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The role of liquid hydrogen in integrated energy systems—A case study for Germany

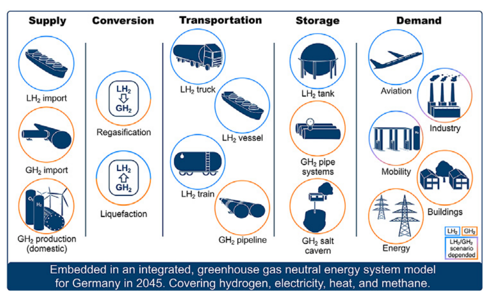
Toni Busch [a,b,*], *Theresa Groß* [a], *Jochen Linßen* [a], *Detlef Stolten* [a,b]

[a] Forschungszentrum Jülich GmbH, Institute of Energy and Climate Research — Techno-economic Systems Analysis (IEK-3), Jülich, 52425, Germany
[b] RWTH Aachen University, Chair for Fuel Cells, Faculty of Mechanical Engineering, Aachen, 52062, Germany

HIGHLIGHTS

- Development of an energy system model featuring a liquid hydrogen supply chain.
- Liquid hydrogen transportation is used only when a liquid hydrogen demand exists.
- The highest hydrogen demand sectors are most suitable to use liquid hydrogen.
- To cover liquid hydrogen demand, first trains, then vessels, then trucks are used.
- Liquid hydrogen transportation reduces the amount of required hydrogen pipelines.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydrogen (H_2) is expected to be a key building block in future greenhouse gas neutral energy systems. This study investigates the role of liquid hydrogen (LH_2) in a national, greenhouse gas-neutral energy supply system for Germany in 2045. The integrated energy system model suite ETHOS is extended by LH_2 demand profiles in the sectors aviation, mobility, and chemical industry and means of LH_2 transportation via inland vessel, rail, and truck.

This case study demonstrates that the type of hydrogen demand (liquid or gaseous) can strongly affect the cost-optimal design of the future energy system. When LH_2 demand is introduced to the energy system, LH_2 import, transportation, and production grow in importance. This decreases the need for gaseous hydrogen (GH_2) pipelines and affects the location of H_2 production plants. When identifying no-regret measures, it must be considered, that the largest H_2 consumers are the ones with the highest readiness to use LH_2.

* *Corresponding author*. Forschungszentrum Jülich GmbH, Institute of Energy and Climate Research — Techno-economic Systems Analysis (IEK-3), Jülich, 52425, Germany.
E-mail address: T.Busch@FZ-Juelich.de (T. Busch).
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Introduction

In order to mitigate the consequences to overshoot the 1.5 °C global warming level, states must pursue major reductions in greenhouse gas emissions [1]. Germany plans to become net greenhouse gas neutral by the year 2045 [2]. Hydrogen (H_2) is considered a critical component in a future German energy systems [3–7]. Both domestic production and imports are relevant H_2 supply option for Germany. Its central location in Europe allows for pipeline import of gaseous hydrogen (GH_2) as well as the operation of harbor terminals to import liquid or bounded H_2 from overseas. These options include cryogenic liquid hydrogen (LH_2), liquid organic hydrogen carriers (LOHC), ammonia and metal hydrides. It is still under discussion which options will be part of future energy systems. In this study, only LH_2 and GH_2 are investigated in accordance with the work of Stolten et al. (2021) [8] and Heuser (2021) [9]. The aim of this investigation is to analyze the role LH_2 in a national hydrogen supply chain (HSC).

The use and transportation of LH_2 in energy systems offers several advantages in comparison to gaseous hydrogen: Liquefying hydrogen leads to a high volumetric energy density of 2.4 MWh/m^3, which is about four times higher than compressed GH_2 at 300 bar and 800 times higher than gaseous hydrogen at 1 bar and 25 °C. This promises higher transportation efficiencies in comparison to gaseous hydrogen.

Furthermore, LH_2 offers high purity levels of 99.97%–99.995% according to ISO-14687:2019 [10]. Maintaining this purity throughout transportation and storage allows for applications in mobile and stationary fuel cells, and for its material use in industry. Although polymer electrolyte membrane (PEM) water electrolysis can reach GH_2 purity levels of 99.97%, the subsequent transportation (e.g., in retrofitted pipelines) and storage (e.g., in salt caverns) can make it susceptible to impurities [11].

The transportation of LH_2 can be organized in a more flexible and modular way in comparison to GH_2 pipelines: Germany has a well-developed transport infrastructure network (highways, railways, waterways). These existing infrastructures enable LH_2 means of transportations (once developed) a faster connection to new destinations in comparison to the construction or repurposing of GH_2 pipelines, as planning, construction, and approval times are lower. Experience in the design and operation of liquefied natural gas (LNG) means of transportation can support the development of LH_2 transportation systems. However, new construction challenges like the need for ultra-high vacuum insulation strategy systems will arise, as the boiling point of hydrogen is 90 °C below that of methane [12].

Literature review

The literature section is divided into three parts: In the first two parts, applications (section LH_2 Applications and Demand) and transportation (section LH_2 Transportation) options are introduced. In the third part (section Study Comparison), relevant studies in LH_2 HSC are presented. From these, the research gap and the proposed approach for this work is derived.

LH_2 applications and demand

Hydrogen is a promising solution for reducing greenhouse gas emissions in the industrial, transport, energy, and buildings sectors [8]. For LH_2, direct and indirect potential use cases will emerge in future energy systems. The aviation sector is an example for the direct use of LH_2. As weight and space must be efficiently managed in air travel [13,14], the high energy density of LH_2 can make it an ideal candidate to substitute kerosene in certain cases. How suitable different options are for the decarbonization of the aviation sector depend on the traveling distance and size of the aircraft: Whereas battery–electric propulsion can be utilized for commuter and regional flights, the aviation industry anticipates long-haul flights to be powered by so-called sustainable aviation fuels (SAFs) like bio-kerosene or synthetic power-to-liquid fuels [15]. LH_2 can be best applied in short-to medium-haul aircraft of up to 150 seats [16]. The market launch of LH_2 in the aviation sector is expected by 2035 [17].

Possible indirect use cases of LH_2 arise when it is utilized to serve (gaseous) hydrogen demands that require high levels of purity. In future energy systems, hydrogen can serve as a fuel for process heat (e.g., in the steel, cement, glass, or paper industries) or as a feedstock in chemical processes (e.g., in Haber-Bosch, Fischer-Tropsch, and methanol synthesis processes). Especially in the case of material use in the chemical industry, high levels of hydrogen purity of over 99.99% are required [18,19].

Not only in industry, but also in the transportation sector, high levels of hydrogen purity are needed. According to ISO-14687:2019, PEM fuel cell vehicles require hydrogen purity levels of over 99.97% with strict requirements of under 10 μmol/mol for contaminations like water, oxygen, and hydrocarbons [10]. Examples for a combined LH_2-GH_2 application include Linde's commercial fueling station in Sacramento (CA), USA, and in Iwatai, Amagasaki City, Japan, that incorporate LH_2 delivery and LH_2 on-site storage to serve GH_2 (at 350 and 700 bar) demands for fuel cell vehicles [20]. These liquid systems have the advantage of requiring a smaller storage footprint in comparison to GH_2 solutions, which are smaller by a factor of four [21].

LH_2 transportation

The transportation of LH_2 is already regulated in the European Agreement concerning the international carriage of dangerous goods by inland waterways (ADN) [22], rail (RID) [23], and road (ADR) [24]. Their applications in the past and present demonstrate a sufficient technology readiness level (TRL) to be considered in a case study for 2045. However, the state of technological and market maturity varies between these transportation options: LH_2 trucks are already in operation today, with cargo capacities of around 50 m^3 [20], whereas LH_2 railcars were last operated during the NASA space program in the 1960 s [25]. Although there are still technical difficulties facing the realization of LH_2 railcars today [25], the US Department of Transportation's agency PHMSA authorized the double-walled, insulated tank-railcars DOT-113A60 W and DOT-113A175 W to be used for the transportation of cryogenic hydrogen [26,27]. These railcars have a storage capacity of up to 130 m^3.

NASA also uses barges for the transportation of LH_2 on inland waters. Tugged LH_2 barges with storage capacities of 3000 m^3 first came into operation in the 1960 s and continue to be used today by NASA [28,29]. In 2020, Kawasaki launched the Suiso Frontier, the first prototype LH_2 carrier for overseas transport [30]. The ship carries 1250 m^3 of LH_2 from Australia to Japan. Its transport capacity is magnitudes smaller than the currently largest overseas LNG ships such as the Q-Max, with up to 266 000 m^3 of storage, but its size is expected to be matched in future LH_2 designs [31,32].

The transport of LH_2 by pipeline has been investigated, e.g., in the *icefuel* project, but its low transportation distance (10 km) and capacity (100–200 kW) make it unsuitable for a national transmission system [33].

Study comparison

To identify the research gaps in literature, the most relevant studies on hydrogen transportation are categorized according to three characteristics: The hydrogen carriers, means of transportation, and the hydrogen demand supplied in the respective study. Table 1 offers an overview of the most relevant studies. In the identified studies, LH_2 is being compared to GH_2, LOHC, and ammonia. The greatest number of studies compare the carriers LH_2 and GH_2 [34–42], followed by the comparison of LH_2, LOHC, and GH_2 [43–47] and the comparison of LH_2 and ammonia [48].

The hydrogen demand is mostly considered in the transportation sector [35,36,38–40,42–44,47]. Additional to mobility, some studies consider energy generation [41,46] and industry applications [37]. The study by Gronau et al. (2023) solely focuses on aviation as a demand sector [34].

In terms of means of transportation, trucks and pipelines are used the most, ship and rail transportation are scarce. Only trucks (for different hydrogen carriers, as mentioned above) are analyzed in Refs. [38,40,44,46,47]. The combination of trucks and pipelines (GH_2) is analyzed in Refs. [34–37,41–43,45]. Trucks and rail are compared in Ref. [39], ship transport (exclusively international) are investigated in Refs. [45,46,48].

Research gap and research question

From the literature review three main research gaps can be identified: First, there is no study conducting a comprehensive analysis of all three LH_2 means of transportation, second there is no study considering a wide range of LH_2 and GH_2 demands (industry, buildings, energy, transportation, aviation) and third, there is no study analyzing the role of LH_2 in a comprehensive and integrated energy system covering hydrogen, electricity, heat, and methane.

In this study, an intensive analysis of a domestic LH_2 supply chain is conducted. The LH_2 transportation options by inland vessels, rail, and truck are embedded in an integrated optimization model of a national energy system for Germany. The model includes the energy carriers electricity, methane, and liquid and gaseous hydrogen, as well as its corresponding demands, supply, storage, conversion, and transmission infrastructures. Within the scope of a scenario analysis, the

Table 1 – Overview of the current status of literature on LH_2 transportation.

