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SIMULATION-BASED ANALYSIS OF A HYDROGEN INFRASTRUCTURE TO SUPPLY A REGIONAL HYDROGEN HUB

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ABSTRACT

Many countries plan to adopt hydrogen as a major energy carrier, which requires a robust infrastructure to meet rising demand. This paper presents a simulation model quantitatively analyzing the capacity of a potential hydrogen infrastructure in a coastal region of Northern Germany to supply a hydrogen hub in Bremen. The model covers ship-based imports of hydrogen, either as liquid hydrogen or ammonia, unloading at port terminals, conversion to gaseous hydrogen, pipeline transport to the hub, and end-use consumption. Various scenarios are simulated to quantitatively assess infrastructure needs under projected demand. Results show that ammonia-based imports offer greater supply reliability under low and medium demand, while liquid hydrogen performs better under high demand due to faster unloading times. Demand-driven supply policies generally outperform fixed-interval approaches by maintaining higher storage levels and aligning supply more closely with consumption patterns.

1 INTRODUCTION

The European Union aims for climate neutrality by 2050 (through the European Green Deal, in accordance with the Paris Agreement) and to reduce greenhouse gas emissions by 55% by 2030 as an interim target, compared to 1990 (European Commission 2011). In pursuit of these goals, Europe has started establishing a large-scale hydrogen economy, as defined in the EU Hydrogen Strategy (European Commission 2020). As a versatile energy carrier and fuel, hydrogen offers the potential to reduce fossil fuel dependency and enable decarbonization in sectors hard or impossible to-electrify, like raw iron production, the chemical and process industry, and long-haul transport. In addition, hydrogen enables the import and storage of renewable energy from regions unsuitable for direct electricity transmission (Chapman et al. 2019).

As a secondary energy carrier not found in nature, hydrogen has to be produced through electrolysis. Hydrogen eletrolysis should use only renewable energy sources, such as wind and solar, in order to reduce carbon dioxide emissions (Acatech 2023). In regions with an abundance of renewable energy sources, such as North Africa and the Middle East (MENA), the potential for production of such “green hydrogen” is considerable. Conversely, Germany, a country with substantial industry, but only limited renewable energy resources, is expected to import a considerable part of the needed hydrogen from abroad. This is stated in the German Hydrogen Strategy (BMWE 2020).

The hydrogen economy may evolve around so called “hydrogen hubs”. These are regional centers pooling infrastructure and consumption in close geographic proximity to facilitate the large-scale adoption and utilization of hydrogen as an energy carrier. Such hubs co-locate production, storage, distribution, and end-use facilities (Moran et al. 2023). One such hub will be established in the Northern German city-state of Bremen. This hub will cluster around the local steel plant as the major anticipated hydrogen consumer, aiming to replace its currently fossil-fueled (coal and coke), blast furnace based, raw iron production process with hydrogen-fueled direct reduction of iron ore (DRI) (Steinbacher et al. 2024). In addition, other local heat dependent industries will need green hydrogen, and part of the locally important logistics sector will likely convert operations to green hydrogen as well (ISL 2023). To meet the large-scale demand, a comprehensive hydrogen infrastructure is being established in Northern Germany. This includes local electrolysis plants, terminals at the nearby North Sea ports specialized for import of hydrogen in different forms, and conversion facilities to convert the hydrogen for pipeline transport. In addition, hydrogen pipelines and underground storage facilities have to be established at salt caverns (BMWE 2020). The infrastructure is currently in the early stages of development. Some components, such as pipelines, can repurpose the existing and well-developed natural gas infrastructure, while others require entirely new construction (Müller-Kirchenbauer et al. 2025). Many facilities, like, e.g., the hydrogen terminal at Bremerhaven port, have not yet entered the construction phase and remain in an early planning stage, with their exact design still undetermined. The optimal configuration and the seamless integration of these diverse elements to enable large-scale hydrogen supply remain unproven. Hydrogen import to Germany uses ship-based transport, either as cryogenic liquid hydrogen (LH2) or as ammonia (NH_3). Liquid hydrogen needs specialized vessels, whereas conventional tankers can carry ammonia. Within Germany, hydrogen is distributed via pipelines and must be in gaseous form; thus, LH2 requires regasification, while hydrogen has to be retracted from ammonia through cracking. Moving the large volumes required over long distances with infrastructure that has not yet been fully developed or tested at scale, will be a significant challenge.

