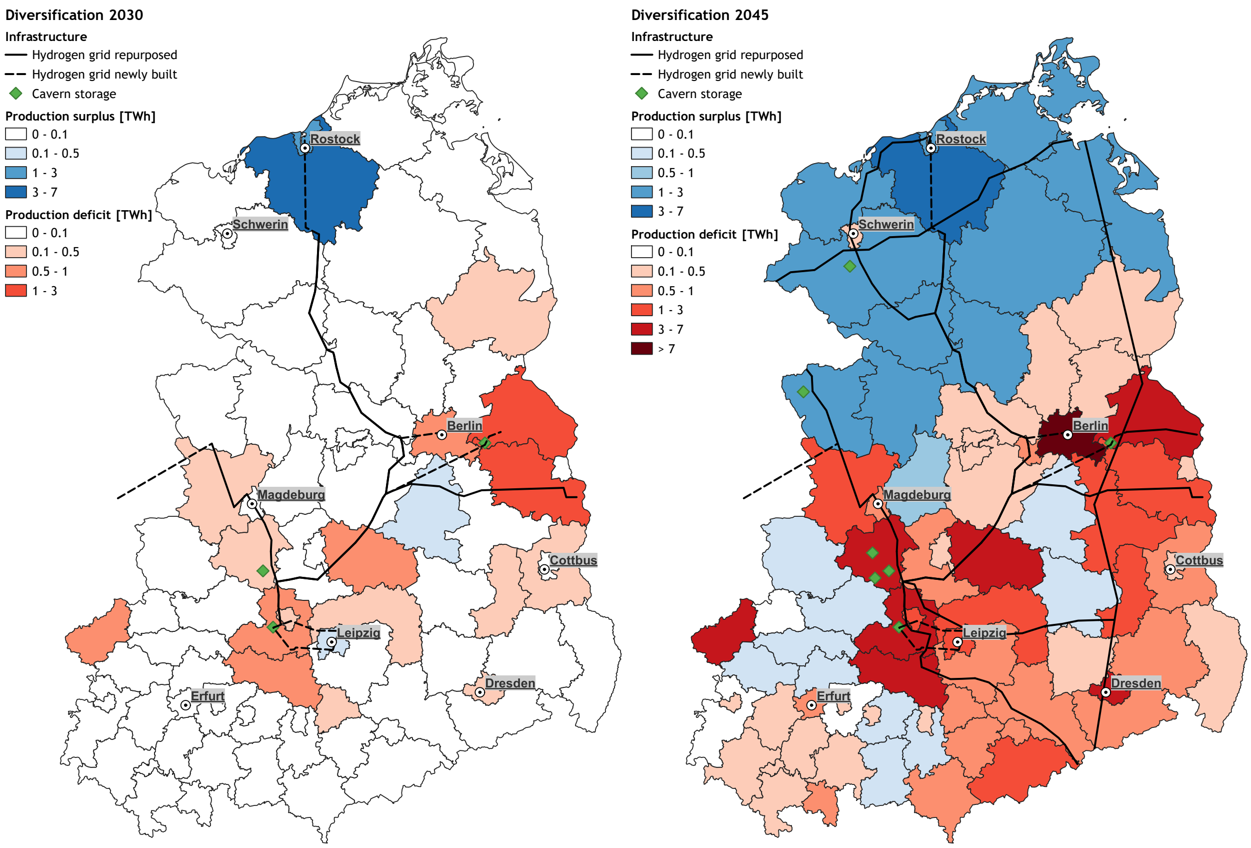


Figure 7: Potential hydrogen grid in the *Diversification* scenario for 2030 (left) and 2045 (right)

Source: Own illustration

A key driver in the sizing and layout of a hydrogen grid, in addition to regional balances and the existing natural gas grid, is the need for transits and the source of imports. In the *Electrification* and *Diversification* scenarios, transits and import sources were taken from the primary source. Thus, in 2045, transits are less than 1 TWh to western Germany (*Electrification*) and up to 48 TWh to southern Germany (*Diversification*). Imports are mainly from northern and eastern Europe and the Baltic states. For the import points, assumptions were made regarding pipeline connections, with northern European imports being routed to the eastern German states via northwestern Germany and eastern European or Baltic imports being fed into the grid via the Mallnow interconnection (East of Berlin). Especially in the *Diversification* scenario, large import and transit capacities need to be created to integrate the eastern German grid into a European hydrogen infrastructure. The eastern German gas grid has large transit capacities in both north-south and east-west directions, which can be repurposed if needed. At the same time, assumptions about import sources, volume and cost potentials, and feed-in points into the eastern German hydrogen grid are subject to uncertainties and have a strong influence on the development of the hydrogen grid. Therefore, further analyses as well as cross-border planning of the hydrogen market ramp-up are useful for an efficient network expansion.