Source	Published	H_2 carrier	MOT[a]	H_2 demand[b]	Region[c]	Year
[34]	2023	LH_2, GH_2	P, T	A	nat	2050
[35]	2022	LH_2, GH_2	P, T	M&T	nat	"long-term"
[43]	2022	LH_2, LOHC, GH_2	P, T	M&T	reg	2050
[44]	2021	LH_2, LOHC, GH_2	T	M&T	nat	2050
[47]	2021	LH_2, LOHC, GH_2	T	M&T	trans	2030, 2050
[45]	2021	LH_2, LOHC, GH_2	P, S_o, T	–	int, nat	2030, 2050
[36]	2021	LH_2, GH_2	P, T	M&T	reg	2050
[48]	2020	LH_2, Ammonia	S_o	–	int	–
[37]	2020	LH_2, GH_2	P, T	I, M&T	nat	2030
[38]	2017	LH_2, GH_2	T	M&T	nat	"near future"
[39]	2016	LH_2, GH_2	R, T	M&T	nat	2030
[46]	2012	LH_2, LOHC, GH_2	S_o, T	E, M&T	int, nat	"early H_2 adoption"
[40]	2009	LH_2, GH_2	T	M&T	nat	2005–2034
[41]	2009	LH_2, GH_2	P, T	E, M&T	nat	2050
[42]	2007	LH_2, GH_2	P, T	M&T	nat/reg	–
This Study		LH_2, GH_2	P, R, S_i, T	A, B, E, I, M&T	nat	2045

[a] Means of transportation: Pipeline, Rail, Ship (overseas/inland), Truck.
[b] H_2 demand: Aviation, Buildings, Energy, Industry, Mobility & Transportation.
[c] Regional scope: international, national, regional, transnational.

impact of different LH_2 demand cases on the hydrogen transportation infrastructure is assessed. The purpose of this analysis is to investigate the role of LH_2 in future energy systems. This incorporates the following research questions.

1. What are applications for LH_2 in future energy systems?
2. What are the most promising technologies for LH_2 transportation?
3. In which cases is LH_2 transportation, and in which is GH_2 transportation the more economical choice?
4. What is the optimal way to design the LH_2 supply in future energy systems?
5. How does the introduction of LH_2 demand affect the remaining infrastructures of the energy system?

Methodology, materials, and model description

To analyze the role of LH_2 in Germany, a national energy supply system model is utilized and expanded to include a liquid hydrogen supply chain. For this purpose, the model suite ETHOS (Energy Transformation Pathway Optimization Suite) is used. Section ETHOS Model Suite presents the previous work used in this study, namely the ETHOS models and the model coupling approach. Section Implementation and Modeling of LH_2 introduces the expansion of the model suite and thus the contribution of this paper. It describes in detail the implementation of a LH_2 supply chain in ETHOS. A visual representation of the most relevant aspects of the model suite for this paper can be found in Fig. 1.

ETHOS model suite

This study is based on previous work, such as the FINE framework [49], as well as the ETHOS model suite [8] and its derived energy system models ETHOS. NESTOR [50] and ETHOS. Infrastructure [51,52] developed at the Institute for Techno-economic Systems Analysis (IEK-3) at the Forschungszentrum Jülich GmbH. Further details on these underlying models can be found in the corresponding literature.

The main focus of this work lies on ETHOS. Infrastructure which is based on FINE. The IEK-3 developed the open-source Python framework FINE (Framework for Integrated Energy System Assessment) for the optimization and analysis of energy systems. Its optimization objective is the optimal design and operation of energy systems at minimal total annual costs. FINE can carry out mixed-integer linear optimization of energy systems with multiple regions, commodities, and time steps. The basic building blocks of the optimization model are transmission, storage, and conversion components, as well as sources and sinks of energy and material flows. From these building blocks, component-specific constraints are derived such as storage rates, conversion efficiencies, transmission losses, demand coverage, CO_2 limits, etc. [49,53].

The case study discussed in this paper investigates the energy system of Germany for a greenhouse gas neutral scenario in 2045. This is the year by which Germany pledges to achieve greenhouse gas neutrality according to the revised Climate Change Act (KSG) passed in 2021 by the German Federal Government [2]. The legislation defines CO_2 reduction targets for 2045 and for milestone years along the transformation path. For the year 2045 it mandates net CO_2 reduction of 100% compared to 1990 across all sectors (industry, energy, buildings, mobility & transportation, agriculture, and waste management). Remaining emissions (such as in agriculture) must be compensated, e.g., by direct air capture (DAC).

To resolve the trade-off between spatial resolution and sectoral coverage, a model coupling approach is implemented. This process and the models used are described in section Single-Region Energy System Model (single-region model),

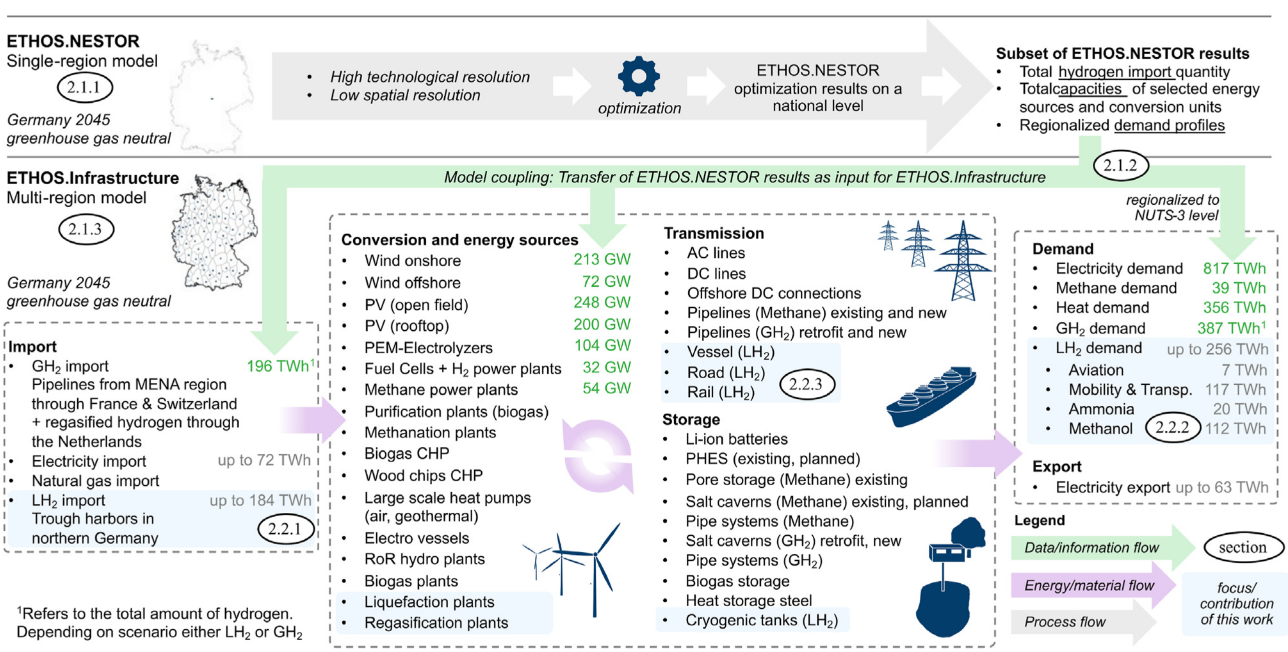


Fig. 1 – Scheme of the ETHOS. Infrastructure model and the model coupling to ETHOS. NESTOR. Circled numbers refer to the corresponding section in the methodology.

section Model Coupling (coupling), and section Multi-Region Energy System Model (multi-region model).

Single-region energy system model

ETHOS.NESTOR is a single-region energy system model with high sectoral coverage covering a single year at an hourly resolution (8760 time steps). The special feature of ETHOS. NESTOR is that a wide variety of reduction measures compete with each other across all sectors (buildings, energy sector, industry, transport). The underlying model algorithm makes it possible to select the most cost-effective reduction measures under the criterion of cost efficiency, which in turn are combined to form a consistent, national greenhouse gas strategy [8].

Model coupling

The model coupling approach was introduced in the case studies by Stolten et al. (2021) [8] and Cerniauskas et al. (2021) [52]. The two models are soft-coupled, such that the ETHOS. NESTOR optimization provides inputs for the ETHOS. Infrastructure model. These inputs include demand profiles for each energy carrier, the installed capacities of energy production and conversion infrastructures (e.g., renewable power plants, electrolysis, electrification plants), and the total amount of annual energy imports (hydrogen, methane, and electricity).

The energy demands are provided by ETHOS. NESTOR calculations from the study “Strategies for a greenhouse gas neutral energy supply by 2045” by Stolten et al. (2021) [8] and listed in Table 2. Both the total annual amount and the spatial distribution of the energy demands are specified exogenously in the ETHOS. Infrastructure model. For this purpose, the calculated national energy demands in ETHOS. NESTOR are regionalized to a NUTS-3 level (a Nomenclature of Territorial Units for Statistics decomposition, here: the 401 administrative districts and cities of Germany). In total, 395 time series of energy demand profiles across the sectors industry, transportation, and building (households and CTS (commerce, trade, and services)) are regionalized on the basis of individual proxies like population, employment, emissions, and gross domestic product. Subsequently, and for each energy carrier, the demand at the NUTS-3 level is aggregated to the spatial resolution of the ETHOS. Infrastructure model.

In the case of the installed capacities, only the total amount is specified exogenously by the ETHOS. NESTOR results. The spatial distribution is left as a decision variable for the ETHOS. Infrastructure optimization [52]. The placement of these capacities, as well as the expansion of transmission infrastructures, are the main results of the ETHOS. Infrastructure model.

Table 2 – Energy demands 2045 in TWh/a as calculated by ETHOS.NESTOR, serving as an input for ETHOS.Infrastructure.

	Electricity	Hydrogen	Heat	Methane
Industry[a]	430	267	180	10
Transport	73	117	0	0
Buildings[b]	314	3	176	30
Total	817	387	356	39

[a] including DAC.
[b] including households and CTS.

On the bases of inputs of a global hydrogen potential model InfH2 [9] developed at IEK-3, ETHOS. NESTOR calculates that 194 TWh/a (5.8 Mt) of hydrogen can be imported. This is approximately half of the amount of hydrogen demands in 2045 (compare Table 2). The other half is produced domestically. To put this into perspective, the “Hydrogen Accelerator” concept accompanying the REPowerEU Action Plan published in 2022 provides for import and production of 333 TWh/a (10 Mt) each in the EU by 2030 [54].

Multi-region energy system model

ETHOS.Infrastructure is a multi-region energy system model with a high spatial resolution covering a single year at an hourly resolution (8760 time steps). It is a linear programming (LP) optimization model for the German energy system. It is built on the FINE framework and serves as the basis for this investigation. The model describes an integrated energy supply and offtake system for the energy carriers of electricity, natural gas, GH_2, and heat with high temporal (hourly) and high regional (80 regions) resolutions. For the present analysis, Germany is divided into 80 regions based on a Voronoi decomposition [55] and an aggregation method developed by Hörsch and Brown[1] [56].

Implementation and modeling of LH_2

For this investigation, the base case energy system is extended with the energy carrier LH_2 and its corresponding means of transportation, sources, sinks, storages, and conversion technologies across a future LH_2 supply chain. The implementation of the core components of this supply chain in the ETHOS model is described in detail in section LH_2 Supply (supply), section LH_2 Demand (demand), and section Inland Distribution of LH_2 (transportation).

LH_2 supply

Liquefaction plants can produce LH_2 by cooling gaseous hydrogen to −253 °C. The liquefaction process is energy-intensive, as it requires up to 40% of the hydrogen's energy content (10–15 kWh/kg_{LH2}) [57–59] and results in high levels of hydrogen purity [60]. In the model, liquid hydrogen can either be produced domestically or imported by ships. The ports in Wilhelmshaven, Stade, and Brunsbüttel are considered potential import locations for LH_2 in this study. These ports are eligible locations for LNG import terminals, and are therefore viable to be retrofitted into LH_2 terminals (with a capacity of 7 GW each) in the future. In total, 194 TWh/a of hydrogen can be imported in the energy system based on the

[1] The method involves the division of an area (here, Germany) into smaller polygons around so-called Voronoi points (here, the 475 nodes of the high-voltage electricity transmission grid). The borders of these Voronoi regions run in such a way that the border lines are equidistant to its two closest Voronoi points. In a subsequent step, these polygons are aggregated into larger regions until the desired number of total regions (here, 80 due to calculation time efficiency during the optimization) is achieved. Between these regions, energy and material flows can be exchanged; within them, the assumption of a “copper plate” applies: transport costs, losses, and capacity restrictions within a region are neglected.

