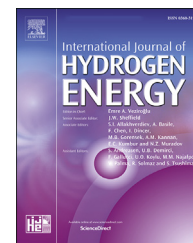


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The role of liquid hydrogen in integrated energy systems—A case study for Germany

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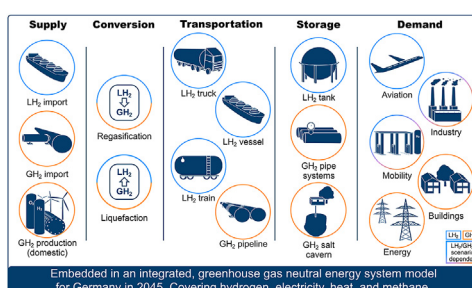
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HIGHLIGHTS

- 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 .

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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 (H₂) is considered a critical component in a future German energy systems [3–7]. Both domestic production and imports are relevant H₂ supply option for Germany. Its central location in Europe allows for pipeline import of gaseous hydrogen (GH₂) as well as the operation of harbor terminals to import liquid or bounded H₂ from overseas. These options include cryogenic liquid hydrogen (LH₂), 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 LH₂ and GH₂ 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 LH₂ in a national hydrogen supply chain (HSC).

The use and transportation of LH₂ in energy systems offers several advantages in comparison to gaseous hydrogen: Liquefying hydrogen leads to a high volumetric energy density of 2.4 MWh/m³, which is about four times higher than compressed GH₂ 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, LH₂ 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 GH₂ 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 LH₂ can be organized in a more flexible and modular way in comparison to GH₂ pipelines: Germany has a well-developed transport infrastructure network (highways, railways, waterways). These existing infrastructures enable LH₂ means of transportations (once developed) a faster connection to new destinations in comparison to the construction or repurposing of GH₂ 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 LH₂ 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 LH₂ Applications and Demand) and transportation (section LH₂ Transportation) options are introduced. In the third part (section Study Comparison), relevant studies in LH₂ HSC are presented. From these, the research gap and the proposed approach for this work is derived.

LH₂ applications and demand

Hydrogen is a promising solution for reducing greenhouse gas emissions in the industrial, transport, energy, and buildings sectors [8]. For LH₂, direct and indirect potential use cases will emerge in future energy systems. The aviation sector is an example for the direct use of LH₂. As weight and space must be efficiently managed in air travel [13,14], the high energy density of LH₂ 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]. LH₂ can be best applied in short-to medium-haul aircraft of up to 150 seats [16]. The market launch of LH₂ in the aviation sector is expected by 2035 [17].

Possible indirect use cases of LH₂ 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 LH₂-GH₂ application include Linde's commercial fueling station in Sacramento (CA), USA, and in Iwatai, Amagasaki City, Japan, that incorporate LH₂ delivery and LH₂ on-site storage to serve GH₂ (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 GH₂ solutions, which are smaller by a factor of four [21].

LH₂ transportation

The transportation of LH₂ 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: LH₂ trucks are already in operation today, with cargo capacities of around 50 m³ [20], whereas LH₂ railcars were last operated during the NASA space program in the 1960s [25]. Although there are still technical difficulties facing the realization of LH₂ 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 m³.

NASA also uses barges for the transportation of LH₂ on inland waters. Tugged LH₂ barges with storage capacities of 3000 m³ first came into operation in the 1960s and continue to be used today by NASA [28,29]. In 2020, Kawasaki launched the Suiso Frontier, the first prototype LH₂ carrier for overseas transport [30]. The ship carries 1250 m³ of LH₂ 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 m³ of storage, but its size is expected to be matched in future LH₂ designs [31,32].

The transport of LH₂ 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, LH₂ is being compared to GH₂, LOHC, and ammonia. The greatest number of studies compare the carriers LH₂ and GH₂ [34–42], followed by the comparison of LH₂, LOHC, and GH₂ [43–47] and the comparison of LH₂ 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 (GH₂) 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 LH₂ means of transportation, second there is no study considering a wide range of LH₂ and GH₂ demands (industry, buildings, energy, transportation, aviation) and third, there is no study analyzing the role of LH₂ in a comprehensive and integrated energy system covering hydrogen, electricity, heat, and methane.

In this study, an intensive analysis of a domestic LH₂ supply chain is conducted. The LH₂ 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 LH₂ 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 H₂ demand: Aviation, Buildings, Energy, Industry, Mobility & Transportation.

^c Regional scope: international, national, regional, transnational.

impact of different LH₂ demand cases on the hydrogen transportation infrastructure is assessed. The purpose of this analysis is to investigate the role of LH₂ in future energy systems. This incorporates the following research questions.

1. What are applications for LH₂ in future energy systems?
2. What are the most promising technologies for LH₂ transportation?
3. In which cases is LH₂ transportation, and in which is GH₂ transportation the more economical choice?
4. What is the optimal way to design the LH₂ supply in future energy systems?
5. How does the introduction of LH₂ demand affect the remaining infrastructures of the energy system?