5.4 Storage

Along the proposed pipelines for the different years and scenarios, there are various natural gas cavern storages that can be repurposed for hydrogen storage. The hydrogen storage demand in Germany is derived from the energy system optimization in the primary source. The storage demand is scaled to the region of eastern Germany and compared with the storage potential via repurposing existing natural gas storages. The storage potential (including withdrawal capacity) is derived from the natural gas cavern storages located close to the hydrogen grid. The results are shown in Table 3.[10]

Table 3: Results of hydrogen storage demand and potential in eastern Germany

Source: Fraunhofer ISI et al. (2021), GIE (2021), Own calculations

Scenario	Year	Storage demand in eastern Germany [TWh]	Storage potential in eastern Germany [TWh]	Potential withdrawal capacity in eastern Germany [GW]
Electrification	2030	0	8	15
	2045	18	12	35
Diversification	2030	0	8	15
	2045	12	14	38

By repurposing all existing natural gas cavern storages, the necessary storage demand of 12 TWh can be achieved in the *Diversification* scenario, which has a potential of 14 TWh. In the *Electrification* scenario, the storage potential is slightly lower, since the Kraak natural gas cavern is located far away from the proposed hydrogen grid and is therefore not repurposed. The storage demand of 18 TWh thus exceeds the potential from repurposing existing cavern storages by 6 TWh. Even with additional connection of the Kraak storage, the potentials are not sufficient to fully cover the storage demand.

In addition to the total storage volume, the potential of withdrawal capacity is important in evaluating a future hydrogen infrastructure, as it plays a central role in the provision of security of supply. Particularly in times of low RES feed-in simultaneous with high electricity demand, hydrogen-fueled peak load power plants are needed, and their load requirements must be covered by the hydrogen infrastructure. To estimate the load demand and potential of the infrastructure,

[10] It is assumed that in 2030, the cavern storage facilities in Rüdersdorf, Bad Lauchstädt and Bernburg can be repurposed in both scenarios. In the *Electrification* scenario, the cavern storages in Peckensen, Peißen and Staßfurt are also repurposed in 2045, while the Kraak storage facility is additionally included in the *Diversification* scenario.

an exemplary peak load situation of one hour is presented below.[11] Figure 8 illustrates the load balance of such a situation. The representation corresponds to an indicative and exemplary situation, derived from the results on sectoral hydrogen demand, imports, transits and storage potentials.

In the *Electrification* scenario, the load demand comes almost entirely from the power sector, as the hydrogen-fueled power plants fulfill an important back-up function (Fraunhofer ISI et al., 2021). The infrastructure capacity is almost entirely provided by storage withdrawal, as only low import capacities are available in this scenario. In the *Diversification* scenario, the power sector has the second highest load demand after the building sector. In addition, transits require a significant amount of capacity. Approximately 40 % of the back-up capacity is provided by the available import capacity and 60 % from storage withdrawal capacity. Both scenarios show that the peak load of the hydrogen infrastructure can be met by imports and storage withdrawal.