ETHOS. NESTOR scenario results. The model can opt to import hydrogen either as LH_2 from the above-mentioned ports in northern Germany providing international hydrogen at 3.22 €/kg, as GH_2 from interconnectors at the French and Swiss border providing hydrogen from the MENA (Middle East and North Africa) regions at 2.10 €/kg, or as GH_2 from an interconnector at the Dutch border providing GH_2 that was imported to the Netherlands as LH_2.

LH_2 demand

The aim of this study is to investigate how the introduction of LH_2 demand influences the design of hydrogen transportation infrastructures. Demand profiles for LH_2 are considered in the sectors chemical industry (methanol and ammonia production), aviation and transport & mobility according to the literature review in section LH_2 Applications and Demand. To investigate the correlation of higher LH_2 demands and changes in the infrastructures, a set of scenarios is developed: In ascending order there is a *Reference (no LH_2)* scenario without any LH_2 demand, four scenarios with LH_2 demand in single sectors, and a *Comprehensive (high LH_2)* scenario that considers LH_2 demand in all the selected sectors.

As LH_2 was not considered in the ETHOS. NESTOR scenario, adjustments must be made to the hydrogen demand: In order to take LH_2 into account in ETHOS. Infrastructure, GH_2 demand profiles from ETHOS. NESTOR are reclassified as LH_2 in the respective scenarios (methanol and ammonia production, transportation & mobility) and additional LH_2 profiles are added to the model (aviation). For all the other sectors (e.g., process heat, buildings), the demands are considered as GH_2. Fig. 2 lists the total liquid and gaseous hydrogen demands for the six scenarios. The following sections describe how these LH_2 applications and demands are implemented in the expanded ETHOS. Infrastructure model for the different scenarios.

In the *Aviation* and *Comprehensive (high LH_2)* scenario, additional hydrogen demand (7 TWh/a) is introduced into the system; in all other scenarios, the total amount of hydrogen demand remains the same. The demand shifts from GH_2 to LH_2 while maintaining the same total hydrogen demand. The electricity, methane, and heat demand levels remain the same across all scenarios. Fig. 3 depicts the distribution of the LH_2 demand at the NUTS-3 level.

Reference (no LH_2) scenario. The hydrogen demand profiles are derived directly from the ETHOS. NESTOR model (see Table 2). All of them are in gaseous form and consist of the demand for

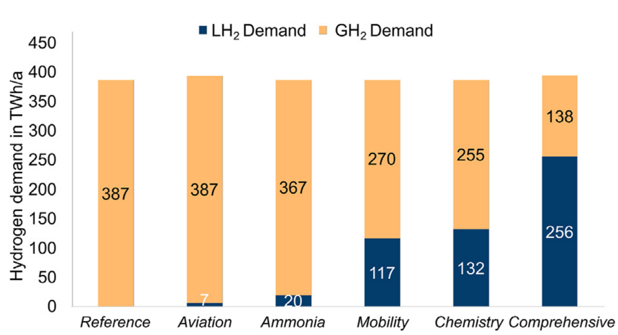


Fig. 2 – Total liquid and gaseous hydrogen demand levels in 2045 for the six LH_2 demand scenarios.

fuel cell vehicles, decentralized heating for buildings, process heat, and material use in industrial processes. The options for LH_2 transportation later described in section Inland Distribution of LH_2 are introduced in the model without incorporating any dedicated LH_2 demand. This aims to show whether the transportation of LH_2 is an economical option for serving GH_2 demand.

Aviation scenario. In ETHOS. NESTOR, only synfuels are considered as substitutes for kerosene in the aviation sector. In this study, LH_2 should be considered as fuel for short- and medium-range aircraft. 14 TWh/a is the designated fuel demand for inland flights in ETHOS. NESTOR. As the case study's scope is a national greenhouse gas neutral energy supply strategy, international flights are not considered in the emission balance.

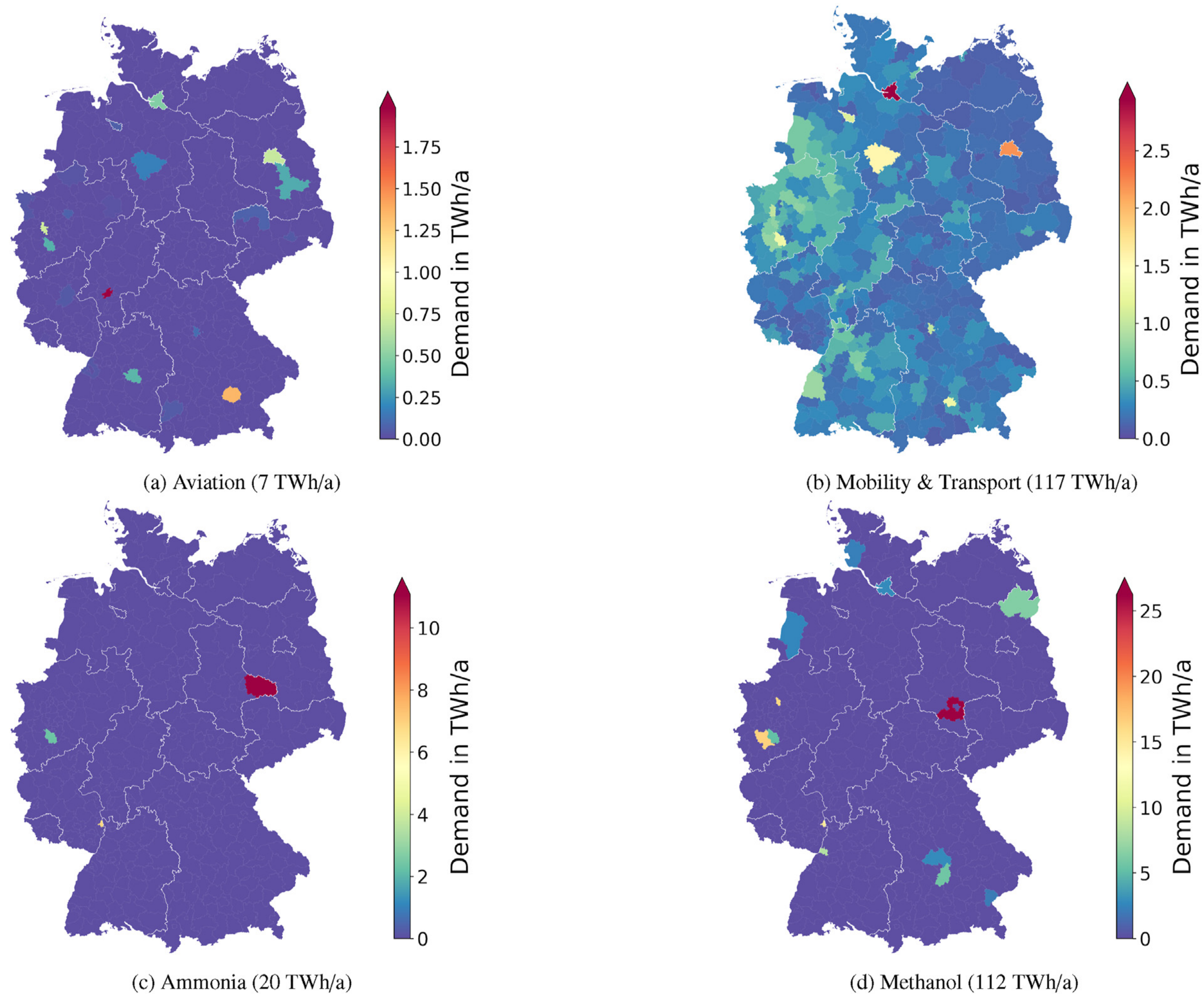
For the *Aviation* scenario, all new domestic aircraft for short- and medium-range flights are assumed to rely on LH_2 propulsion by 2035, as discussed in the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) study "Hydrogen-powered aviation" [17]. With a technical lifetime of 20 years, this leads to a share of 50% LH_2 powered short- and medium-range aircraft by 2045. The LH_2 demand is spatially-distributed on the basis of the location and passenger volume of the 24 largest airports in Germany in 2019 [61,62]. The synfuels in the ETHOS. NESTOR calculation are not produced domestically, but imported. In order to account for this in the energy balance, additional LH_2 imports for the aviation sector (7 TWh/a) are included in this scenario.

Chemical industry scenario: methanol and ammonia. According to the ETHOS. NESTOR calculation, two major consumers of hydrogen in the chemical industry are the production of methanol (112 TWh/a) and ammonia (20 TWh/a). These are now assumed to be in liquid instead of gaseous form. Two demand scenarios are differentiated: in the low-demand one, only LH_2 demand in the ammonia industry is considered (*Ammonia* scenario); in the high-demand one, LH_2 demand for ammonia as well as methanol production are considered (*Chemistry* scenario).

The hydrogen demand for ammonia is distributed in accordance with today's production facilities. CO_2 emissions serve as a proxy for the amount of ammonia produced. As the methanol production increases significantly by 2045 in the investigated case study, not only the current production facilities of methanol but also those of refineries are considered future production sites. In both cases, the CO_2 emissions at the corresponding production plants in 2019 [63] serve as a proxy to allocate the LH_2 demand.

Mobility & transportation scenario. In the *Mobility & Transportation* scenario, the hydrogen demand for cars (32 TWh/a), trucks (73 TWh/a), buses (6.5 TWh/a), and selected train connections (4.7 TWh/a) are covered entirely by LH_2 instead of GH_2. These demands are distributed on the basis of current petrol station locations and those of non-electrified rail tracks [64].

Comprehensive (high LH_2) scenario. In the *Comprehensive (high LH_2)* scenario, the LH_2 demands of aviation and



(a) Aviation (7 TWh/a)

(b) Mobility & Transport (117 TWh/a)

(c) Ammonia (20 TWh/a)

(d) Methanol (112 TWh/a)

Fig. 3 – Spatial distribution of the LH_2 demand in the different sectors on a NUTS-3 level.

transportation, as well as in the chemical industry, are incorporated in one model.

Inland distribution of LH_2

Waterway, rail, and road transportation are identified as potential LH_2 transportation options for future energy systems. The following subsections motivate the selection of these three means of transportation and provide techno-economic data based on a review of the corresponding literature. Subsequently, the selection and processing of the route networks for the different means of transportation in order to obtain the traveling distances between the regions is presented. These distances are needed as inputs for the optimization model and are required to convert the techno-economic data into a format that can be used in the ETHOS. Infrastructure model. This data transformation and a comparison of the processed techno-economic data for the different means of transportation conclude this section.

Means of transportation. Table 3 lists techno-economic parameters for LH_2 inland transportation from the studies introduced in section LH_2 Transportation and additional literature. For truck and rail transport, literature sources and already-implemented systems offer good reference for techno-economic data; for waterway transportation on the other hand, data from the literature and industry is scarce, why estimates must be made.

In the optimization model, the truck is considered to have a transport capacity of 61 m^3, the techno-economic parameters being taken from Reuβ et al. (2021) [44]. For railcars, the capacity is assumed to be 128 m^3, with techno-economic parameters from Amos (1998) [65]. As multiple lines in the German rail network face congestion [67], restrictions for rail transport are applied: only two trains (each with 25 railcars) per day are allowed to depart and arrive in each region. This equates to a maximum of 5.5 TWh/a LH_2 that can be sent out and received per region. For the waterway transport, a class V-type vessel, according to the CEMT (European Conference of Ministers of Transport) classification system of inland waterways, is found suitable [68]. This corresponds to a type C self-propelled liquefied-gas tanker according to EU regulation and the IGC code [69–71]. These vessels feature 14 cargo tanks, a

Table 3 – Techno-economic data on rail, road, and inland vessel transportation of LH_2 according to literature.