1.1 Research Contribution

This paper provides a simulation-based approach to analyze the potential capacity of the hydrogen supply infrastructure in the coastal region in Northern Germany. Its focus is on the supply of the hydrogen hub in Bremen, which is clustered around a steel mill with additional hydrogen consumers from industry and logistics. The simulation aims to determine whether the hydrogen supply through the planned Wilhelmshaven and Bremerhaven import terminals (employing liquid and ammonia-based hydrogen transport) is sufficient for various demand levels of the hub in Bremen or not, and to identify locations where bottlenecks may occur or redundancies exist. In addition it compares two different supply policies, namely a) a fixed-interval policy and b) a demand-driven supply policy. The fixed-interval policy refers to a push strategy, with regular vessel schedules and fixed intervals between vessel departures. The demand-driven supply policy implements a pull strategy. It triggers new vessel voyages when hydrogen stockpile levels in local storage caverns fall below a threshold. The goal is to evaluate which hydrogen supply chain performs best under each demand situation and supply policy and provide further insight how to balance supply security with ease of logistics operations.

Though simulation is often used to study future hydrogen infrastructures, many studies adopt a macro perspective, examining international hydrogen supply chains, often with a focus on costs rather than capacity, (Notteboom und Haralambides 2023; Kim et al. 2025), or national hydrogen distribution infrastructures (Moran et al. 2023). Simulation-based studies of maritime hydrogen transport also focus on transport costs (Johnston et al. 2022, Bergström et al. 2024). Other studies, conversely, adopt a micro-perspective, focusing on a local level (Sun et al. 2023; Hasché et al. 2024) or specialized supply chain cases and consumers (Wanniarachchi et al. 2023; Ait Alla et al. 2024). What is missing is simulation studies focusing on supply capacity of a hydrogen infrastructure to meet demand of a regional hydrogen hub, like, e.g., a large steel mill. The present work fills this gap and uses discrete-event simulation to investigate the expected capacity extension of a regional supply infrastructure to meet incrementally growing demand at a hydrogen hub. Our simulation also allows for detailed geospatial analysis of the supply infrastructure elements. Our simulation does not include cost aspects because prevailing uncertainties regarding future input prices, regulatory environments, technological developments, and infrastructure utilization prevent the derivation of reliable or robust cost estimates for hydrogen supply at the Bremen hub.

2 GREEN HYDROGEN INFRASTRUCTURE

Our simulation model maps the elements of the extensive hydrogen infrastructure currently being established in Northern Germany, including local electrolysis plants, import terminals at the nearby North Sea ports, hydrogen pipelines, and underground storage facilities established at salt caverns.

2.1 Green Hydrogen Production

The production of green hydrogen uses water electrolysis (WE) to split water into hydrogen and oxygen, using electricity gained from renewable energy sources. In northern Germany, wind energy in particular is used as a renewable source of electricity. The hydrogen forms as a gas at the cathode and can subsequently be stored, or transported to the location of consumption.

In order to produce at least part of the required hydrogen, an electrolysis facility (electrolyzer) is currently in installation at the Bremen hydrogen hub, and several more in the region around Bremen (Bremerhaven, Wilhelmshaven and Emden). These will start with capacities of ranging from 10 MW to 50 MW and gradually expand capacities to 100 MW-200 MW. However, it is clear that these will only be able to produce a small proportion of the hydrogen required.

2.1.1 Hydrogen Import and Conversion

Most of the hydrogen required is expected to be imported from abroad using maritime transport. Source regions may be Scandinavia, the North Sea (offshore wind energy installations), North Africa and the Middle East (MENA), South Africa, South America and Australia. We do not include export in our study, assuming unlimited supply at export ports.