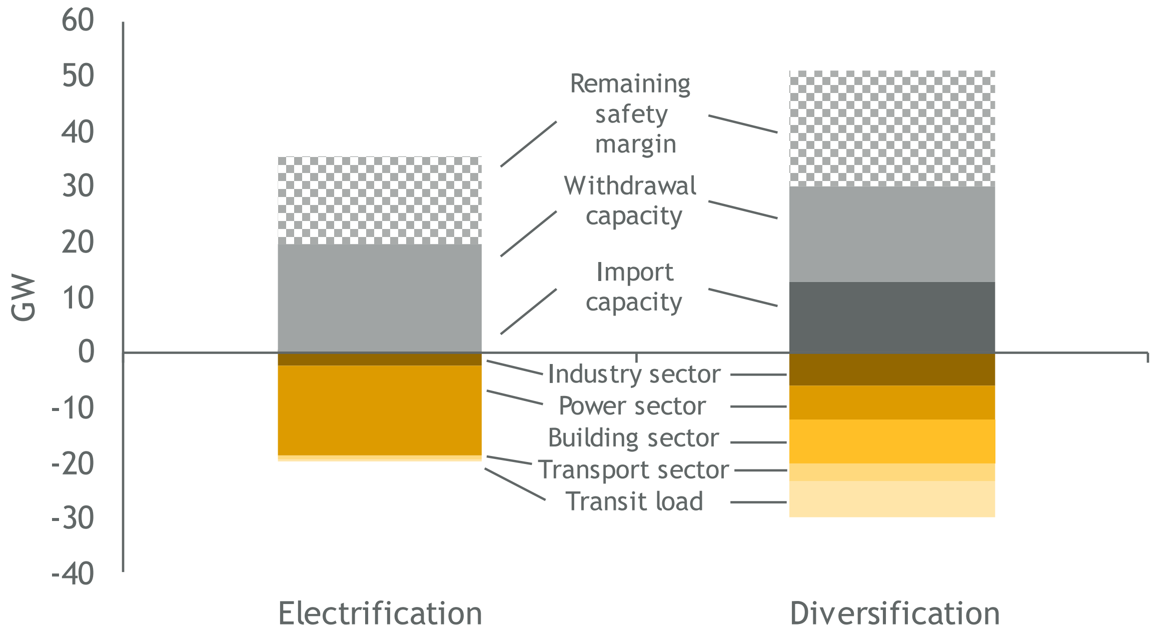


Figure 8: Examplary load balance in the peak load case in 2045

Source: Own illustration

The back-up capacity exceeds the load demand, such that a safety margin remains regarding the withdrawal capacity (shaded area). A prerequisite for this, however, is that sufficiently large quantities of hydrogen have previously been injected into the storages. At the same time, the analysis assumes that transits do not increase in such a situation. However, since transits in the *Diversification* scenario are directed particularly to southern Germany, it is conceivable that the load demand of the neighboring region increases at the same time, thus increasing the transit demand. Since southern Germany does not have any cavern storage capacities, the entire load

[11] Assumptions for the consideration of a peak load situation: no domestic hydrogen production; import pipelines, transits, and industrial sector supply/procure with constant load over the whole year; hydrogen-fueled gas-fired power plants are fully utilized in this hour; the load of the building sector corresponds to the constant load with respect to half a year.

demand of the region would have to be covered by imports and transits, such as from eastern Germany.[12]

5.5 Variant of Diversification with technology-neutral production

Following the results of the primary source, the previous analyses of the hydrogen balances and infrastructure needs considered only the production of electricity-based green hydrogen. In order to increase the production potential, the use of other production technologies besides water electrolysis is conceivable. In particular, reforming of natural gas and methane pyrolysis could be used. When fossil natural gas is used, climate-neutral hydrogen can be produced with both processes if CO_2 emissions or solid carbon are stored underground or used for other purposes so that a return to the carbon cycle is prevented. The technologies have the advantage of being scalable, less dependent on power supply, and thus less dependent on volatile RES feed-in. Thus, in addition to increasing the production potential of carbon-neutral hydrogen, natural gas-based hydrogen production can also contribute to security of supply by providing back-up capacities in the hydrogen supply even during peak load situations.

The production costs of green hydrogen are essentially dependent on the cost of electricity and the availability of electricity, which has an influence on the full-load hours and thus on the distribution of the fixed costs of the production plant. In this context, electricity can be purchased, for example, through the electricity market or by directly coupling RES and hydrogen production plant. In the former, the varying wholesale electricity price is thus decisive for the calculation of the variable costs, while in the latter, the constant electricity production costs of the RES plant determine the electricity costs (Schlund & Theile, 2021). A cost comparison of directly coupled plants shows that in 2045 the import of green hydrogen from southern Europe (Greece, Spain) with an average of 2.1 €/kg and from northern Europe (Sweden, Denmark, Norway) with an average of 2.4 €/kg are the cheapest options for Germany. Countries in the East and the Baltic States (Poland, Estonia, Ukraine) appear to be comparatively expensive export countries within Europe with an average of 3 €/kg (Brändle et al., 2021).[13] In addition to the investment costs of reformers or pyrolysis plants, the alternative production of climate-neutral hydrogen from natural gas depends primarily on the price of natural gas. Under given assumptions[14] the costs of domestic production of blue hydrogen can be estimated at 2 €/kg and turquoise hydrogen at 1.9 €/kg in 2045 (Brändle et al., 2021). In 2030, the production costs of blue hydrogen are below the costs of green hydrogen for all production regions, as strong cost reduction for electrolysers and RES plants are not yet realized until then (Schulte et al., 2020).