Methodology, materials, and model description

To analyze the role of LH₂ 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 LH₂ introduces the expansion of the model suite and thus the contribution of this paper. It describes in detail the implementation of a LH₂ 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, CO₂ 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 CO₂ reduction targets for 2045 and for milestone years along the transformation path. For the year 2045 it mandates net CO₂ 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),

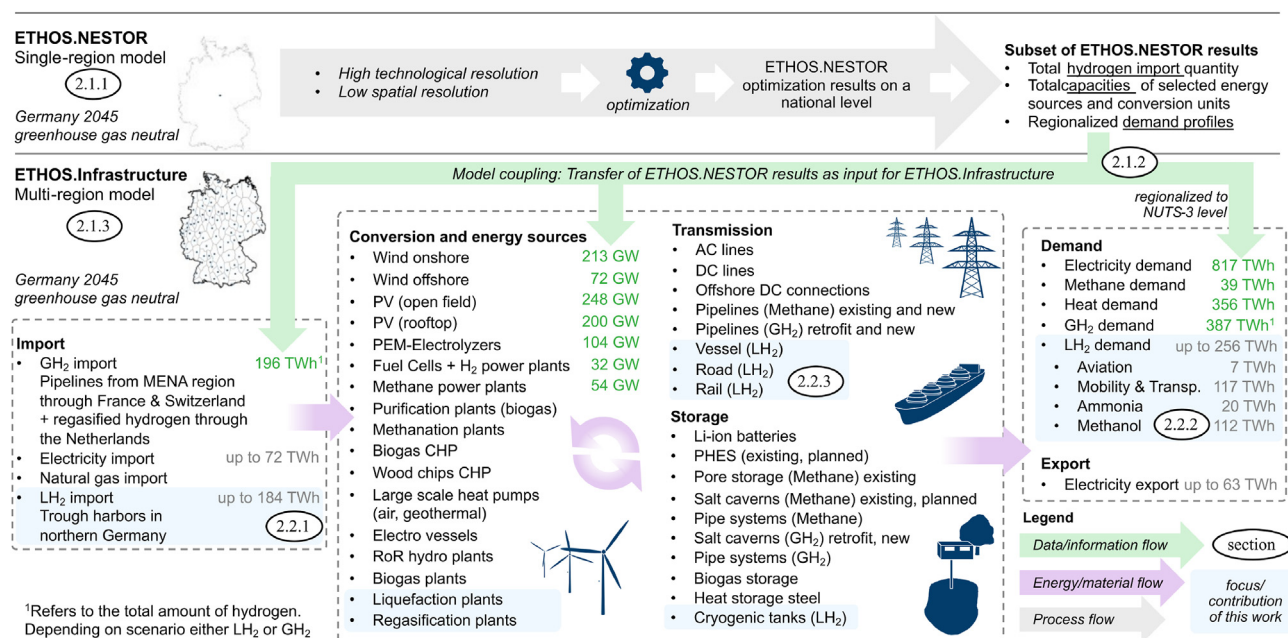


Fig. 1 – Scheme of the ETHOS. Infrastructure model and the model coupling to ETHOS. NESTOR. Circled numbers refer to the corresponding section in the methodology.

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 off-take system for the energy carriers of electricity, natural gas, GH₂, 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 Brown¹ [56].

Implementation and modeling of LH₂

For this investigation, the base case energy system is extended with the energy carrier LH₂ and its corresponding means of transportation, sources, sinks, storages, and conversion technologies across a future LH₂ supply chain. The implementation of the core components of this supply chain in the ETHOS model is described in detail in section LH₂ Supply (supply), section LH₂ Demand (demand), and section Inland Distribution of LH₂ (transportation).

LH₂ supply

Liquefaction plants can produce LH₂ 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 LH₂ in this study. These ports are eligible locations for LNG import terminals, and are therefore viable to be retrofitted into LH₂ 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 LH₂ from the above-mentioned ports in northern Germany providing international hydrogen at 3.22 €/kg, as GH₂ 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 GH₂ from an interconnector at the Dutch border providing GH₂ that was imported to the Netherlands as LH₂.

LH₂ demand

The aim of this study is to investigate how the introduction of LH₂ demand influences the design of hydrogen transportation infrastructures. Demand profiles for LH₂ are considered in the sectors chemical industry (methanol and ammonia production), aviation and transport & mobility according to the literature review in section LH₂ Applications and Demand. To investigate the correlation of higher LH₂ demands and changes in the infrastructures, a set of scenarios is developed: In ascending order there is a *Reference (no LH₂)* scenario without any LH₂ demand, four scenarios with LH₂ demand in single sectors, and a *Comprehensive (high LH₂)* scenario that considers LH₂ demand in all the selected sectors.

As LH₂ was not considered in the ETHOS. NESTOR scenario, adjustments must be made to the hydrogen demand: In order to take LH₂ into account in ETHOS. Infrastructure, GH₂ demand profiles from ETHOS. NESTOR are reclassified as LH₂ in the respective scenarios (methanol and ammonia production, transportation & mobility) and additional LH₂ profiles are added to the model (aviation). For all the other sectors (e.g., process heat, buildings), the demands are considered as GH₂. Fig. 2 lists the total liquid and gaseous hydrogen demands for the six scenarios. The following sections describe how these LH₂ applications and demands are implemented in the expanded ETHOS. Infrastructure model for the different scenarios.

In the *Aviation* and *Comprehensive (high LH₂)* 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 GH₂ to LH₂ 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 LH₂ demand at the NUTS-3 level.