Transport will use hydrogen tanker vessels to the ports on the North Sea coast. The tanker vessels may transport hydrogen in gaseous or liquefied form, or hydrogen derivatives, like Liquid Organic Hydrogen Carriers (LOHC) and ammonia (Notteboom and Haralambides 2023):

- Compressed Gaseous hydrogen (CGH_2): This form is not suited for maritime transport of meaningful volumes due to its low volumetric energy density and we will not consider it here.
- Liquid hydrogen (LH_2): Liquefaction significantly increases energy density during transport but requires specialized tankers with cryogenic tanks and cooling of the hydrogen to temperatures below -253 °C. In addition, boil-off losses occur during transport. Only small prototypes of liquid hydrogen vessels are operational yet. However, we expect that larger ships, including "Handysize" as well as "Very Large Hydrogen Carrier" (Kryo-LH2-VLHC) classes, with transport capacities of up to 120.000 m^3 (equals 8.500 tons) of hydrogen will be available by 2035. The hydrogen must be gasified before further transport with pipelines or usage.
- Liquid Organic Hydrogen Carriers (LOHC): Organic liquids like Benzyltoluene can bind hydrogen and are compatible with existing oil or chemical tankers (Li et al. 2024; Herzinger and Wolf 2024). The destination places need specialized facilities to extract the hydrogen via energy-intensive dehydrogenation. As no concrete plans for establishing such facilities at the Bremen hubs or the considered import terminals exist, we do not include LOHC in our study.
- Ammonia: Ammonia (NH_3) contains 17.6% of its mass as hydrogen, and remains liquid at temperatures below -33° C or at moderate pressures. Thus, conventional tank vessels can transport it, with 200 ammonia tankers currently in use. We expect that by 2035 "Very Large Ammonia Carriers" (VLACs) of 120.000 tons dead-weight (DWT) will be available, with a transport capacity of 70.000 tons of ammonia (equivalent to 12.300 tons of hydrogen). Again, destination places need specialized cracking facilities and substantial energy to convert the ammonia back into hydrogen.

Several North Sea ports are being developed into strategic import hubs, with specialized hydrogen import terminals in the planning or development phase (Müller-Kirchenbauer et al. 2025). At the JadeWeserPort of Wilhelmshaven, Germany's premier ammonia import hub is under construction, in order to supply 15-20% of Germany's hydrogen demand by 2030 (ISL 2023). The deep-water access terminal with two dedicated berths is capable of accommodating VLAC vessels up to 120,000 DWT. Starting in

2026, operations shall expand to unloading 5 million tons of ammonia (880,000 tons H_2) annually by 2035. Storage capacity is set to expand to 216,000 tons ammonia, and a local ammonia cracking facility will take up operations with a processing capacity of 1.6 million tons of ammonia (280,000 tons of hydrogen) per year. As this terminal will supply hydrogen to many industrial regions in Germany, the Bremen hub will only receive a limited share (15%-20%) of the terminal's capacity.

The port of Bremerhaven is exploring the establishment of a smaller import hub for liquid hydrogen, including a gasification facility, though no concrete capacities have been decided. Draft restrictions limit vessel size to "Handysize" tankers of 40,000 DWT. Bremen will receive most of the hydrogen imported via Bremerhaven, though the lower Weser region will receive some part as well.

We assume that both liquid hydrogen and ammonia will be sourced from the MENA region using Saudi Arabian Red Sea ports such as Jeddah and Yanbu for export. One-way maritime voyage durations from these ports to German North Sea ports typically range between 19 and 23 days via the Suez Canal route, while complete round-trip cycles, including loading and unloading, requires approximately 40–50 days. Ammonia shipments achieve the shortest turnaround times due to established handling procedures, while LH_2 transports require an additional 3–5 days per port call for cryogenic operations.