[12] Detailed assessments of the infrastructure peak load situations require extensive network simulations. Here, the discussion is presented in a simplified form.

[13] The fact that imports originate from eastern and Baltic regions nevertheless in the previous scenarios is because European electricity markets are optimized in the primary source. Thus, the electricity price for hydrogen production in the source study is not derived from the electricity production costs of RES but from the simulated electricity prices of the respective region. At the same time, many assumptions must be made for the electricity market simulation, which can influence the electricity prices.

[14] Assumptions: Natural gas price: 25 €/MWh (own assumption based on IEA (2020), IEA (2021) and BMU (2021)); CO_2 price: 175 €/t; CCS costs: 17 €/t. Methodology and other assumptions follow Brändle et al. (2021).

Thus, natural gas-based production of climate-neutral hydrogen is a cost-efficient alternative to electricity-based production technologies.

To produce climate-neutral hydrogen with pyrolysis and reforming, in addition to the possibility of storage or utilization of CO_2/carbon, a reliable natural gas supply is necessary. Due to declining European natural gas production capacities in the coming years, especially in the Netherlands and Norway, Russia remains as a major supplier of low-cost pipeline-sourced gas as an alternative to more expensive liquefied natural gas imports. Through the Nord Stream and Nord Stream 2 pipelines, eastern Germany has a direct connection to Russian gas exports and thus has great potential for natural gas-based production of climate-neutral hydrogen.

The following variant therefore considers the case of technology-neutral production of climate-neutral hydrogen based on the *Diversification* scenario. The variant discusses the implications of additional production capacities on the grid structure, transit potentials, and import needs. While the production volumes, imports and transit flows of the *Electrification* and *Diversification* scenarios were optimized by the electricity market modeling of the primary source, the following discussion does not correspond to a cost-optimized allocation of parameters but represents an indicative restructuring of hydrogen trade flows between the regions under given grid constraints.

Figure 9 illustrates the possible implications on the hydrogen grid if large-scale production of climate-neutral hydrogen from Russian natural gas supplies is realized on the Baltic Sea coast. The yellow arrows indicate the range of production and transit potentials based on the described methodology.

In 2030, by assumption, some natural gas pipelines cannot be repurposed due to the need for natural gas transits. Starting from the Baltic Sea coast, in eastern Germany this applies in particular to the NEL pipeline leading to western Germany and the OPAL/EUGAL pipelines leading to the South.[15] For the latter, it is assumed that at least one of the two parallel pipelines can be repurposed for hydrogen in 2030. This forms a north-south connection in addition to the initial hydrogen grid, which will be the most important route for transporting climate-neutral hydrogen produced at the coast by 2030. Further repurposing is not necessary, as the largest regions of demand are already supplied by the initial hydrogen grid. The north-south transport capacity is the main limitation for additional transport of climate-neutral hydrogen. Thus, although up to 137 TWh of natural gas can be converted to hydrogen under the assumptions made in Section 4.6, a maximum of 94 TWh[16] can be transported via the repurposed pipelines.

Due to the additional production and transit potentials, eastern Germany changes from a net importer to an exporter of climate-neutral hydrogen in 2030 (for comparison: in the *Diversification* scenario, the net import demand is 2 TWh). Hydrogen demand within the region of eastern Germany (total hydrogen demand in the *Diversification* scenario: 10 TWh) can be fully met, which reduces the pressure on the expansion of RES capacities to produce electricity-based

[15] NEL - North European Gas Pipeline; OPAL - Baltic Sea Pipeline Interconnector; EUGAL - European Gas Interconnector.

[16] It is expected that compression of hydrogen will not take place up to 2030. Depending on the pipeline pressure, the full transport capacity would therefore be used to a limited extent.

hydrogen. On the other hand, there is the possibility of climate-neutral hydrogen exports, especially towards the Czech Republic to satisfy local hydrogen demand or routing hydrogen back to Germany to supply the southern German regions. In addition, some of the climate-neutral hydrogen can be transported further to Leipzig via the new pipeline construction projects around Berlin, either to meet the demand there or to connect the western German regions via the new construction projects in central Germany. In 2030 Germany has a total hydrogen demand of 41 TWh in the *Diversification* scenario with an import demand of 34 TWh (based on Fraunhofer ISI et al., 2021). The demand could thus be completely met by natural gas-based hydrogen from eastern Germany. The share of the total German hydrogen and import demand that can be covered by natural gas-based hydrogen from eastern Germany depends mainly on the dynamics of the hydrogen network expansion, that would distribute the volumes produced on the Baltic Sea coast to other regions in Germany.