Quantity	Unit	Reuβ*, 2021 [44]	Teichmann, 2012 [46]	Niermann, 2021 [45]	Amos*, 1998 [65]	Teichmann, 2012 [46]	Ishimoto*, 2020 [48]	Altmann, 2001 [66]
Transport option	[–]	Truck	Truck	Truck	Rail	Vessel	Vessel	Vessel
	[t]	4.3	3.5	4.5	9.1	1050	354	1050
Freight capacity	[m^3]	61	49	64	128	14 831	5000	14 831
	[GWh]	0.14	0.12	0.15	0.3	35	12	35
Investment[1]	[m. €]	0.86	0.61	1.02	0.42	146	41	104
(un)loading time	[h]	3	3	3	24	48	24	16
Fuel costs[1]	[€/l]	1.2[2a]	1.2[2a]	1.2	0.1	0.3[2a]	0.3[2a]	0.3[2a]
Fuel consumption	[l/100 km]	34.5	27.6	40	88	9.3[2a]	9.3[2a]	9.3[2a]
Operating hours	[h/a]	2000	3500	3500	8400	8000[2a]	8000[2a]	8000[2a]
Average velocity	[km/h]	60	45	60	40	33	30	33
Operating costs[1]	[€/h]	35	35[2b]	35[2b]	3	479[2c]	479[2c]	479[2c]
Service & Maintenance	[$\%_{Invest/a}$]	5%	5%	4%	1%	2%[2a]	2%[2a]	2%[2a]
Losses	[%]	0.30%	0.30%	1.40%	0.30%	0.10%	0.20%	0.10%
Technical lifetime	[a]	11	11	12	15	25	25[2a]	25[2a]
Cumulative inflation	[$\%_{2021}$]	–	12%	–	40%	12%	3%	34%

*Selected for this investigation.
[1]Data according to literature source, without inflation. Inflation is subsequently taken into account in the model.
[2]Information added from other source. [a]Niermann, 2021 [45], [b]Reuβ, 2021 [44]; [c]Teichmann, 2012 [46].

total storage capacity of 5000 m^3 with the length of 110 m, breadth of 11.5 m, and drought of 3.5 m [72]. With these dimensions, they are able to ply the major rivers and canals in Germany [73]. The techno-economic data is taken from Ishimoto[2] et al. (2020) [48].

LH_2 transportation routes. The existing road network [74], railway lines [75], and federal waterways [76] serve as potential transmission routes in the model. Transportation is only considered between, but not within, the regions. The distance between two regions is defined by the length of the shortest path through the route network between their centroids. If existing transport routes do not run through a region centroid, a direct connection between the centroid and the closest point on the existing route is added to the network. Using Dijkstra's algorithm [77], the shortest path between the region's centroids is calculated for the different means of transportation. A visual depiction of the shortest routes between the regions can be found in Fig. 4.

Data transformation. To avoid discrete energy quantities within this LP energy system model and to reduce model complexity, the means of transportation are modeled with average transport capacities C between two regions i, j. These are based on the techno-economic data in Table 3 and the following formulas:

$$C_{i,j} = \frac{E\, n_{i,j}}{8760\, h/a} \tag{1}$$

where E is the transportable energy content per LH_2 shipment and n the maximum number of roundtrip cycles per year. The number of cycles results from the roundtrip duration of a delivery and the yearly operation time:

$$n_{i,j} = \frac{t_{operation}}{t_{roundtrip\, i,j}} \tag{2}$$

A roundtrip cycle consists of the loading, unloading, and commuting (outward and return) time between two regions:

$$t_{roundtrip\, i,j} = t_{load} + \frac{2D_{i,j}}{v} + t_{unload} \tag{3}$$

where $D_{i,j}$ is the shortest distance between two regions (as shown in Fig. 4) and v the average traveling speed. This results in an average annual transmission capacity that corresponds to the route length:

$$C_{i,j} = \frac{E}{t_{load} + \frac{2D_{i,j}}{v} + t_{unload}} \frac{t_{operation}}{8760\, h/a} \tag{4}$$

All costs in the model are expressed as a function of the capacity and are thus dependent on the distance. In order to avoid non-linearity in the system, the costs are calculated a priori for each combination of regions and each mode of transport. Investment costs as well as fixed (depending on the installed capacity) and variable (depending on the usage) operation costs (OPEX) are considered. The specific investment costs as a function of capacity and distance (m. €/km GW) are calculated as follows:

$$I_{i,j} = \frac{I_0}{C_{i,j} D_{i,j}}$$
$$\Leftrightarrow I_{i,j} = 2\frac{I_0}{E}\left(\frac{t_{load}}{D_{i,j}} + \frac{1}{v}\right)\frac{8760\, h/a}{t_{operation}} \tag{5}$$

assuming that the loading and unloading times are equal ($t_{unload} = t_{load}$). The annual fixed OPEX costs (m. €/km GW) result from:

$$OPEX_{Cap\ i,j} = k_{OM} I_{i,j}$$
$$\Leftrightarrow OPEX_{Cap\ i,j} = 2k_{OM}\frac{I_0}{E}\left(\frac{t_{load}}{D_{i,j}} + \frac{1}{v}\right)\frac{8760\, h/a}{t_{operation}} \tag{6}$$

[2] The provided investment costs of 484 m € refer to an overseas vessel with a capacity of 200 000 m^3. Using the exponential relation $I(E_1) = I_0 (\frac{E_1}{E_0})^n$ with $n = 0.67$ as utilized in the paper, the costs are scaled down to an inland vessel.

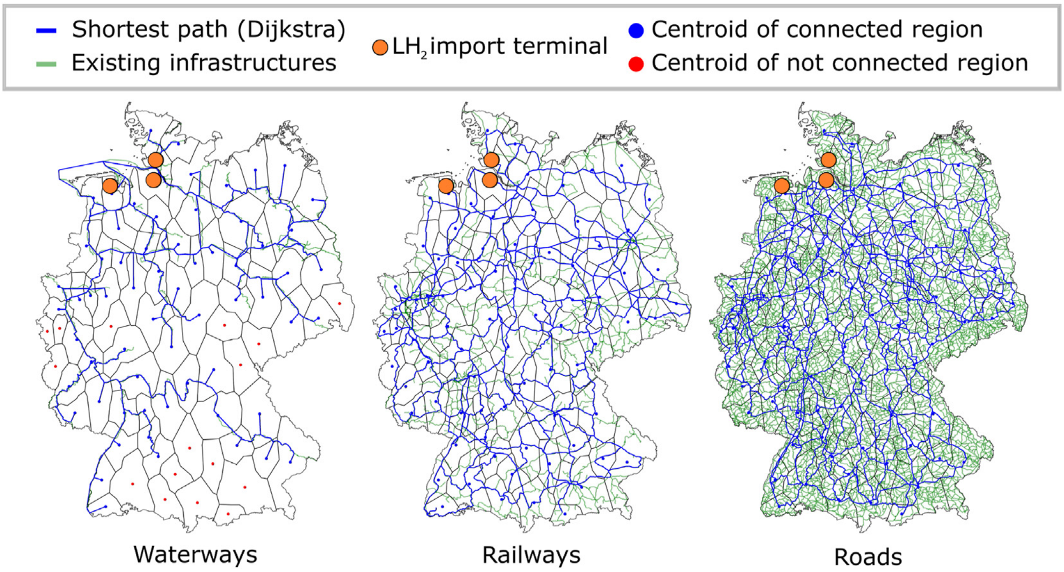


Fig. 4 – Shortest route by inland waterways, railways, and road between regions.

where k_{OM} describes the annual operation and maintenance costs as an annual percentage of the investment costs.

The OPEX costs for operation (m. €/km GW h) consist of costs per operation time, p_t and distance travelled, p_d. The former includes personnel costs; the latter includes fuel costs:

$$\begin{aligned} \mathrm{OPEX}_{\mathrm{Op}\ i,j} &= \frac{1}{8760\,h/a}\left(p_t t_{\mathrm{operation}} + p_d 2 D_{i,j} n_{i,j}\right) \\ \Leftrightarrow \mathrm{OPEX}_{\mathrm{Op}\ i,j} &= \frac{t_{\mathrm{operation}}}{8760\,h/a}\left(p_t + p_d\left(\frac{t_{\mathrm{load}}}{D_{i,j}} + \frac{1}{v}\right)^{-1}\right) \end{aligned} \tag{7}$$

Comparison of investment costs. Fig. 5 shows the specific investment costs according to Eq. (5) for the transport options introduced in Table 3 as a function of the distance between two regions. For comparison, the costs for newly-built and retrofitted GH_2 pipelines are also incorporated in this figure [78].

The results show that for distances under 1000 km, pipelines are cheaper in comparison to all means of liquid hydrogen transportation for moving the same energy quantity of hydrogen. This indicates that the higher energy density of LH_2 does not offset the higher investment costs. The cheapest option for LH_2 transport is rail. In comparison to inland vessels, trucks are the cheaper option for shorter distances of under 200 km (depending on the literature source); beyond this distance, it reverses, and the inland vessel becomes the cheaper option.

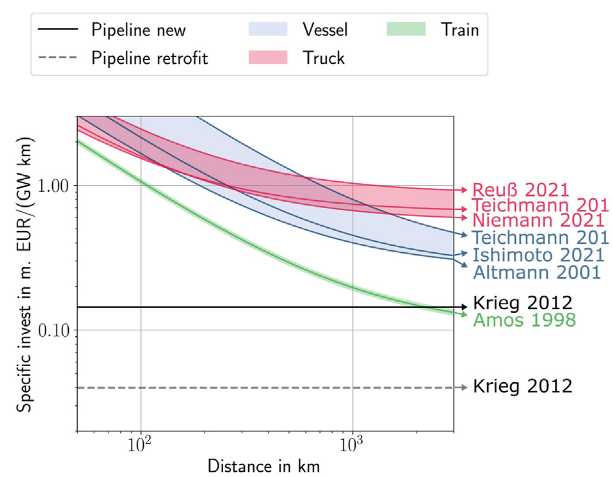


Fig. 5 – Investment costs for liquid and gaseous H_2 means of transportation as a function of the transport distance (inflation adjusted to 2021).

Results and discussion

The discussion of the results is divided into three parts: In section Cumulative Results, the focus lies on the cumulative results (not spatially resolved) of the entire energy system to compare the different scenarios. In section Spatially-Resolved Results, the *Reference (no LH_2)* and *Comprehensive (high LH_2)* scenario are highlighted to analyze the spatial distribution of selected infrastructures. In these two parts, the main observations are presented, followed by an explanation. The discussion closes with a contextualization of the optimization results (section Contextualization).

Cumulative results

The key observation is a shift of the energy system towards higher LH_2 imports, production, and transportation induced by higher LH_2 demand. This shift increases the TAC of the entire energy system due to the changed supply situation and thus higher costs for transportation, production, and import. The share of transport costs in the energy system (TAC, including loading terminals and compressor stations) more than doubles from 0.8% in the *Reference (no LH_2)* scenario to 2% in the *Comprehensive (high LH_2)* scenario. Figs. 6 and 7 depict the results of the scenario calculations. They present the quantity of transported LH_2 by rail, truck, and inland vessel as well as the supply of hydrogen for the six scenarios. The scenarios are arranged in ascending order of LH_2 demand.