2.1.2 Hydrogen Pipelines and Storage

Pipelines offer the most efficient way to transport hydrogen in large amounts over medium (terrestrial) distances, however they can only transport compressed gaseous hydrogen. A hydrogen pipeline network is under construction to connect key import ports and industrial sites and ensure efficient distribution. In 2024, Germany passed plans for a national hydrogen pipeline network, which will be expanded gradually until 2032 and integrated into the European Hydrogen Backbone (EHB) pipeline network (Müller-Kirchenbauer et al. 2025; v. Mikulicz-Radecki et al. 2023). The "Hyperlink 1/2" pipeline will connect the Dutch hydrogen network (with the ports of Rotterdam and Eemshaven) with the German industrial areas around Hamburg and Salzgitter, passing closely by the south of Bremen, where a stub line will branch off to the Bremen hydrogen hub. The "Hyperlink 4" pipeline will start at the port of Wilhelmshaven and link to the "Hyperlink 1/2" to the west of Bremen, whereas the "H2Marsch" pipeline is planned to connect the port of Bremerhaven with the "Hyperlink 1/2".

As Northern Germany's existing salt caverns offer excellent potential as storage facilities for compressed gaseous hydrogen, plans are in place to convert some of them to this purpose until 2030 (Alms et al. 2023). This includes the Huntorf salt cavern, located near the Bremen hydrogen hub, which will be connected to the "Hyperlink 1/2" pipeline via a stub pipeline. In addition, the Etzel cavern is being considered as an additional storage site for hydrogen imported via the Wilhelmshaven terminal. All caverns are currently used for natural gas and will be retrofitted for hydrogen storage. Their storage capacities will range from 300,000 to over 1 million cubic meters, with projected hydrogen loss rates below 1% per day. In addition, import terminals, conversion facilities and larger industrial consumers will also establish smaller hydrogen tanks as local buffer storage capacities.

2.1.3 Hydrogen Consumption

Future large-scale consumers of green hydrogen at the Bremen hydrogen hub include energy-intensive industries that need to significantly reduce their carbon dioxide emissions. A key industry is the steel industry, as its production of raw iron production currently relies on carbon-intensive coke and coal. The direct reduction of iron ore using hydrogen or, as an intermediary solution, natural gas, can strongly reduce carbon dioxide emissions. Consequently, the Bremen steel plant aims to establish a new direct reduction plant, using mostly natural gas at the beginning (in 2030) and gradually converting to hydrogen. When complete, this will consume 150.000 tons of hydrogen per year (Fuhrlaender et al. 2025).

In addition, other heat dependent industries and households, as well as transport and logistics sectors will require a reliable supply of green hydrogen (ISL 2023). Larger consumers will get their individual stub pipeline connection to the pipeline supplying the steel mill. In the transport and logistics sector, hydrogen refueling stations are to be established for hydrogen-fueled long-haul truck traffic at key junctions of the road network (Ait Alla et al. 2024). Supply of these smaller consumers will use road-based hydrogen trailers to cover the final distance from the distribution point located at the steel mill.

2.1.4 Resulting Hydrogen Supply Chains

In summary, we consider two possible supply chains (Figure 1). The first supply chain includes transport of ammonia with VLAC class tanker vessels from Saudi-Arabian ports to Wilhelmshaven, unloading, then cracking at Wilhemshaven, and further transport to Bremen by pipeline ("HyperLink 4" and "HyperLink 1-2"), with possible intermediate buffer storage at Etzel and Huntorf caverns, until local distribution and consumption at the Bremen hydrogen hub. The second supply chain covers transport of LH_2 with "Handysize" vessels to Bremerhaven with unloading and gasification at Bremerhaven. The subsequent stages of the supply chain are very similar to the first supply chain, transport to Bremen by pipeline ("H2Marsch" and "HyperLink 1-2"), with possible intermediate buffer storage at Huntorf cavern.