Reference (no LH₂) 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

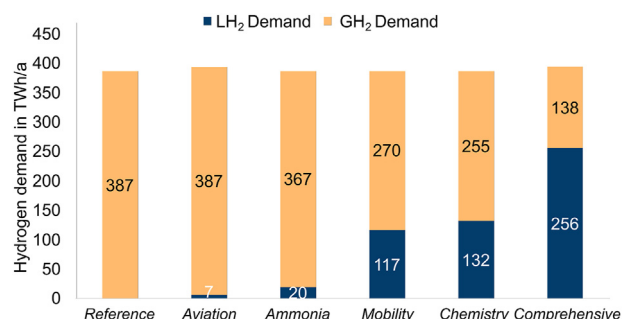


Fig. 2 – Total liquid and gaseous hydrogen demand levels in 2045 for the six LH₂ demand scenarios.

fuel cell vehicles, decentralized heating for buildings, process heat, and material use in industrial processes. The options for LH₂ transportation later described in section Inland Distribution of LH₂ are introduced in the model without incorporating any dedicated LH₂ demand. This aims to show whether the transportation of LH₂ is an economical option for serving GH₂ demand.

Aviation scenario. In ETHOS. NESTOR, only synfuels are considered as substitutes for kerosene in the aviation sector. In this study, LH₂ 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 LH₂ 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% LH₂ powered short- and medium-range aircraft by 2045. The LH₂ 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 LH₂ 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 LH₂ demand in the ammonia industry is considered (*Ammonia* scenario); in the high-demand one, LH₂ 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. CO₂ 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 CO₂ emissions at the corresponding production plants in 2019 [63] serve as a proxy to allocate the LH₂ 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 LH₂ instead of GH₂. These demands are distributed on the basis of current petrol station locations and those of non-electrified rail tracks [64].

Comprehensive (high LH₂) scenario. In the *Comprehensive (high LH₂)* scenario, the LH₂ demands of aviation and

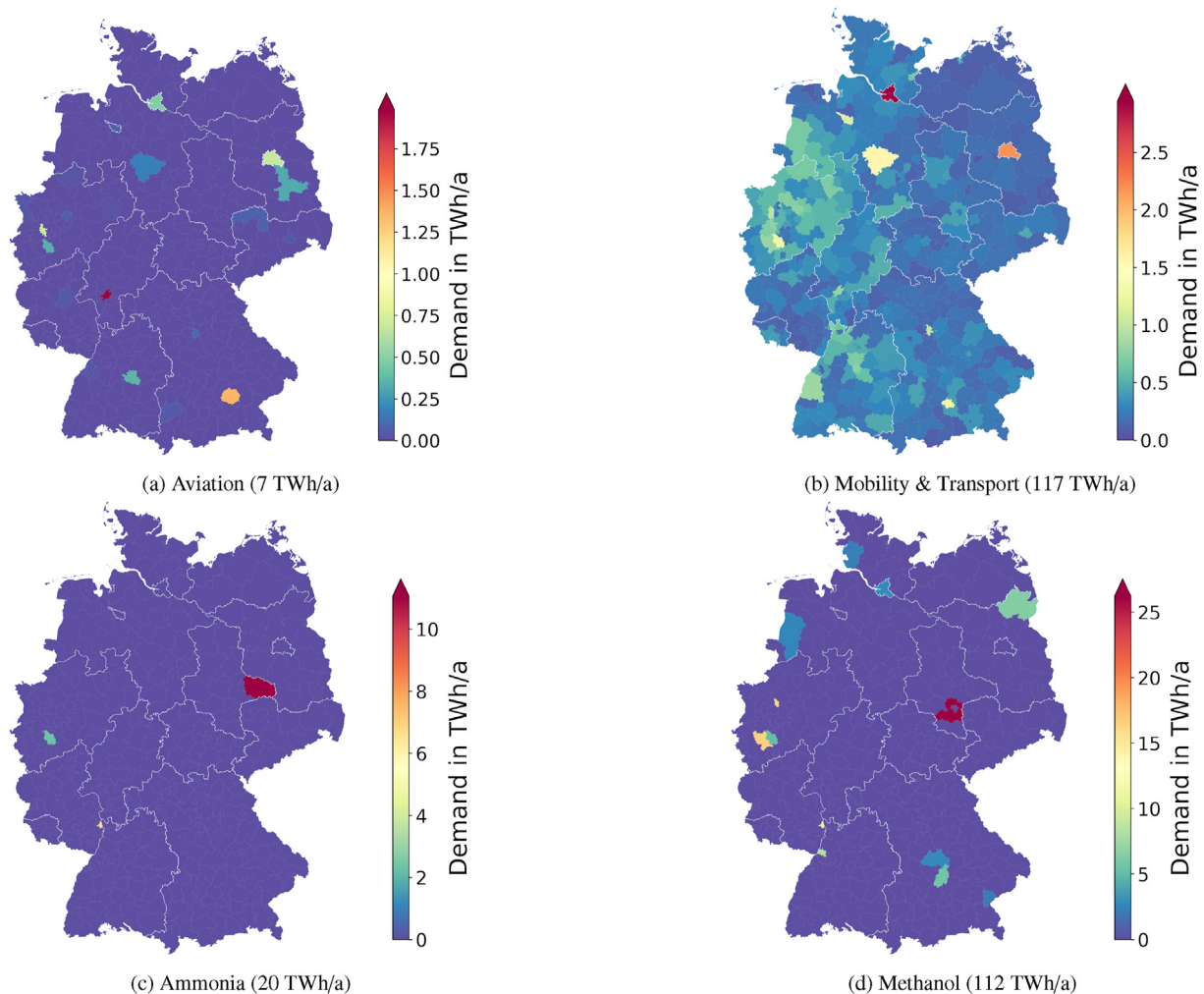


Fig. 3 – Spatial distribution of the LH₂ demand in the different sectors on a NUTS-3 level.