LH_2 transportation is only utilized when LH_2 demands exist

The results of the *Reference (no LH_2)* scenario show that there is no import, production, and transportation of LH_2 when there is no LH_2 demand (see Fig. 6). The higher energy density of LH_2 in comparison to GH_2 does not sufficiently offset the higher import and transportation costs (as shown in Fig. 5). In a scenario variation where only LH_2 imports were allowed, no domestic LH_2 transport takes place. Instead, the LH_2 is regasified at the import location and transported via pipeline. Under the given techno-economic conditions, LH_2 transportation only makes sense in cases where there are LH_2 demands. Possible applications of LH_2 transportation without any LH_2 demands are the distribution of hydrogen on a lower regional level ("last mile" e.g., to individual filling stations or production sites) or the transmission of hydrogen in scenarios in which the construction of new GH_2 pipelines or the rededication of natural gas pipelines (retrofit) is not feasible.

To cover LH_2 demand, first trains, then vessels, then trucks are used

As LH_2 demands increase from one scenario to another, all means of LH_2 transportation are eventually utilized in the model, as shown in Fig. 6. They come into operation in ascending order of cost: First trains, then vessels, then trucks. The low LH_2 demand in the *Aviation* scenario can be fully supplied by rail transportation. As the LH_2 demand increases in the other scenarios, the limit for rail transport of 11 TWh/a (maximum send out in the two regions where the LH_2 import harbors are located) equivalent to four train deliveries with 25 railcars per day on average is reached. Vessel transportation is first utilized in the *Ammonia* scenario (10 TWh/a) and is expanded in the scenarios with higher LH_2 demands. In the *Comprehensive (high LH_2)* scenario the vessel transportation reaches 166 TWh/a, which is equivalent to an average of 38 vessel deliveries per day making up over 90% of the transported LH_2 in this scenario. The *Mobility & Transport* scenario is characterized by a high and decentralized LH_2 demand. As the rail capacities are exhausted and not all regions can be reached through waterways, the trucks come into operation in this scenario, delivering 1 TWh/a. Trucks also make a small contribution to the LH_2 transportation in the *Chemistry* and *Comprehensive (high LH_2)* scenario of up to 4 TWh/a which corresponds to an average of 72 truck deliveries per day. As Fig. 6 shows, rail transportation serves as a base load constantly delivering 11 TWh/a of LH_2 in the medium to high LH_2 demand scenarios. Trucks operate in high LH_2 demand scenarios to supply regions without waterway connections. Vessels serve as the main means of transportation as they scale up with the LH_2 demand in the system.

LH_2 transportation replaces pipeline transportation (to some extent)

As GH_2 demands are replaced by LH_2, and so is the amount of GH_2 transportation. Where in the *Reference (no LH_2)* scenario all the transported hydrogen was transmitted via pipeline, this share drops to 56% in the *Comprehensive (high LH_2)* scenario. The transport of GH_2, however, decreases less than the GH_2 demands: Although 65% of the GH_2 demands are replaced by LH_2 in the *Comprehensive (high LH_2)* scenario, only 44% of the transported GH_2 is replaced by LH_2. There are two reasons for this: First, GH_2 pipelines are still used to transport hydrogen to storage facilities (large-scale salt cavern storage). Secondly, it is used to supply liquefaction plants. The results show that domestically-produced LH_2 is not transported through the country, but rather produced on-site at the demand location. The necessary GH_2 can be produced directly within the LH_2 demand region. Alternatively, GH_2 is produced in the regions with high renewable energy potentials, and subsequently transported to the LH_2 demand regions. In the latter case, transportation is facilitated with pipelines.

First, the imports shift to LH_2, then the production

The visualization of the hydrogen supply in Fig. 7 can be divided into two segments: The bottom part represents hydrogen imports; the top domestic production. The maximum total amount of imports is determined by the ETHOS. NESTOR calculation and is therefore constant. The role of LH_2 imports and production steadily increases with higher LH_2 demand. The difference is that the GH_2 imports are replaced earlier and to a greater extent by LH_2 than in domestic production: With no LH_2 demand, all the hydrogen is imported as GH_2; with high LH_2 demand (exceeding the total amount of importable hydrogen), over 90% of the hydrogen is imported in liquid form. The low amount of remaining GH_2 imported (17 TWh/a) is used to supply GH_2 demands in the region of the GH_2 interconnector in the Saarland at the French border. None of the imported GH_2 is transported

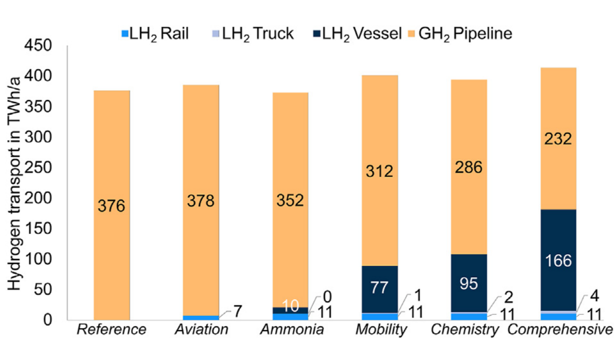


Fig. 6 – Transportation of liquid and gaseous hydrogen.

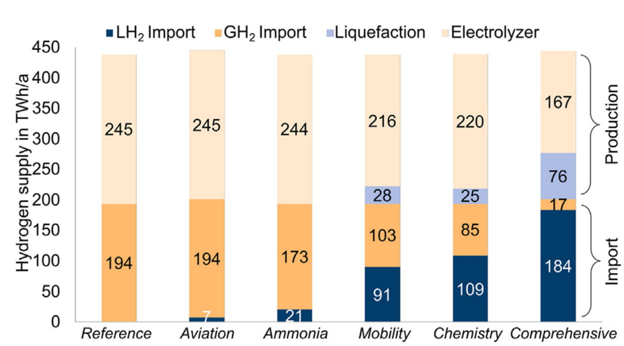


Fig. 7 – Supply of liquid and gaseous hydrogen.

further domestically. Thus, the domestic pipelines in the *Comprehensive (high LH_2)* scenario only carry domestically-produced hydrogen. Domestic liquefaction first arises in the *Mobility & Transport* scenario. With higher LH_2 demand, domestic liquefaction plays a more significant role. This is for two reasons: When the LH_2 demand exceeds the amount of hydrogen that can be imported, domestic liquefaction becomes necessary. Even before the import limit is reached, liquefaction takes place, predominately in southern Germany. Under the constraints of limited rail transport, limited river connections in southern Germany and the high costs of truck transportation, on-site liquefaction is the most economical option in these cases.

Spatially-resolved results

In the spatially resolved results, three main aspects are focused: the course of the LH_2 transportation options (discussed using Fig. 8), the influence on the hydrogen infrastructures in general (discussed using Fig. 9) and its influence on the GH_2 pipeline capacities in particular (discussed using Figs. 10 and 11). The analysis is based on the *Reference (no LH_2)* and *Comprehensive (high LH_2)* scenario.

LH_2 means of transportation are used to supply the greatest demand sites

The volume of LH_2 demand, import, and transportation of the different means of transportation is shown in Fig. 8 for the *Comprehensive (high LH_2)* scenario. The vessel transportation is split up into two major routes as shown in Fig. 8a: Imports from the harbor in Wilhelmshaven are directed in the direction of industry centers in North-Rhine Westphalia and Ludwigshafen in western Germany; imports from Brunsbüttel and Stade are forwarded to industrial sites in eastern Germany. Fig. 8b shows the optimal rail routes in the *Comprehensive (high LH_2)* scenario. They are also used to supply major hydrogen demand in the west and southwest of Germany. In the *Aviation* scenario where the overall LH_2 demand is lower, rail transportation is sufficient to supply all airports (e.g., in Cologne, Frankfurt, Munich, and Berlin) with hydrogen. Truck transportation plays a subordinate role in the LH_2 supply chain (see Fig. 8c). It is mainly used on a short route to transport LH_2 from the import to a neighboring region. Intermodal transport, where different means of LH_2 transportation are used in combination, can not be observed even though the model formulation allows it.

There is no distribution of domestically-produced LH_2

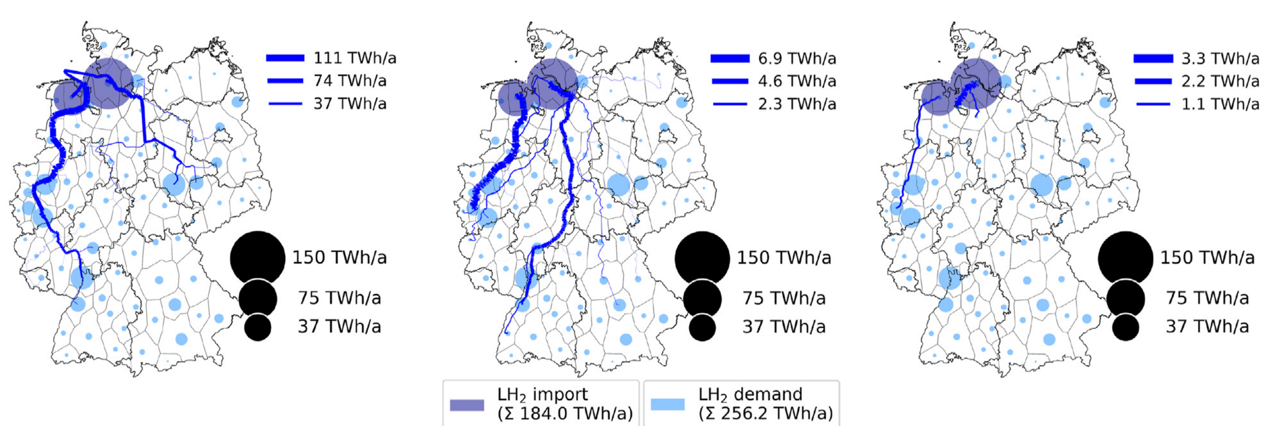
All LH_2 transportation starts from the import regions. Although there is domestic liquefaction in the *Comprehensive (high LH_2)* scenario, these plants are placed close to the demand in southern Germany (as discussed later), not close to favorable LH_2 production sites in northern Germany. No transport of domestically-produced LH_2 can be observed in this case study. This implies that the high transportation costs of LH_2 do not offset cheaper LH_2 production, and thus dictate the spatial distribution of the liquefaction plants.

LH_2 demand influences the GH_2 infrastructures

On the spatial scale, the key observation is that the GH_2 transmission infrastructures change drastically as LH_2 demand increases. This affects in particular western Germany (the federal states of North Rhine-Westphalia and Rhineland-Palatinate) and southern Germany (the federal states of Baden-Württemberg and Bavaria). This goes hand in hand with a change in the supply structure. Fig. 9 shows the spatially-resolved results of the *Reference (no LH_2)* (left) and the *Comprehensive (high LH_2)* scenario (right). The figures depict the GH_2 sinks (demands, re-electrification plants, e.g., hydrogen gas turbines, and liquefaction plants), sources (imports and electrolyzers), as well as the major pipeline routes.

Domestic liquefaction emerges in southern Germany

As the demands of LH_2 exceed the maximum allowed import in *Comprehensive (high LH_2)* scenario, domestic liquefaction becomes necessary. The results of the optimization show that the most economical distribution of the imported LH_2 is to first supply the regions closest to the import location. As the imports come from the north, many regions in southern Germany (Baden-Württemberg and Bavaria) are neither supplied



(a) Vessel transportation routes. Traffic on the busiest sections of the route is equivalent to 26 vessels per day.

(b) Rail transportation routes. Traffic on the busiest sections of the route is equivalent to 2 trains (á 25 railcars) per day.

(c) Truck transportation routes. Traffic on the busiest sections of the route is equivalent to 57 trucks per day.

Fig. 8 – LH_2 transportation infrastructures, LH_2 demand, and LH_2 import in the *Comprehensive (high LH_2)* scenario.