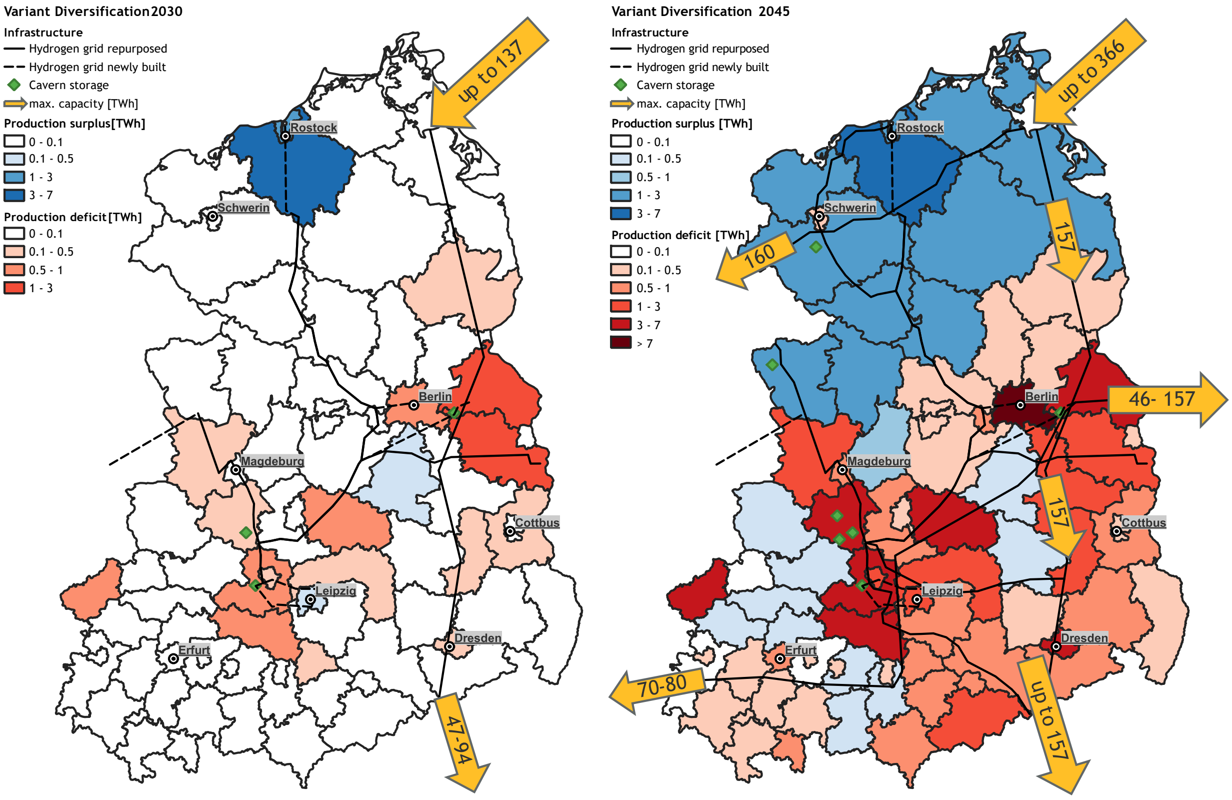


Figure 9: Possible hydrogen grid with technology-neutral production in the *Diversification* scenario for 2030 (left) and 2045 (right)

Source: Own illustration

In 2045, production potential of up to 366 TWh can be realized in eastern Germany under the assumptions made in chapter 4.6. To further transport the production volumes, repurposing of additional pipelines is necessary compared to the *Diversification* scenario. Eastern Germany has large pipeline capacities in north-south as well as east-west direction, which allow a further distribution of the climate-neutral hydrogen. Therefore, in the North, the NEL will be repurposed for further transport towards northwest Germany, and in the South, an additional connection via

Thuringia to western Germany will be created. The limiting factors for production on the Baltic Sea coast are the transport capacities of the NEL pipeline in the East-West direction and the OPAL and EUGAL pipelines in the North-South direction. In total, a maximum of 317 TWh can be transported from the Baltic Sea coast. This means that a complete utilization of the potential to produce natural gas-based hydrogen in the North of eastern Germany in the amount of 366 TWh is not possible under the assumptions made.