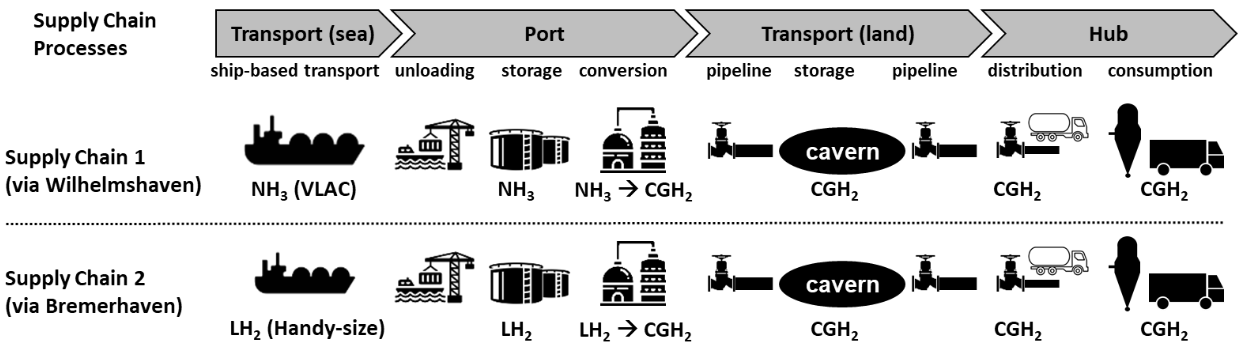

Figure 1: Hydrogen Supply Chains for Bremen hydrogen hub.

The principal components of the hydrogen infrastructure, which have been described in this section, form the principal elements of the simulation model.

3 SIMULATION APPROACH

3.1 Structure of the Simulation Model

To represent the hydrogen supply chain, we have developed a discrete-event simulation (DES) model, which also implements some aspects of a multi-agent-system (MAS). The model is implemented using the AnyLogic simulation platform (version 8.7.11), which provides the flexibility to represent both, discrete-event flows and agent behaviors. The hydrogen supply chain is modeled with hydrogen entering the system through two import ports—Bremerhaven (handling liquid hydrogen) and Wilhelmshaven (handling ammonia). Both ports includes on-site processing into compressed gaseous hydrogen and are connected to the Bremen hub and other parts of Northern Germany via pipelines, as shown in Figure 2.

For simplicity, we have modelled both ports with both, fixed unloading capacities of incoming hydrogen shipments (140 kg/s) and fixed port-side hydrogen processing rates (28 kg/s).