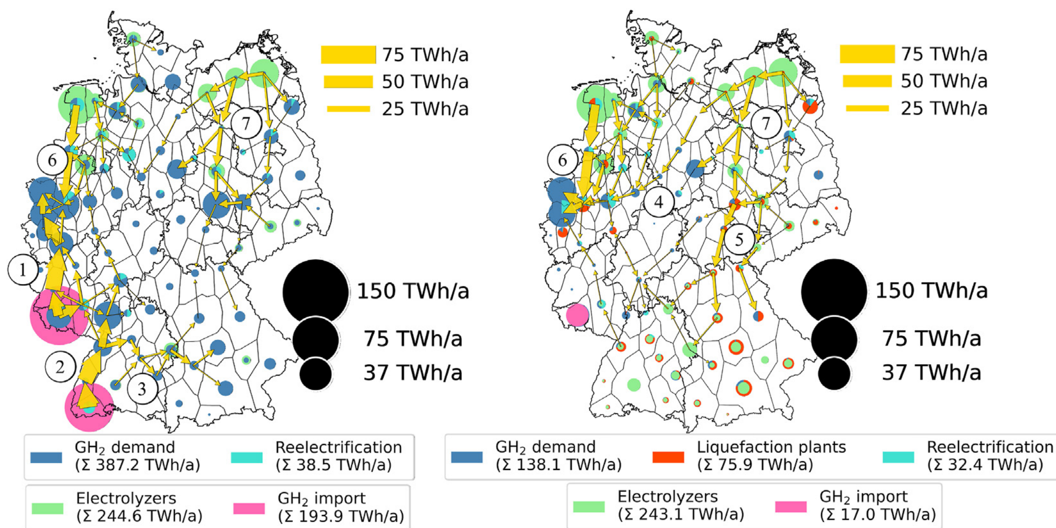


Fig. 9 – GH_2 transportation infrastructures, demand profiles, and supply of the *Reference (no LH_2)* scenario (left) and *Comprehensive (high LH_2)* scenario (right). Only pipeline routes with a capacity of over 1 GW (diameter > 350 mm) are included. The arrow indicates the direction of the net flow between two regions.

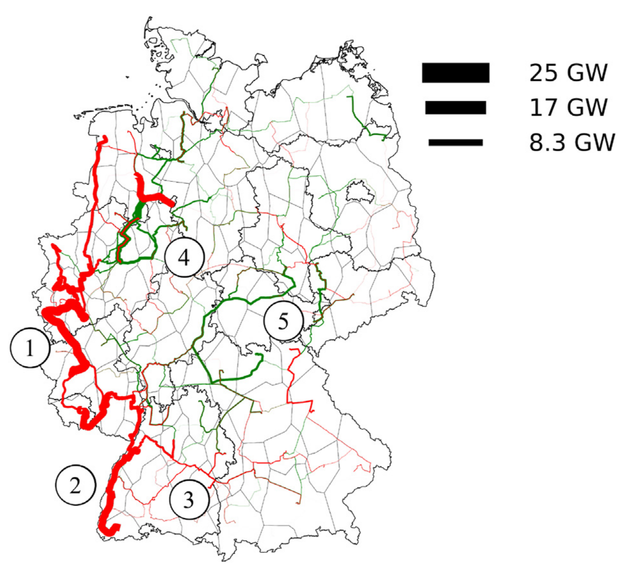


Fig. 10 – Pipeline expansion (green) and reduction (red) in the *Comprehensive (high LH_2)* scenario compared to the *Reference (no LH_2)* scenario. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

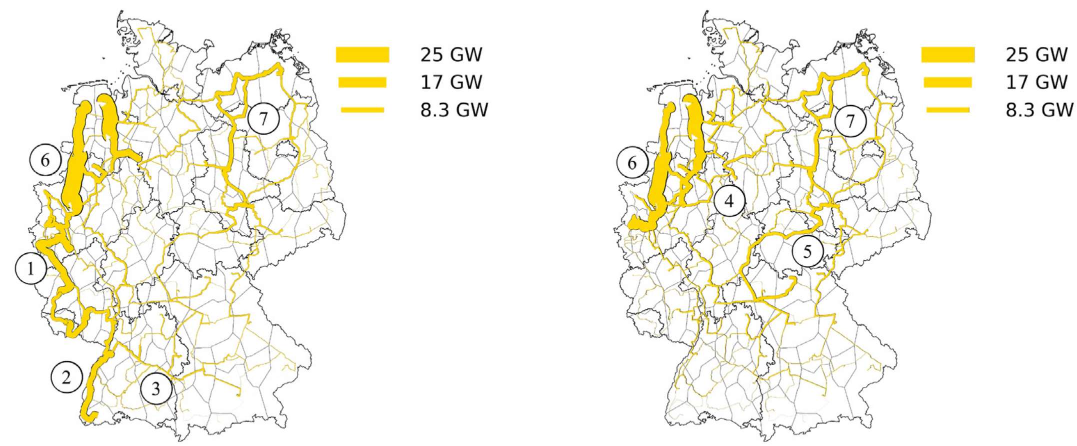
by rail, vessel nor truck. Instead, liquefaction is used in these regions, as shown in Fig. 9.

Electrolysis capacities move from north to south

The liquefaction of hydrogen in southern Germany uses both GH_2 that has been produced within the region and transferred GH_2 produced in northern Germany. The liquefaction of imported GH_2 does not take place under the given techno-economic conditions. In order to supply the liquefaction plants with a sufficient amount of GH_2, more electrolysis capacity is needed in the south (see Fig. 9). As the total amount of electrolysis capacity is set exogenously, only the spatial distribution of electrolyzers is endogenously optimized. Of the 105 GW_{el} of electrolyzer capacity, 19 GW_{el} more are located in Bavaria and Baden-Württemberg in the *Comprehensive (high LH_2)* scenario in comparison to the *Reference (no LH_2)* scenario. About 20% of the electrolyzer capacity undergo some change of regional distribution in the two scenarios. The majority of electrolyzers are placed in the northwest and northeast of Germany due to favorable production conditions for renewable energy, independently of the LH_2 demand.

Directions and the course of GH_2 pipelines change as the supply situation shifts

In the *Reference (no LH_2)* scenario, the west and south of Germany are primarily supplied by major retrofitted pipelines delivering imported GH_2 from France and Switzerland (see pipeline connections ①, ②, and ③ in Figs. 9 and 11). These pipelines, however, do not occur in the optimal solution of the *Comprehensive (high LH_2)* scenario (see Fig. 10), as no imported GH_2 is transported further inland (the remaining GH_2 imports (17 TWh/a) are used directly in the region of the interconnector). Instead, new pipeline routes arise or are being expanded: Three pipeline routes arise or change direction (in comparison to the *Reference (no LH_2)* scenario) in order to carry GH_2 produced by electrolyzers along the North Sea coast to North Rhine-Westphalia (see ④). In addition, the routes transporting hydrogen from the Baltic Sea coast to Bavaria and Baden-Württemberg are extended as shown at ⑤. This means that as the GH_2 supply shifts from imports towards domestic production, the flow direction and course of the GH_2 pipelines change as well. South-to-north connections are



(a) Pipeline routes built in the *Reference (no LH_2)* scenario.

(b) Pipeline routes built in the *Comprehensive (high LH_2)* scenario.

Fig. 11 – Built pipeline capacities in the *Reference (no LH_2)* and *Comprehensive (high LH_2)* scenario, and the difference in capacities between these scenarios. Routes (1), (2), and (3) are most significant in the *Reference (no LH_2)* scenario (connection to interconnectors), routes (4) and (5) gain importance in the *Comprehensive (high LH_2)* scenario (transport of LH_2 to west and south Germany), and routes (6) and (7) are crucial in all scenarios (connecting the electrolyzers at the North and Baltic Sea coast).

replaced by north-to-south ones in the high LH_2 demand scenarios.

Two other major routes remain the same in both scenarios: One connecting the electrolyzers at the North Sea coast with North Rhine-Westphalia; the other connects the electrolyzers along the Baltic Sea Coast with central (southeastern) Germany (see ⑥ and ⑦). These routes remain the same in both scenarios and can be considered *no regret measures*, as they are robust against changes in the supply structure.

Pipeline grids remain important even at high LH_2 demand levels
As noted earlier, pipelines continue to have a high significance as LH_2 demands rise: The total length of hydrogen pipelines increases from 26 700 km (including all GH_2 pipelines with a diameter of over 100 mm) in the *Reference (no LH_2)* scenario to 28 300 km in the *Comprehensive (high LH_2)* scenario. This increase of 7% goes along with a decrease in the average capacity (diameter) of the grid of 10%. Therefore, although the transmission capacity of the network and the total amount of transported hydrogen decrease, the length of the pipeline system remains at a high (and slightly increasing) level. What diminishes in importance is the application of newly-built pipelines. The vast majority of pipelines in the system are retrofitted. Only 0.4% of the pipelines are newly-built in the *Reference (no LH_2)* scenario. They are used to facilitate the transfer of hydrogen from the region of the GH_2 interconnector at the French border. The capacity of this pipeline section is reduced as LH_2 demand rises. The construction of new pipelines becomes fully obsolete in the *Chemistry* and *Comprehensive (high LH_2)* scenario.

Contextualization

The contextualization of the results focuses on the implementation of LH_2 in comparison to GH_2 pipeline transportation options and aims to put the transported LH_2 quantities in perspective in order to estimate the feasibility to implement the optimization results in the German energy system.

These results are consistent with the findings of Yang et al. (2007) [42]. The authors conclude that "liquid delivery is ideal for long distance delivery and moderate demand and pipeline delivery is ideal for dense areas with large hydrogen demand" [42]. The LH_2 demand in the regions of our study is predominantly (significantly) higher than 1 TWh/a (83 t/day) thus falling in the area of high demands in the Yang study, suggesting pipeline transportation as the most economical means of transportation.

The only other study analyzing LH_2 transportation by rail is Almansoori et al. (2016) [39]. In their study, they compare LH_2 and GH_2 transportation by rail and truck. The authors conclude, that " [h]ydrogen in liquid form is the preferred product delivery option given its higher energy density; while allowing transporting larger quantities of hydrogen. Furthermore, railcars are the most suitable product distribution option given its fuel price, flexibility, and availability in Germany." [39] This falls in line with the results of this study. Similar to our study, rail is used on the majority of routes in their model. Only a short connection (between Berlin and Potsdam) is covered by LH_2 transportation via truck. In our results, truck is also only used to overcome small distances of neighboring regions.

The truck volume of up to 72 trucks/day is small in comparison to other studies and to the traffic on Germany highways. The total level of truck traffic in Germany is at 1.13 m Trucks/day in 2021 [79]. On a single highway section, the traffic reaches about 1100 trucks/day [80]. In the study of Reuβ et al. (2021) [44] the authors investigate the transportation of hydrogen in the form of LH_2, compressed GH_2, and LOHC between hydrogen production sites and refueling stations in Germany. The results show, that the traffic volume induced by hydrogen transportation results in 1849 trucks/day (LH_2 trailers for distances over 130 km, GH_2 trucks for short distances) [44]. This shows that by also considering GH_2 pipeline transportation and alternative LH_2 means of transportation (rail, vessel) in this study, the congestion on the road network can be reduced.