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

Inland distribution of LH₂

Waterway, rail, and road transportation are identified as potential LH₂ 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 LH₂ inland transportation from the studies

introduced in section LH₂ 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 m³, the techno-economic parameters being taken from Reuß et al. (2021) [44]. For railcars, the capacity is assumed to be 128 m³, 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 LH₂ 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 LH₂ according to literature.

Quantity	Unit	Reuß*, 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
Freight capacity	[t]	4.3	3.5	4.5	9.1	1050	354	1050
	[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.

¹Data according to literature source, without inflation. Inflation is subsequently taken into account in the model.

²Information added from other source. ^aNiermann, 2021 [45], ^bReuß, 2021 [44]; ^cTeichmann, 2012 [46].

total storage capacity of 5000 m³ 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 Ishimoto² et al. (2020) [48].

LH₂ 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:

$$C_{ij} = \frac{E n_{ij}}{8760 h/a} \quad (1)$$

where E is the transportable energy content per LH₂ 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:

² The provided investment costs of 484 m € refer to an overseas vessel with a capacity of 200 000 m³. Using the exponential relation $I(E_1) = I_0 (E_1/E_0)^n$ with $n = 0.67$ as utilized in the paper, the costs are scaled down to an inland vessel.

$$n_{ij} = \frac{t_{\text{operation}}}{t_{\text{roundtrip},ij}} \quad (2)$$

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

$$t_{\text{roundtrip},ij} = t_{\text{load}} + \frac{2D_{ij}}{v} + t_{\text{unload}} \quad (3)$$

where D_{ij} 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:

$$C_{ij} = \frac{E}{t_{\text{load}} + \frac{2D_{ij}}{v} + t_{\text{unload}}} \frac{t_{\text{operation}}}{8760 h/a} \quad (4)$$

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:

$$I_{ij} = \frac{I_0}{C_{ij} D_{ij}} \quad (5)$$

$$\Leftrightarrow I_{ij} = 2 \frac{I_0}{E} \left(\frac{t_{\text{load}}}{D_{ij}} + \frac{1}{v} \right) \frac{8760 h/a}{t_{\text{operation}}}$$

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

$$\text{OPEX}_{\text{Cap } ij} = k_{\text{OM}} I_{ij} \quad (6)$$

$$\Leftrightarrow \text{OPEX}_{\text{Cap } ij} = 2 k_{\text{OM}} \frac{I_0}{E} \left(\frac{t_{\text{load}}}{D_{ij}} + \frac{1}{v} \right) \frac{8760 h/a}{t_{\text{operation}}}$$

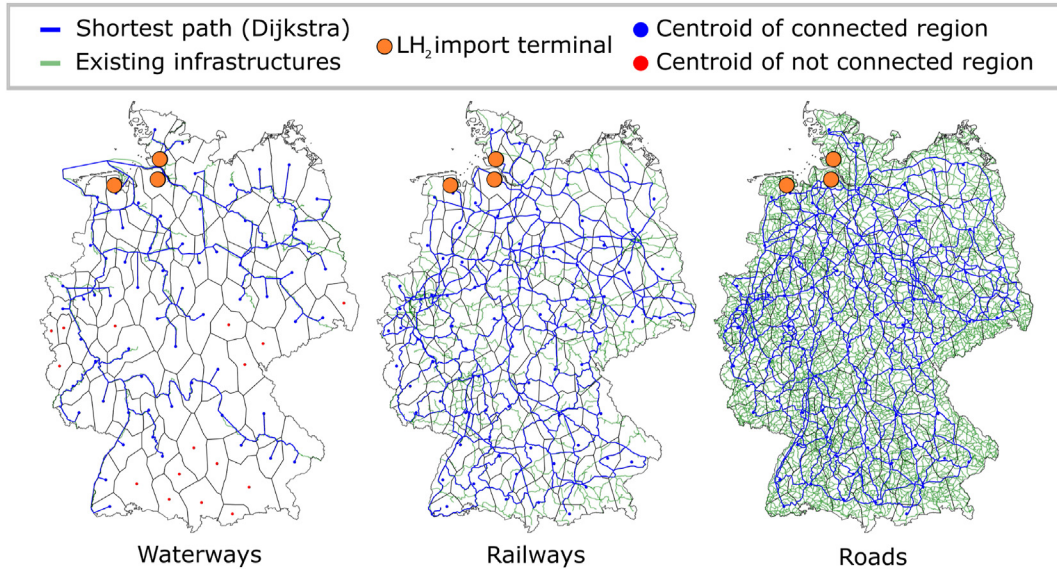


Fig. 4 – Shortest route by inland waterways, railways, and road between regions.