The hydrogen demand in eastern Germany increases significantly to as much as 116 TWh in the same period. In the *Diversification* scenario, about 54 TWh of this is covered by imports and 62 TWh by domestic electricity-based hydrogen production. Most of the imports come from eastern European and Baltic countries. However, these countries in particular have comparatively high generation costs for RES-based hydrogen (Brändle et al., 2021), so it is uncertain whether competitive imports of this magnitude can be realized by 2045. In contrast, the import demand of eastern Germany can be completely covered by natural gas-based hydrogen production in the variant scenario; in addition, large potential for exports remain. These can, for example, be exported to Poland, to the Czech Republic and from there back to Germany (up to 157 TWh, limited by the OPAL or EUGAL transport capacity), via Thuringia to southern Germany (up to 80 TWh) or to northwestern Germany (up to 160 TWh). Looking at the overall German hydrogen demand of 664 TWh with an import demand of 511 TWh (Fraunhofer ISI et al., 2021), even if the complete production potential of natural gas-based hydrogen in eastern Germany is realized, imports from other European regions and domestic electricity-based hydrogen production will still be necessary.

Under the assumptions made, about half of the import capacity of Russian natural gas will be used to produce hydrogen in the North of eastern Germany. Residual volumes of natural gas can still be transported to other countries via the north-south connection of the non-repurposed OPAL or EUGAL pipeline. Thus, in addition to hydrogen production from natural gas on the Baltic coast, there is also the possibility of transporting natural gas and converting it to hydrogen at the point of consumption. Therefore, to realize this potential, it may be necessary to not repurpose a portion of the natural gas network and continue to maintain it for natural gas transport. This option was not further considered in this variant.

It is also conceivable that higher availability of climate-neutral hydrogen will influence the demand side and lead to higher penetration of hydrogen in the sectors, for example by using fuel cells in the building sector. Higher demand leads to stronger incentives for hydrogen grid expansion, which can lead to repurposing and new construction of more hydrogen pipelines. In addition to the direct impact of natural gas-based hydrogen production on hydrogen grid expansion, other systemic effects are conceivable. It is likely that the increased availability of hydrogen generation capacity will reduce pressure on the expansion of RES capacity needed to produce electricity-based hydrogen. By making natural gas-based hydrogen production independent of weather, it may be possible to reduce storage demand and improve system reliability by increasing the security of supply of the hydrogen infrastructure. Comprehensive analysis of this requires integrated optimization of the system and consideration of the interactions with the power sector. Therefore, the discussion is presented here in a simplified form.

6 Regulatory framework

Climate-neutral hydrogen currently still faces the challenge that it is neither competitive with conventional gray hydrogen used as a feedstock in industry nor with CO_2-intensive fuels for energetic use. The market ramp-up faces a three-sided chicken-and-egg problem, as demand does not emerge due to a gap in economic viability, and thus there is no incentive to produce carbon-neutral hydrogen. As a consequence, there are also no investment incentives for the infrastructure needed to connect supply and demand to create the transport capacity (Schlund et al., 2021). The critical variables for planning a future hydrogen grid in eastern Germany are the hydrogen balances of the districts and the physical cross-border trade. Their uncertain development represents a risk for investments in a hydrogen infrastructure. Thus, the distribution of the investment risk in the infrastructure remains a central task within the hydrogen market ramp-up.

In the early phase of the hydrogen market ramp-up up to 2030, it is necessary to support supply, demand, and infrastructure development. The challenge during the market ramp-up arises from the mutual interdependence of all three aspects. Thus, each project needs to be evaluated with its suitability in terms of ramp-up of supply, demand, and infrastructure. In particular, the creation of concentrated clusters can facilitate the ramp-up. For example, on the demand side, urban and industrial centers can be formed as hydrogen clusters. On the supply side, regions with high RES potentials and connections to energy imports (e.g., ports, import pipelines) are particularly suitable locations for cluster formation. In the early phase of the ramp-up, clusters are characterized mainly by sectors that have few alternatives for decarbonization besides the use of hydrogen, e.g., the steel industry or air transport. Substitution of today's gray hydrogen with climate-neutral hydrogen, e.g., in the chemical industry and mineral oil refining, also represents a useful measure to support the development of production capacities while reducing CO_2 emissions. The starting points of the hydrogen infrastructure should therefore first connect these clusters, so that the utilization of the infrastructure and the security of supply of the clusters can be guaranteed. Due to the lower costs compared to new constructions, repurposing existing gas pipelines should be preferred. In the further course of the ramp-up, capacities can then be expanded, and further regions can be connected. In this context, the extent to which the hydrogen grid is capable of realizing additional imports and transits should be increasingly considered.