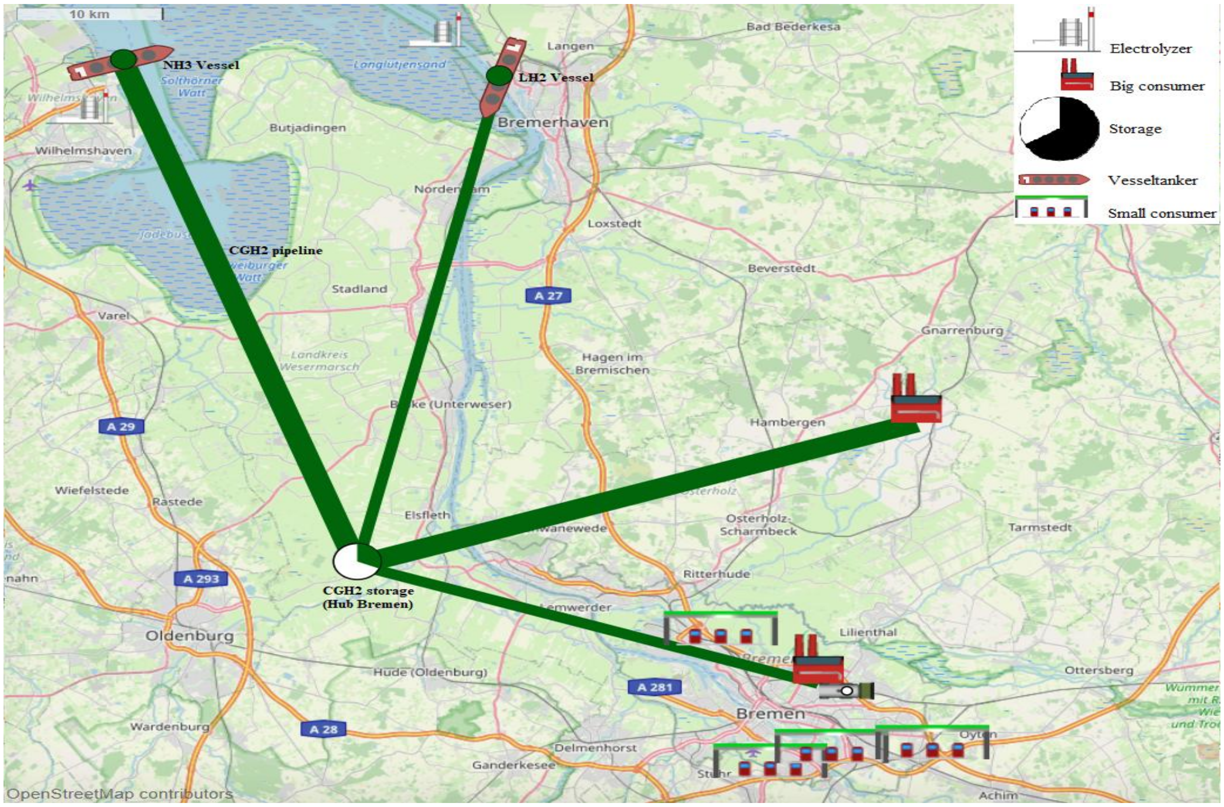

Figure 2: Screenshot of the simulation model (based on OpenStreetMap).

In addition to imports, we have also included local hydrogen production via electrolysis at each port. Two electrolyzers (100 MWh each) produce hydrogen at a combined rate of approximately 1,800 kg/hour, which is, however, marginal compared to imports and only serves as supplementary input. All hydrogen is transported via pipelines to the central hub in Huntorf, modelled with a limited storage capacity of 500 tons of hydrogen. From there, hydrogen is distributed in two directions: At the Bremen hub, large industrial consumers are served directly via pipelines, whereas small consumers, such as hydrogen fueling stations, are served via truck fleets operating from the hub, using routes derived from OpenStreetMap. In addition, the Huntorf cavern is connected to other hydrogen consumers across Germany, since the Bremen region accounts for only about one-third of the total imported hydrogen demand. The model aggregates these other consumers as one large separate hydrogen consumer (sink) separate from the Bremen hub.

Key components of the simulation have been modelled as agents. This includes vessels for importing hydrogen, electrolyzers for local hydrogen production, pipelines, storage units at ports (terminal storage) and at the central hub (Huntorf), and, both, large industrial and small hydrogen consumers. Each agent is a process holder and is implemented using agent-based modeling features of AnyLogic. Agent internal behaviors are defined either via state charts (e.g., vessel status: waiting, unloading, idle) or through the Process Modeling Library (e.g., handling queues, delays, flow constraints). The agents are reactive and interact via event-triggered messaging, ensuring that processes are executed based on actual system states (e.g., sending an import request when storage levels fall below a threshold). Consumer agents (large and small) include short-term temporal demand variability, fluctuating between 75% and 125% of their average consumption over the day. However, vessel agent behavior has been modelled as deterministic, without variability in capacities, vessel arrival times or other operational disruptions. The number of vessels is driven dynamically by hydrogen demand. This agent design allows the simulation to reflect some aspects of the dynamic and reactive nature of real-world supply chains, while avoiding unnecessary detail and concentrating on strategic feasibility of hydrogen supply.

3.2 Definition of Scenarios and Experiments

The simulation scenarios are defined by a combination of expected hydrogen demand growth, differing hydrogen supply policies, and processing characteristics at port terminals. The primary objective is to evaluate how these factors interact and affect the overall performance of the hydrogen supply chain. Simulation experiments are executed over a one-year time horizon. They keep track of hydrogen deliveries and average vessel unloading times at both ports—Bremerhaven (for liquid hydrogen) and Wilhelmshaven (for ammonia), average daily hydrogen storage levels and average hydrogen consumption by end-users. Persistent gaps between consumer demand and delivered hydrogen supplies may indicate bottlenecks in the system in the supply infrastructure. European hydrogen strategies aim for a fast introduction of the hydrogen economy. Nevertheless, the transformation will take time. We include this temporal aspect of transformation in our simulation by covering differing scenarios set at three different dates in the future over the years 2030 to 2045. These are characterized by increased demand for hydrogen as well as additional supply infrastructure elements becoming progressively available, or already available elements increasing their capacities. The situation at year 2030 (S-2030) is characterized by limited demand for hydrogen; at year 2035 (S-2035) it is characterized by expanded, but still not full demand for hydrogen; and at year 2045 (S-2045) it is characterized by full demand for hydrogen. Table 1 provides additional data on the various demand quantities at these dates. All demand has been modelled as temporally variable, with intra-daily consumption fluctuating between 125% of the average daily demand between 6:00 AM and 6:00 PM, and 75% between 6:00 PM and 6:00 AM.