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:

$$\begin{aligned} OPEX_{Op\ ij} &= \frac{1}{8760\ h/a} (p_t t_{operation} + p_d 2D_{ij} n_{ij}) \\ \Leftrightarrow OPEX_{Op\ ij} &= \frac{t_{operation}}{8760\ h/a} \left(p_t + p_d \left(\frac{t_{load}}{D_{ij}} + \frac{1}{v} \right)^{-1} \right) \end{aligned} \quad (7)$$

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 GH₂ 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 LH₂ does not offset the higher investment costs. The cheapest option for LH₂ 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.

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 LH₂) and Comprehensive (high LH₂)

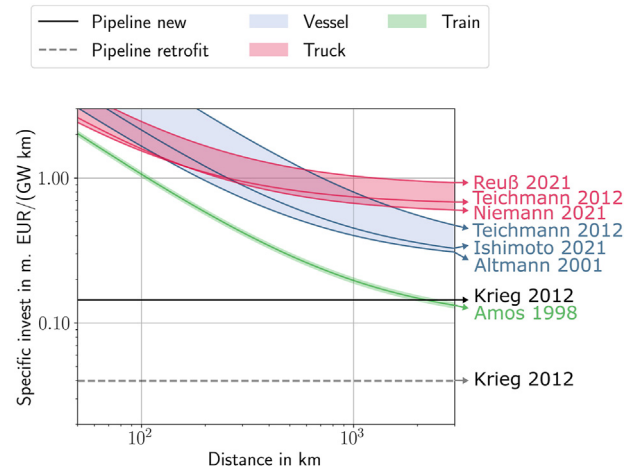


Fig. 5 – Investment costs for liquid and gaseous H₂ means of transportation as a function of the transport distance (inflation adjusted to 2021).

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 LH₂ imports, production, and transportation induced by higher LH₂ 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 LH₂)* scenario to 2% in the *Comprehensive (high LH₂)* scenario. Figs. 6 and 7 depict the results of the scenario calculations. They present the quantity of transported LH₂ 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 LH₂ demand.

LH₂ transportation is only utilized when LH₂ demands exist

The results of the *Reference (no LH₂)* scenario show that there is no import, production, and transportation of LH₂ when there is no LH₂ demand (see Fig. 6). The higher energy density of LH₂ in comparison to GH₂ does not sufficiently offset the higher import and transportation costs (as shown in Fig. 5). In a scenario variation where only LH₂ imports were allowed, no domestic LH₂ transport takes place. Instead, the LH₂ is regasified at the import location and transported via pipeline. Under the given techno-economic conditions, LH₂ transportation only makes sense in cases where there are LH₂ demands. Possible applications of LH₂ transportation without any LH₂ 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 GH₂ pipelines or the rededication of natural gas pipelines (retrofit) is not feasible.

To cover LH₂ demand, first trains, then vessels, then trucks are used

As LH₂ demands increase from one scenario to another, all means of LH₂ 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 LH₂ demand in the *Aviation* scenario can be fully supplied by rail transportation. As the LH₂ demand increases in the other scenarios, the limit for rail transport of 11 TWh/a (maximum send out in the two regions where the LH₂ 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 LH₂ demands. In the *Comprehensive (high LH₂)* 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 LH₂ in this scenario. The *Mobility & Transport* scenario is characterized by a high and decentralized LH₂ 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 LH₂ transportation in the *Chemistry* and *Comprehensive (high LH₂)* 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 LH₂ in the medium to high LH₂ demand scenarios. Trucks operate in high LH₂ demand scenarios to supply regions without waterway connections. Vessels serve as the main means of transportation as they scale up with the LH₂ demand in the system.

LH₂ transportation replaces pipeline transportation (to some extent)

As GH₂ demands are replaced by LH₂, and so is the amount of GH₂ transportation. Where in the *Reference (no LH₂)* scenario all the transported hydrogen was transmitted via pipeline, this share drops to 56% in the *Comprehensive (high LH₂)* scenario. The transport of GH₂, however, decreases less than the GH₂ demands: Although 65% of the GH₂ demands are replaced by LH₂ in the *Comprehensive (high LH₂)* scenario, only 44% of the transported GH₂ is replaced by LH₂. There are two reasons for this: First, GH₂ 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 LH₂ is not transported through the country, but rather produced on-site at the demand location. The necessary GH₂ can be produced directly within the LH₂ demand region. Alternatively, GH₂ is produced in the regions with high renewable energy potentials, and subsequently transported to the LH₂ demand regions. In the latter case, transportation is facilitated with pipelines.