The second central point in the development of a hydrogen infrastructure in eastern Germany is the consideration of cross-border hydrogen transport. The development of individual clusters and their interconnection should not be limited to the national level but should also take into account developments in neighboring countries, especially since Germany will most likely depend on hydrogen imports in the future. The production technology of hydrogen has an influence on the amount and direction of transits. In the scenarios, it becomes clear that different routes could emerge depending on the technology used. At the same time, a technology-neutral approach enables additional production capacities and creates additional back-up capacities in the future hydrogen system. The emergence of different hydrogen production technologies requires the implementation of a cross-border and transparent certification system, especially with a technology-neutral approach. It facilitates the tracking of emission reductions, increases competition between different hydrogen sources, and allows for a technology-neutral hydrogen value chain. Thus, it is an enabler for transnational hydrogen trade while ensuring compliance with national climate targets. Similar to the interconnection of hydrogen clusters, a transnational hydrogen grid could further diversify supply sources and thus increase security of supply.

Even if a hydrogen infrastructure proves useful in future scenarios and is politically desirable, investments are not guaranteed. The fundamentally uncertain development of hydrogen demand and supply leads to a high-risk scenario when investing in future hydrogen infrastructure. The high capital intensity requires a greater degree of certainty. Without some degree of certainty regarding the utilization of the networks or with regard to the refinancing of the investments, there is little incentive for network operators to actually build such an infrastructure. At the same time, the long investment cycles and the time-consuming infrastructure planning and implementation make it necessary to initiate the required network expansion measures at an early stage. Without a reliable investment framework for hydrogen grids and the associated clarity with respect to financing, timely investments could fail to materialize and the hydrogen market ramp-up could be delayed.

7 Conclusions

The study examines the development of regional hydrogen balances and a corresponding hydrogen infrastructure in eastern Germany based on the reference years 2030 and 2045. For this purpose, based on the scenarios *Electrification* and *Diversification*, the hydrogen demand of the sectors industry, transport, building and power and the hydrogen production for the eastern German districts are determined. *Electrification* focuses on the increased use of electricity in the final energy consumption sectors, while *Diversification* relies not only on electricity but also on a high penetration of climate-neutral hydrogen as an energy carrier in all final energy consumption sectors.

The resulting hydrogen balances yield a hydrogen surplus of almost 3 TWh in 2030 and a deficit of 2 TWh in 2045 in the *Electrification* scenario, while in the case of *Diversification* the hydrogen deficit is around 2 TWh in 2030 and up to 54 TWh in 2045. The northern districts especially emerge as production regions since their high production potentials face low hydrogen demand from industry and transport. The South and especially the metropolitan areas of Leipzig and Berlin develop into import regions, as there is low production potential with high hydrogen demand from industry, transport, and the building sector.

An alternative to electricity-based hydrogen production is pyrolysis or reforming of natural gas with capture of CO_2 emissions or solid carbon. In a direct cost comparison, natural gas-based production of climate-neutral hydrogen is a cost-efficient option to green hydrogen and enables the realization of further production potential. It can also increase security of supply by providing additional back-up capacity and reducing dependence on volatile RES feed-in.

Based on the balances and the assumed transit demand, indicative hydrogen grids can be derived. It is shown that an initial hydrogen grid in the context of planned IPCEI Hydrogen projects covers a large part of the transport demand by 2030, which mainly extends from north to south, and is reasonable regardless of the scenario. In 2045, the indicative grids diverge more. In the *Diversification* scenario, more capacity is needed for hydrogen transport. In this scenario, for example, additional north-south pipelines are repurposed to transport imports and production from the North to industrial sites and population centers in the South and to provide transits via the Czech Republic to southern Germany. In addition, interconnectors to the West and East will be needed to import hydrogen from northern and eastern European countries. Furthermore, should climate-neutral hydrogen be produced on the Baltic Sea coast using imported natural gas, eastern Germany may become a significant exporter of climate-neutral hydrogen. This will create additional demand for transport capacity to all neighboring regions. Eastern Germany thus positions itself as an important hub for climate-neutral hydrogen.