To the best knowledge of the authors, there are no other studies investigating the transportation of LH_2 via inland vessels in Germany. In order to still validate the results, they shall be put into perspective. The number of 38 vessels/day (as presented in section Cumulative Results for the *Comprehensive (high* LH_2*)* scenario) is split up into two major routes, one in the direction of industry centers in North-Rhine Westphalia and Ludwigshafen in western Germany and one to eastern Germany, as shown in Fig. 8a. The former route has the higher traffic, with 26 vessels/day on average. This route leads along the rivers Weser, Hunte, the Küstenkanal (Coastal Canal) and the Dortmund-Ems Canal to the Rhine. A bottleneck might occur in the first parts of this route. 26 vessels/day equated to 9490 vessels/year. The Oldenburg lock (entrance point of the Küstenkanal) registers 3100 ships/year in both directions in the year 2021 [81]. Considering the return route of the LH_2 vessels, the volume of LH_2 traffic would be six times that of today's total number of ships on this route. This is not necessarily reason for concern, as this estimation applies to the *Comprehensive* scenario with the highest LH_2 demand. In other scenarios and in interim years leading up to 2045 possible LH_2 demand levels are significantly lower. Furthermore, a more detailed routing system for the inland vessels could lead to a better distribution of the traffic. In this optimization, the Küstenkanal is chosen as the shortest and most economic route. With a more detailed system in place, the traffic could be outsourced to the more southern Mittellandkanal.

Conclusions

In this work, a comprehensive comparison of LH_2 transportation options and its effect on a national energy system was conducted. For this purpose, an existing integrated energy system LP model was extended to cover LH_2 import, storage, transportation, and demand.

The literature review shows that LH_2 can be applied directly to supply fuel for the aviation sector. This option can gain relevance in domestic aviation from 2035 onwards. The other use case of LH_2 comes into play when high levels of hydrogen purity are required. This occurs in the application of fuel cell vehicles, or in the material use of hydrogen, e.g., in ammonia and methanol production. Rail transport, inland shipping, and trucks are identified as the most promising means of LH_2 transportation. For the first time, all three means of transportation and a broad range of hydrogen demand sectors are analyzed, embedded in a holistic energy system model also covering the commodities electricity, heat, and methane.

The case study for Germany shows LH_2 transportation is primarily used to connect LH_2 import regions with LH_2 demand regions. Without explicit LH_2 demand, however, LH_2 transport is not observed in a cost-optimal system. If further constraints such as high GH_2 purity requirements or the restriction of GH_2 pipeline expansion were added, LH_2 transportation could become useful in serving GH_2 demand. Furthermore, LH_2 transportation could play an important role in the distribution of hydrogen on a smaller regional scale, which was not investigated in this study.

In this investigation, different demand scenarios are developed. The key observation is, that the importance of LH_2 imports, transmission, and production grows as the demand for LH_2 increases. The individual means of transportation take on different roles in this system: Rail transport is the most economical transportation option evaluated in this investigation. The railway network in Germany is wide-ranging, but its capacity was the most restricted one due to congestion. The rail is used to its maximum potential in the scenarios where LH_2 demand must be served. Inland vessels are used for high-volume transportation, e.g., for the hydrogen supply of large chemical plants. In the high LH_2 demand scenarios, they carry the majority of transported LH_2. Trucks are the most expensive mode of transportation and best utilized in regions without waterway connections and when rail capacities are exhausted. The role of truck transportation could increase when investigating the distribution of hydrogen to areas where quantities are smaller, or the construction of pipelines is too expensive or technically-unfeasible (e.g., “last mile” delivery). Liquefaction can play an important role when LH_2 demand is high. These plants are placed in a decentralized pattern close to the demand sites, predominately in the south of Germany. The transportation of domestically-produced LH_2 is not observed.

The introduction of LH_2 demand has a significant effect on the GH_2 imports, the pipelines, and the placement of electrolyzers. When LH_2 demand is assumed for all sectors (mobility, chemical industry, and aviation), there are next to none GH_2 imports from France and Switzerland. This results in the decline of the corresponding domestic pipeline capacities in comparison to an all GH_2 scenario. Hydrogen demand in the south and west of Germany is subsequently no longer supplied by these routes. Instead, transmission pipelines from electrolyzers at the coasts are extended. The north-to-south GH_2 transmission corridor grows in importance. The need for liquefaction plants in high LH_2 demand scenarios also affects the spatial distribution of electrolyzers: Electrolyzer capacities from the west and center of Germany move closer to the regions in the south where liquefaction plants are operated.

In summary, LH_2 means of transportation can play a significant role in future energy systems. Railways constitute a cost-effective option, but bottlenecks in the rail network limit their potential. Inland waterway vessels can be an important means of transportation to supply chemical production plants with large quantities of hydrogen. The use of LH_2 means of transportation highly depends on hydrogen demand: High purity requirements favor the application of LH_2 railcars, vessels, and trucks in the energy system. Furthermore, the GH_2 infrastructures are highly affected by whether hydrogen demand is in liquid or gaseous form. This is of high importance for the identification of no regret measures, as the highest hydrogen demands in future energy systems are the ones with the highest LH_2 readiness.

For future research, the role of hydrogen purity can further be investigated. In this paper, GH_2 was modeled as a homogeneous good and LH_2 demands were defined exogenously based on scenario assumptions. In a follow-up investigation, the supply, demand, storage, transportation, and conversion of hydrogen can be modeled with specific hydrogen purity levels. In this way, different hydrogen infrastructure components like high purity pipelines, LH_2 means of transportation, and on-site purification could compete with each other in order to serve hydrogen demands of a certain purity. Furthermore, the role of LOHC, ammonia, and metal hydrides can be analyzed. In this case study, only LH_2 and GH_2 demands were considered. The effect other hydrogen carriers have on the domestic hydrogen supply chain is part of further research.

Declaration of competing interest

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

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REFERENCES

[1] IPCC. Summary for policymakers. In: Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, Craig M, Langsdorf S, Löschke S, Möller V, Okem A, Rama B, editors. Climate change 2022: impacts, adaptation and vulnerability. Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change. Cambridge, UK and New York, USA: Cambridge University Press; 2022 [Press].
[2] Bundestag Deutscher. Bundes-Klimaschutzgesetz: KSG. 2021.
[3] Energiewende Agora. Klimaneutrales Deutschland 2045: wie Deutschland seine Klimaziele schon vor 2050 erreichen kann. 2021.
[4] Jugel C, Albicker M. Dena-Leitstudie Aufbruch Klimaneutralität: Eine gesamtgesellschaftliche Aufgabe. 2021.
[5] BCG BDI. Klimapfade 2.0: ein Wirtschaftsprogramm für Klima und Zukunft. 2021.
[6] Sensfuss F, Sensfuß F, Lux B, Bernath C, Kiefer C, Pfluger B, et al. Langfristszenarien für die Transformation des Energiesystems in Deutschland 3: Kurzbericht: 3 Hauptszenarien. 2021.
[7] Luderer G, Kost C. Dominika, Deutschland auf dem Weg zur Klimaneutralität 2045: szenarien und Pfade im Modellvergleich. 2021.
[8] Stolten D, Markewitz P, Schöb T, Kullmann F, Kotzur Le a. New targets using old pathways? Strategies for a greenhouse gas neutral energy supply by 2045. 2021.
[9] Heuser P-M. Weltweite Infrastruktur zur Wasserstoffbereitstellung auf Basis erneuerbarer Energien. Ph.D. thesis. RWTH AAchen University; 2021.
[10] ISO. ISO 14687:2019 Hydrogen fuel quality — product specification. 27.10.2022. URL, https://www.iso.org/standard/69539.html.
[11] Nationaler Wasserstoffrat. Wasserstofftransport. 2021. URL, https://www.wasserstoffrat.de/fileadmin/wasserstoffrat/media/Dokumente/2021-07-02_NWR-Grundlagenpapier_Wasserstofftransport.pdf.
[12] Ratnakar RR, Gupta N, Zhang K, van Doorne C, Fesmire J, Dindoruk B, Balakotaiah V. Hydrogen supply chain and challenges in large-scale LH2 storage and transportation. Int J Hydrogen Energy 2021;46(47):24149–68. URL, https://www.sciencedirect.com/science/article/pii/S0360319921017067.
[13] Baroutaji A, Wilberforce T, Ramadan M, Olabi AG. Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors. Renew Sustain Energy Rev 2019;106:31–40.
[14] Baharozu E, Soykan G, Ozerdem MB. Future aircraft concept in terms of energy efficiency and environmental factors. Energy 2017;140:1368–77. URL, https://www.sciencedirect.com/science/article/pii/S036054421731513X.
[15] ATAG, Waypoint 2050. Balancing growth in connectivity with a comprehensive global air transport response to the climate emergency: a vision of net-zero aviation by mid-century. 2021. https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf.
[16] Airports Council International. Integration of hydrogen aircraft into the air transport system. https://www.ati.org.uk/wp-content/uploads/2021/08/aci-ati-hydrogen-report-1.pdf; 2021.
[17] FCH JU Clean Sky 2 Joint Undertaking, Hydrogen-powered aviation: a fact-based study of hydrogen technology, economics, and climate impact by 2050. Luxembourg: Wiley-VCH; May 2020.
[18] Elvers B, Ullmann F, editors. Ullmann's encyclopedia of industrial chemistry. 7th ed. Weinheim: Wiley-VCH; 2011.
[19] Bañares-Alcántara R, Dericks G, Fiaschetti M, Grünewald P, Masa Lopez J, Tsang E, Yang A, Ye L, Zhao S. Analysis of islanded ammonia-based energy storage systems. https://eng.ox.ac.uk/media/11082/ammonia-based_ess.pdf; 2015.
[20] Linde Engineering, Linde Hydrogen FuelTech. Tomorrow's fuel today. 2020. https://www.linde-gas.com/en/images/RLD_01_K19004_15_Hydrogen_Fuel_Tech_Broschuere_RZ_VIEW_tcm17-610582.pdf.
[21] Decker L. Liquid hydrogen distribution technology: HYPER closing seminar. 2019. https://www.sintef.no/globalassets/project/hyper/presentations-day-2/day2_1105_decker_liquid-hydrogen-distribution-technology_linde.pdf.
[22] United Nations Economic Commission for Europe. European Agreement concerning the international carriage of dangerous goods by inland waterways: (ADN) including the annexed regulations. applicable as from 1 January 2021, New York and Geneva. 2021. https://unece.org/sites/default/files/2021-01/ADN%202021%20English.pdf.
[23] Intergovernmental Organisation for International Carriage by Rail. Rid 2021: regulations concerning the international carriage of dangerous goods by rail. 2019.
[24] United Nations Economic Commission for Europe, Adr I. European agreement concerning the international carriage of dangerous goods by road. 2018.
[25] Narson S, Larson R. LNG on the rails - precursor to LH2 on the rails?. http://palmettocleanfuels.org/files/hydrogen/Nason_Chart_Rail.pdf; 2019.
[26] Department of transportation, code of federal regulations: title 49 - transportation, Part 179 - specifications for tank cars. 2017. https://www.ecfr.gov/current/title-49.
[27] Baird A, Ehrhart B, Glover A, LaFleur C. Federal oversight of hydrogen systems. 2021.
[28] J. Harbaugh, Barges Fill NASA Rocket Stage with Liquid Propellant, NASA (06.01.2021). URL https://www.nasa.gov/systems/sls/multimedia/barges-fill-nasa-rocket-stage-with-liquid-propellant.html.