First, the imports shift to LH₂, 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 LH₂ imports and production steadily increases with higher LH₂ demand. The difference is that the GH₂ imports are replaced earlier and to a greater extent by LH₂ than in domestic production: With no LH₂ demand, all the hydrogen is imported as GH₂; with high LH₂ demand (exceeding the total amount of importable hydrogen), over 90% of the hydrogen is imported in liquid form. The low amount of remaining GH₂ imported (17 TWh/a) is used to supply GH₂ demands in the region of the GH₂ interconnector in the Saarland at the French border. None of the imported GH₂ is transported

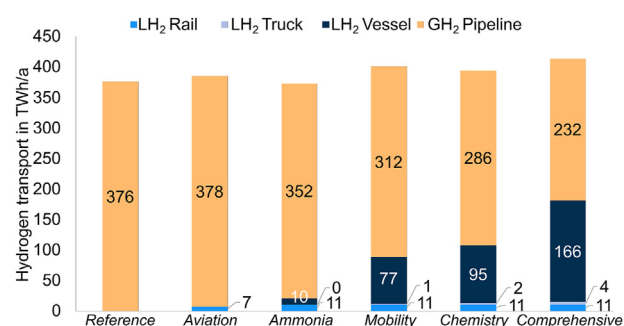


Fig. 6 – Transportation of liquid and gaseous hydrogen.

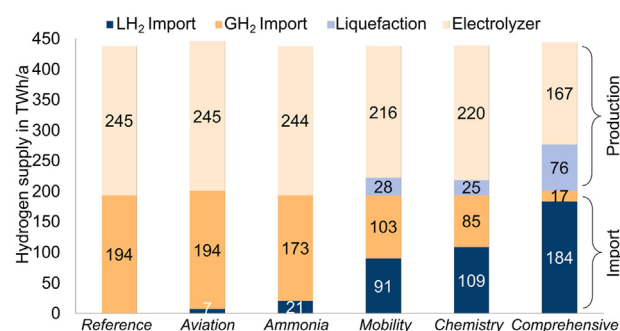


Fig. 7 – Supply of liquid and gaseous hydrogen.

further domestically. Thus, the domestic pipelines in the *Comprehensive (high LH₂)* scenario only carry domestically-produced hydrogen. Domestic liquefaction first arises in the *Mobility & Transport* scenario. With higher LH₂ demand, domestic liquefaction plays a more significant role. This is for two reasons: When the LH₂ 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 LH₂ transportation options (discussed using Fig. 8), the influence on the hydrogen infrastructures in general (discussed using Fig. 9) and its influence on the GH₂ pipeline capacities in particular (discussed using Figs. 10 and 11). The analysis is based on the *Reference (no LH₂)* and *Comprehensive (high LH₂)* scenario.

LH₂ means of transportation are used to supply the greatest demand sites

The volume of LH₂ demand, import, and transportation of the different means of transportation is shown in Fig. 8 for the *Comprehensive (high LH₂)* 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 LH₂)* scenario. They are also used to supply major hydrogen demand in the west and southwest of Germany. In the *Aviation* scenario where the overall LH₂ 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 LH₂ supply chain (see Fig. 8c). It is mainly used on a short route to transport LH₂ from the import to a neighboring region. Intermodal transport, where different means of LH₂ transportation are used in combination, can not be observed even though the model formulation allows it.

There is no distribution of domestically-produced LH₂

All LH₂ transportation starts from the import regions. Although there is domestic liquefaction in the *Comprehensive (high LH₂)* scenario, these plants are placed close to the demand in southern Germany (as discussed later), not close to favorable LH₂ production sites in northern Germany. No transport of domestically-produced LH₂ can be observed in this case study. This implies that the high transportation costs of LH₂ do not offset cheaper LH₂ production, and thus dictate the spatial distribution of the liquefaction plants.

LH₂ demand influences the GH₂ infrastructures

On the spatial scale, the key observation is that the GH₂ transmission infrastructures change drastically as LH₂ 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 LH₂)* (left) and the *Comprehensive (high LH₂)* scenario (right). The figures depict the GH₂ 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 LH₂ exceed the maximum allowed import in *Comprehensive (high LH₂)* scenario, domestic liquefaction becomes necessary. The results of the optimization show that the most economical distribution of the imported LH₂ 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