Table 1: Demand parameters for scenario design.

Consumer	Situation in 2030 (S-2035)	Situation in 2035 (S-2035)	Situation in 2045 (S-2045)
Steel mill	50% hydrogen (75,000 t/a), 50% natural gas	100% hydrogen (150,000 t/a)	100% hydrogen (150,000 t/a)
Other industries	10% hydrogen (17,000 t/a), 90% other	50% hydrogen (85,000 t/a), 50% other	100% hydrogen (170,000 t/a)
airport	10% hydrogen (3,500 t/a), 90% other	50% hydrogen (17,500 t/a), 50% other	100% hydrogen (35,000 t/a)
Road traffic	10% hydrogen (1,200 t/a), 90% other	50% hydrogen (6,000 t/a), 50% other	100% hydrogen (12,000 t/a)

In addition to different demand, we examine two types of hydrogen supply policies for each scenario:

- Demand-Based Policy: Vessel orders are triggered dynamically when the amount of hydrogen stored at the hub falls below 50% of its capacity. This approach responds to real-time demand and aims to prevent undersupply by maintaining a safety buffer.
- Fixed-Interval Policy: Vessel arrivals are scheduled based on forecasted average hydrogen demand. While this can simplify logistics, it may lead to inefficiencies under demand variability.

The goal of both policies is to maintain a stable hydrogen flow while minimizing empty storage periods, which can signal inadequate supply planning or infrastructure limitations.

3.3 Results of the Simulation Experiments

This section presents the simulation results of the hydrogen supply chains of the Bremen hydrogen hub, using two hydrogen import methods: liquid hydrogen (Bremerhaven) and ammonia (Wilhelmshaven). As mentioned, we have considered three demand scenarios to deal with demand increasing over time (scenarios S-2030**,** S-2035, and S-2045) and two supply policies: fixed-interval policy and demand-based supply policy**.** The evaluation focuses on four key performance indicators (KPIs): total imported hydrogen quantities, hub storage levels, hydrogen demand fulfillment, and average vessel unloading times. This allows us to assess which hydrogen import form is best suited for each scenario and policy. The unloading time is calculated from the arrival time of the vessel at the port until its departure, and does not include the travel time. Tables 2, 3 and 4 show the outcomes of the simulations of the three demand scenarios, each implemented with fixed-interval and demand-based supply policies.

3.3.1 Scenario S-2030: Low Demand

In the 2030 scenario, representing an early stage of hydrogen infrastructure deployment, the total consumer demand is approximately 320,000 tons. Both supply policies successfully meet this demand, but with notable differences in import strategy (Table 2). Under the fixed-interval policy, around 107,000 tons of liquid hydrogen and 193,000 tons of ammonia are imported. In contrast, the demand-based policy heavily favors ammonia, importing 260,000 tons, while importing only 31,000 tons of liquid hydrogen. Under the fixed-interval policy in S-2030, the ammonia supply is maintained with an average interval of 554 hours between vessel arrivals, whereas liquid hydrogen vessels arrive approximately every 115 hours.

Table 2: Simulation results of the scenario S-2030 (low demand).