With the launch of the IPCEI Hydrogen, the foundation has thus been laid to provide sufficient infrastructure to supply eastern Germany with hydrogen in 2030. For a climate-neutral Germany in 2045 that relies on hydrogen as an energy carrier, further pipeline repurposing is needed to meet import and transit needs. To ensure the planning and realization of these long-term projects, the timely definition of an appropriate investment framework is therefore of great importance. This applies especially to the planning of a hydrogen grid in eastern Germany.

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Appendix

A.1 Assumptions

Table A.1: IPCEI Hydrogen projects considered and resulting hydrogen volumes in 2030

Source: BMWi (IPCEI), Gascade & Ontras (2021)

Project name	Location	NUTS 3 Code	Goal (H2 volume 2030 in TWh)
Production			
doing hydrogen - APEX Energy	Rostock	DE80K	100 MW Electrolysis (0.2 TWh)
doing hydrogen - Enertrag	Rostock	DE803	55 MW Electrolysis (0.1 TWh)
doing hydrogen - Enertrag	Sperenberg	DE40H	100 MW Electrolysis (0.2 TWh)
doing hydrogen - Enertrag	Treuenbritzen	DE40E	30 MW Electrolysis (0.1 TWh)
doing hydrogen - Enertrag	Bobbau	DEE05	25 MW Electrolysis (0.1 TWh)
Green Hydrogen Hub	Leuna	DEE0B	24 MW Electrolysis (0.1 TWh)
LHyVE Production	Leipzig	DED51	50.000 t/a SAF-Kerosene (0.2 TWh)
LHyVE System	Leipzig	DED51	1.500 t/a Green Hydrogen (0.1 TWh)
HyTechHafen Rostock	Rostock	DE803	1.000 MW Electrolysis (2.4 TWh)
doing hydrogen TRIA	Rostock-Poppendorf	DE80K	150.000 t/a Green Hydrogen (5 TWh)
Demand			
doing hydrogen - CEMEX	Rüdersdorf	DE409	60,000 t/a H_2 for green hydrocarbons (2 TWh)
doing hydrogen - Vattenfall	Berlin	DE300	27,000 t/a H_2 for PtH and CHP projects (0.9 TWh)
DRIBE2	Eisenhüttenstadt	DE40C	3,5 million t/a of green steel in Bremen and Eisenhüttenstadt (0.8 TWh)
Distribution			
doing hydrogen - Gascade	Rostock - Berlin	-	H_2-Pipeline: 140 km new construction, 335 km conversion
doing hydrogen - ONTRAS	Berlin - Leipzig	-	
Green Octopus MD - ONTRAS	Salzgitter - Leipzig	-	H_2-Pipeline: 200 km between Salzgitter and Leipzig
Green Octopus MD - Bad Lauchstädt	Bad Lauchstädt	-	Connection of Bad Lauchstädt cavern storage facility
LHyVE Transport - ONTRAS	Leipzig	-	H_2-Pipeline: 70 km new construction H_2 circle around Leipzig

A.2 Results

Table A.2: Hydrogen balance of both scenarios in 2030 and 2045 in TWh

	2030		2045	
	Electrification	Diversification	Electrification	Diversification
Hydrogen balance	**2.6**	**-1.5**	**-1.6**	**-53.9**
Production	8.5	8.5	36.1	62.1
Demand	5.9	10.0	37.7	116.0
Industry	2.9	7.0	21.4	52.7
Ammonia	0.1	0.6	5.8	5.8
Mineral oil	0.3	0.3	2.4	2.4
Methanol	0.5	0.5	4.5	4.5
Steel	1.3	1.3	2.5	2.5
Process heat	0.7	4.3	6.2	37.5
Transport	2.0	2.0	5.7	26.6
Passenger Car	0	0	2.9	6.9
LCV	0	0	0.3	0.3
Truck	0	0	0.1	16.8
Rail Transport	0	0	0	0.2
Inland Shipping	0	0	0.2	0.2
Airborne Transport	2.0	2.0	2.2	2.2
Buildings	0.5	0.5	0.5	34.7
Power	0.5	0.5	10.1	2.0