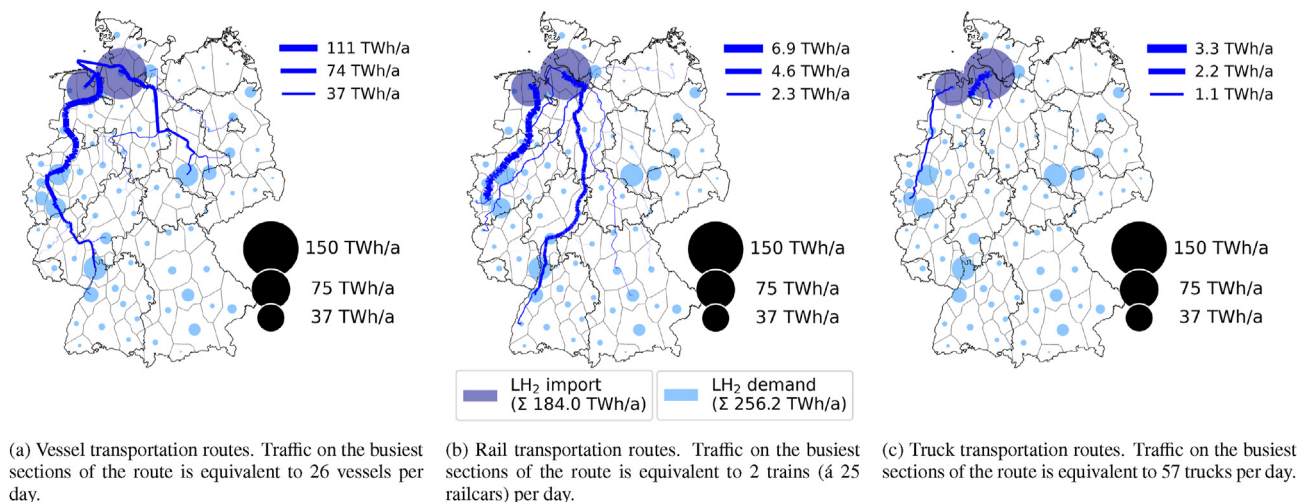


Fig. 8 – LH₂ transportation infrastructures, LH₂ demand, and LH₂ import in the *Comprehensive (high LH₂)* scenario.

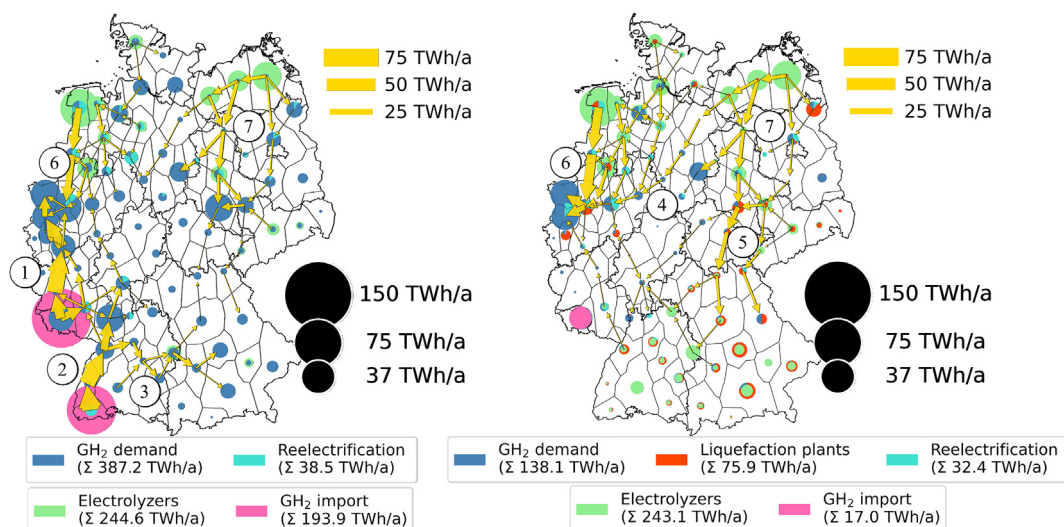


Fig. 9 – GH₂ transportation infrastructures, demand profiles, and supply of the *Reference (no LH₂)* scenario (left) and *Comprehensive (high LH₂)* scenario (right). Only pipeline routes with a capacity of over 1 GW (diameter > 350 mm) are included. The arrow indicates the direction of the net flow between two regions.

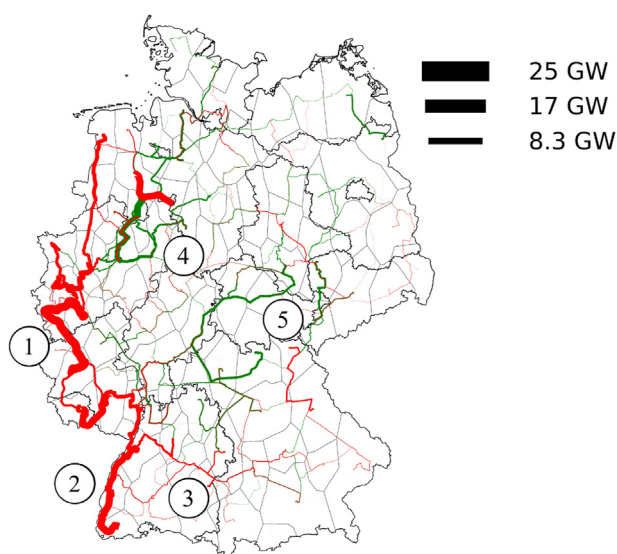


Fig. 10 – Pipeline expansion (green) and reduction (red) in the *Comprehensive (high LH₂)* scenario compared to the *Reference (no LH₂)* scenario. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

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 GH₂ that has been produced within the region and transferred GH₂ produced in northern Germany. The liquefaction of imported GH₂ does not take place under the given techno-

economic conditions. In order to supply the liquefaction plants with a sufficient amount of GH₂, 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 LH₂)* scenario in comparison to the *Reference (no LH₂)* 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 LH₂ demand.