[29] Harbaugh J. NASA loads liquid hydrogen tank test article on barge pegasus, NASA. https://www.nasa.gov/exploration/systems/sls/multimedia/nasa-loads-liquid-hydrogen-tank-test-article-on-barge-pegasus.html; 2018.
[30] Kawasaki, World's First Liquefied. Hydrogen carrier SUISO FRONTIER launches building an international hydrogen energy supply chain aimed at carbon-free society. Kawasaki Heavy Industries, Ltd; 2019.
[31] Alkhaledi AN, Sampath S, Pilidis P. A hydrogen fuelled LH2 tanker ship design. Ships Offshore Struct 2022;17(7):1555–64.
[32] Kawasaki heavy industries, ltd. Liquefied Hydrogen Carriers; 2020. https://global.kawasaki.com/en/stories/articles/vol18/.
[33] Markowz G, Dylla A, Elliger T. Icefuel an infrastructure system for cryogenic hydrogen storage, distribution and decentral use. In: Stolten D, Grube T, editors. 18th World Hydrogen Energy Conference 2010 - WHEC 2010, Schriften des Forschungszentrums Jülich Reihe Energie & Umwelt, Forschungszentrum IEF-3. Jülich; 2010. p. 365–71.
[34] Gronau S, Hoelzen J, Mueller T, Hanke-Rauschenbach R. Hydrogen-powered aviation in Germany: a macroeconomic perspective and methodological approach of fuel supply chain integration into an economy-wide dataset. Int J Hydrogen Energy 2023;48(14):5347–76.
[35] Parolin F, Colbertaldo P, Campanari S. Development of a multi-modality hydrogen delivery infrastructure: an optimization model for design and operation. Energy Convers Manag 2022;266:115650. https://www.sciencedirect.com/science/article/pii/S0196890422004460.
[36] He G, Mallapragada DS, Bose A, Heuberger CF, Gencer E. Hydrogen supply chain planning with flexible transmission and storage scheduling. IEEE Trans Sustain Energy 2021;12(3):1730–40.
[37] Cerniauskas S, Jose Chavez Junco A, Grube T, Robinius M, Stolten D. Options of natural gas pipeline reassignment for hydrogen: cost assessment for a Germany case study. Int J Hydrogen Energy 2020;45(21):12095–107.
[38] Cardella U, Decker L, Klein H. Roadmap to economically viable hydrogen liquefaction. Int J Hydrogen Energy 2017;42(19):13329–38. https://www.sciencedirect.com/science/article/pii/S0360319917302355.
[39] Almansoori A, Betancourt-Torcat A. Design of optimization model for a hydrogen supply chain under emission constraints - a case study of Germany. Energy 2016;111:414–29.
[40] Almansoori A, Shah N. Design and operation of a future hydrogen supply chain: multi-period model. Int J Hydrogen Energy 2009;34(19):7883–97. https://www.sciencedirect.com/science/article/pii/S036031990901235X.
[41] Strachan N, Balta-Ozkan N, Joffe D, McGeevor K, Hughes N. Soft-linking energy systems and GIS models to investigate spatial hydrogen infrastructure development in a low-carbon UK energy system. Int J Hydrogen Energy 2009;34(2):642–57. https://www.sciencedirect.com/science/article/pii/S036031990801402X.
[42] Yang C, Ogeden J. Determining the lowest-cost hydrogen delivery mode. Int J Hydrogen Energy 2007;32(2):268–86.
[43] Narayanan TM, He G, Gençer E, Shao-Horn Y, Mallapragada DS. Role of liquid hydrogen carriers in deeply decarbonized energy systems. ACS Sustainable Chem Eng 2022;10(33):10768–80.
[44] Reuß M, Dimos P, Léon A, Grube T, Robinius M, Stolten D. Hydrogen road transport analysis in the energy system: a case study for Germany through 2050. Energies 2021;14(11):3166. https://www.mdpi.com/1996-1073/14/11/3166.
[45] Niermann M, Timmerberg S, Drünert S, Kaltschmitt M. Liquid Organic Hydrogen Carriers and alternatives for international transport of renewable hydrogen. Renew Sustain Energy Rev 2021;135:110171.
[46] Teichmann D, Arlt W, Wasserscheid P. Liquid Organic Hydrogen Carriers as an efficient vector for the transport and storage of renewable energy. Int J Hydrogen Energy 2012;37(23):18118–32.
[47] Lahnaoui A, Wulf C, Dalmazzone D. Optimization of hydrogen cost and transport technology in France and Germany for various production and demand scenarios. Energies 2021;14(3):744. https://www.mdpi.com/1996-1073/14/3/744/htm.
[48] Ishimoto Y, Voldsund M, Nekså P, Roussanaly S, Berstad D, Gardarsdottir SO. Large-scale production and transport of hydrogen from Norway to Europe and Japan: value chain analysis and comparison of liquid hydrogen and ammonia as energy carriers. Int J Hydrogen Energy 2020;45(58):32865–83.
[49] Welder L, Ryberg D, Kotzur L, Grube T, Robinius M, Stolten D. Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in Germany. Energy 2018;158:1130–49.
[50] Kullmann F, Markewitz P, Kotzur L, Stolten D. The value of recycling for low-carbon energy systems - a case study of Germany's energy transition. Energy 2022;256:124660. https://www.sciencedirect.com/science/article/pii/S0360544222015638.
[51] Groß T. Multiregionales Energiesystemmodell mit Fokus auf Infrastrukturen, Ph.D. thesis. RWTH AAchen University; 2023.
[52] Cerniauskas S, Markewitz P, Linßen J, Kullmann F, Groß T, Lopion P, Heuser P-M, Grube T, Robinis M, Stolten D. Wissenschaftliche Begleitstudie der Wasserstoff Roadmap Nordrhein-Westfalen, Vol. Band 535 of Schriften des Forschungszentrums Jülich : [...], Reihe Energie & Umwelt, Forschungszentrum Jülich GmbH. Jülich: Zentralbibliothek, Verlag; 2021.
[53] Welder L, thesis PhD. Optimizing cross-linked infrastructure for future energy systems. RWTH AAchen University; 2022.
[54] European Commission. Commission staff working document implementing the REPowerEU action plan: investment needs. Hydrogen Accelerator and Achieving the Bio-Methane Targets; 2022.
[55] Okabe A. Spatial tessellations: concepts and applications of Voronoi diagrams. 2nd ed. Chichester: Wiley series in probability and statistics, Wiley; 2000. https://ebookcentral.proquest.com/lib/kxp/detail.action?docID=470072.
[56] Horsch J, Brown T. The role of spatial scale in joint optimisations of generation and transmission for European highly renewable scenarios, in: 2017 14th International Conference on the European Energy Market (EEM). IEEE; 2017. p. 1–7.
[57] Barthelemy H, Weber M, Barbier F. Hydrogen storage: recent improvements and industrial perspectives. Int J Hydrogen Energy 2017;42(11):7254–62.
[58] Al Ghafri SZ, Munro S, Cardella U, Funke T, Notardonato W, Trusler JPM, Leachman J, Span R, Kamiya S, Pearce G, Swanger A, Rodriguez ED, Bajada P, Jiao F, Peng K, Siahvashi A, Johns ML, May EF. Hydrogen liquefaction: a review of the fundamental physics, engineering practice and future opportunities. Energy Environ Sci 2022;15(7):2690–731. https://pubs.rsc.org/en/content/articlelanding/2022/ee/d2ee00099g.
[59] Drnevich R. Hydrogen delivery: liquefaction and compression. https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/liquefaction_comp_pres_praxair.pdf; 2003.
[60] Bonadio L. Fuels – HYDROGEN STORAGE | liquid. In: Garche J, editor. Encyclopedia of electrochemical power sources. Amsterdam: Elsevier; 2009. p. 421–39. https://www.sciencedirect.com/science/article/pii/B9780444527455003233.

[61] Eurostat. GISCO airports 2013 dataset. 2013. https://ec.europa.eu/eurostat/de/web/gisco/geodata/reference-data/transport-networks.
[62] Eurostat. Air passenger transport by main airports in each reporting country. 2019. https://appsso.eurostat.ec.europa.eu.
[63] Emissionshandelsstelle Deutsche. Emissionshandelspflichtige anlagen in deutschland 2019. 2020. https://www.dehst.de/SharedDocs/downloads/DE/anlagenlisten/2019.html.
[64] Cerniauskas S. Einführungsstrategien für Wasserstoff Infrastruktur. RWTH Aachen University; 2022.
[65] Amos WA. Costs of storing and transporting hydrogen. 1998.
[66] Altmann M, Gaus Landinger, stiller Wurster. Wasserstofferzeugung in offshore Windparks: killer-Kriterien, grobe Auslegung und Kostenabschätzung. 2001.
[67] Db Netz AG. Sachstand überlastete schienenwege 2022. 2022. https://fahrweg.dbnetze.com/resource/blob/4816508/e26bd54ecfd361a245e9b95852ad6e67/Sachstand-UeLS-Strecken-data.pdf.
[68] European conference of Ministers of transport, resolution No. 92/2 on new classification of iinland wwaterways. 1992.
[69] European Commission. Comission Regulation (EC) No 425/2007 of 19 April 2007 implementing Regulation (EC) No 1365/2006 of the European Parliament and of the Council on statistics of goods transport by inland waterways. 2007. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32007R0425&from=en.
[70] European Parliament. Directive 2008/106/EC of the European Parliament and of the Council of 19 November 2008 on the minimum level of training of seafarers (recast). 2008. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0106&from=PT.
[71] International Maritime Organization. Igc code. 2016. https://www.imo.org/en/OurWork/Safety/Pages/IGC-Code.aspx.
[72] Lantz J, Sutnikas A, Breitenbach S, Kluge B. Handbook on Technical Barge Concepts: for use under BSR specific navigation conditions. https://www.project-emma.eu/sites/default/files/EMMA_Act.%202.2.%20Report_final.pdf; 2018.
[73] Generaldirektion Wasserstraßen und Schifffahrt, Bundesministerium für Digitales und Verkehr, Bundeswasserstraßenkarte. https://www.gdws.wsv.bund.de/SharedDocs/Downloads/DE/Karten/Karten/DBWK1000_Generaldirektion_2022.pdf;jsessionid=C3547F222D80C465B7B26E7A65426B9A.live21304?__blob=publicationFile&v=3; 2022.
[74] European Commission, Geoportal Straßennetz - INSPIRE. https://inspire-geoportal.ec.europa.eu/results.html?country=de&view=details&theme=tn; 2020.
[75] Db Netz AG. Strecken und Bauwerke nach INSPIRE. https://data.deutschebahn.com/dataset/data-streckennetz.html; 2019.
[76] Wasserstraßen- und Schifffahrtsverwaltung des Bundes, Verkehrsnetz Bundeswasserstraßen. https://www.gdws.wsv.bund.de/DE/service/karten/03_VerkNet-BWaStr/VerkNet-BWaStr_node.html; 2020.
[77] Dijkstra EW. A note on two problems in connexion with graphs. Numer Math 1959;1(1):269–71.
[78] Krieg D. Konzept und Kosten eines Pipelinesystems zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff: zugl.: aachen. Techn. Hochsch., Diss 2012;144. of Schriften des Forschungszentrums Jülich Reihe Energie & Umwelt, Forschungszentrum Jülich, Jülich, 2012. URL, http://hdl.handle.net/2128/4608.
[79] Kraftfahrt-Bundesamt. Verkehrsaufkommen 2021. 2021. https://www.kba.de/DE/Statistik/Kraftverkehr/deutscherLastkraftfahrzeuge/vd_Verkehrsaufkommen/vd_verkehrsaufkommen_node.html.
[80] Wietschel M, Gnann T, Kühn A, Plötz P, Moll C, Speth D, Buch J, Boßmann T, Stütz S, Schellert M, Rüdiger D, Balz W, Frik H, Waßmuth V, Paufler-Mann D, Rödl A, Schade W, Mader S. Machbarkeitsstudie zur Ermittlung der Potentiale des Hybrid-Oberleitungs-Lkw. 2017.
[81] Generaldirektion Wasserstraßen und Schifffahrt. Verkehrsbericht 2021. 2021. https://www.gdws.wsv.bund.de/SharedDocs/Downloads/DE/Verkehrsberichte/Verkehrsbericht_2021.pdf?__blob=publicationFile&v=4.