Directions and the course of GH₂ pipelines change as the supply situation shifts

In the *Reference (no LH₂)* scenario, the west and south of Germany are primarily supplied by major retrofitted pipelines delivering imported GH₂ 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 LH₂)* scenario (see Fig. 10), as no imported GH₂ is transported further inland (the remaining GH₂ 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 LH₂)* scenario) in order to carry GH₂ 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 GH₂ supply shifts from imports towards domestic production, the flow direction and course of the GH₂ pipelines change as well. South-to-north connections are

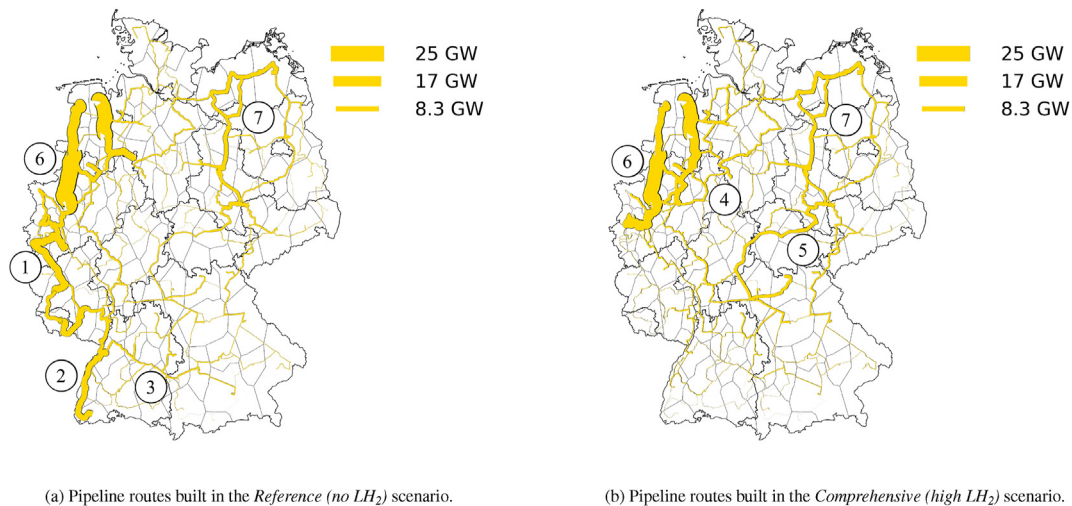


Fig. 11 – Built pipeline capacities in the Reference (no LH₂) and Comprehensive (high LH₂) scenario, and the difference in capacities between these scenarios. Routes (1), (2), and (3) are most significant in the Reference (no LH₂) scenario (connection to interconnectors), routes (4) and (5) gain importance in the Comprehensive (high LH₂) scenario (transport of LH₂ 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 LH₂ 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 LH₂ demand levels
As noted earlier, pipelines continue to have a high significance as LH₂ demands rise: The total length of hydrogen pipelines increases from 26 700 km (including all GH₂ pipelines with a diameter of over 100 mm) in the Reference (no LH₂) scenario to 28 300 km in the Comprehensive (high LH₂) 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 LH₂) scenario. They are used to facilitate the transfer of hydrogen from the region of the GH₂ interconnector at the French border. The capacity of this pipeline section is reduced as LH₂ demand rises. The construction of new pipelines becomes fully obsolete in the Chemistry and Comprehensive (high LH₂) scenario.

Contextualization

The contextualization of the results focuses on the implementation of LH₂ in comparison to GH₂ pipeline

transportation options and aims to put the transported LH₂ 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 LH₂ 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 LH₂ transportation by rail is Almansoori et al. (2016) [39]. In their study, they compare LH₂ and GH₂ 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 LH₂ 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 Reuß et al. (2021) [44] the authors investigate the transportation of hydrogen in the form of LH₂, compressed GH₂, 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 (LH₂ trailers for distances over 130 km, GH₂ trucks for short distances) [44]. This shows that by also considering GH₂ pipeline transportation and alternative LH₂ 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 LH₂ 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 LH₂)* 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 LH₂ vessels, the volume of LH₂ 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 LH₂ demand. In other scenarios and in interim years leading up to 2045 possible LH₂ 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 LH₂ 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 LH₂ import, storage, transportation, and demand.

The literature review shows that LH₂ 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 LH₂ 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 LH₂ 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 LH₂ transportation is primarily used to connect LH₂ import regions with LH₂ demand regions. Without explicit LH₂ demand, however, LH₂ transport is not observed in a cost-optimal system. If further constraints such as high GH₂ purity requirements or the restriction of GH₂ pipeline expansion were added, LH₂

transportation could become useful in serving GH₂ demand. Furthermore, LH₂ 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 LH₂ imports, transmission, and production grows as the demand for LH₂ 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 LH₂ 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 LH₂ demand scenarios, they carry the majority of transported LH₂. 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 LH₂ 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 LH₂ is not observed.

The introduction of LH₂ demand has a significant effect on the GH₂ imports, the pipelines, and the placement of electrolyzers. When LH₂ demand is assumed for all sectors (mobility, chemical industry, and aviation), there are next to none GH₂ imports from France and Switzerland. This results in the decline of the corresponding domestic pipeline capacities in comparison to an all GH₂ 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 GH₂ transmission corridor grows in importance. The need for liquefaction plants in high LH₂ 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, LH₂ 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 LH₂ means of transportation highly depends on hydrogen demand: High purity requirements favor the application of LH₂ railcars, vessels, and trucks in the energy system. Furthermore, the GH₂ 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 LH₂ readiness.

For future research, the role of hydrogen purity can further be investigated. In this paper, GH₂ was modeled as a

homogeneous good and LH₂ 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, LH₂ 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 LH₂ and GH₂ 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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