Supply Policy	**form**	**Import (LH_2 / NH_3) (tons)**	**Unloading Times (min/mean/max) (hours)**	**Demand Bremen / Other (tons)**	**Storage level at hub (min/mean/max) (tons)**
fixed-interval	LH_2	107,116 /	36.0 / 69.7 / 372.0	100,506 / 219,286	250 / 499 / 500
	NH_3	192,576	327.0 / 425.0 / 525.0		
demand-based	LH_2	31,245	38.0 / 354.3 / 370.0	100,506 / 219,286	250 / 499 / 500
	NH_3	259,635	327.0 / 328.4 / 331.0		

Despite the differing strategies, both policies maintain a stable storage level at the hub, with minimum values at or above 250 tons and maximum utilization of 500 tons, which indicates no significant shortage or overfilling. However, a key difference lies in vessel unloading times. The vessel unloading times differ markedly between the two strategies. For liquid hydrogen, unloading times range from 36.0 to 372.0 hours, with a mean of 69.7 hours under the fixed-interval policy, whereas under the demand-based policy, the mean increases significantly to 354.3 hours. For ammonia, unloading times are consistently higher in the fixed-interval case (mean: 425.0 hours), while the demand-based strategy achieves a narrower and lower time range (mean: 328.4 hours).

3.3.2 Scenario S-2035: Medium Demand

The results of Scenario S-2035 illustrate the performance of the hydrogen supply chain under increasing demand and reveal important differences between fixed-interval and demand-based supply policies (Table 3). Under the fixed-interval policy, the ammonia supply is maintained with an average interval of 206 hours between vessel arrivals, whereas liquid hydrogen vessels arrive approximately every 43 hours. A total of 290,280 tons of liquid hydrogen and 514,884 tons of ammonia is imported. With demand-based policy, ammonia becomes the dominant supply mode with 637,406 tons, whereas liquid hydrogen imports decrease to 188,711 tons. This shift suggests that demand-based supply more strongly favors ammonia, likely due to its greater flexibility and compatibility with responsive ordering strategies.

Conversely, liquid hydrogen imports result in significantly shorter average unloading durations compared to ammonia under both policies. For example, for the fixed-interval policy, the average unloading time for LH_2 is 18.3 hours, while for NH_3 it is 189.6 hours. However, under demand-based supply, the unloading time for LH_2 increases to 43.0 hours, reflecting more irregular usage and possible congestion effects. Still, LH_2 continues to outperform NH_3 in terms of speed of unloading.

Table 3: Simulation results of the scenario S-2035 (medium demand).

Supply Policy	**form**	**Import (LH_2 / NH_3) (tons)**	**Unloading Times (min/mean/max) (hours)**	**Demand Bremen / Other (tons)**	**Storage level at hub (min/mean/max) (tons)**
fixed-interval	LH_2	290,280	14.0 / 18.3 / 78.0	265,180 / 574,860	0 / 461 / 500
	NH_3	514,884	182.0 / 189.6 / 199.0		
demand-based	LH_2	188,711	17.0 / 43.0 / 107.0	270,593 / 590,386	250 / 499 / 500
	NH_3	637,406	137.0 / 158.4 / 224.0		

Despite these variations, hydrogen demand is fully met in both policies, with Bremen and external regions receiving around 265,000–270,000 tons and 575,000–590,000 tons, respectively. This demonstrates the system's ability to ensure supply continuity under both strategies. Storage levels at the central hub vary significantly. While the fixed-interval policy results in occasional depletion (minimum of 0 tons), with the demand-based policy storage never drops below 250 tons and reaches the full capacity of 500 tons. This underscores the benefit of demand-based strategies in maintaining stable storage conditions and avoiding critical shortages. Overall, the simulation results show that the demand-based policy leads to better storage performance and greater reliance on ammonia imports, while liquid hydrogen offers operational advantages due to significantly shorter unloading times. These findings highlight the need for a balanced supply mix, optimized infrastructure for ammonia handling, and possibly strategic use of LH_2 in high-throughput applications.

3.3.3 Scenario S-2045: High Demand

Scenario S-2045 reflects projected consumption over the long term (Table 4). With the fixed-interval policy in S-2045, the ammonia supply is maintained with an average interval of 144 hours between vessel arrivals, whereas liquid hydrogen vessels have to arrive approximately every 30 hours. The results show that both supply strategies—fixed-interval and demand-based—are capable of meeting the significantly increased hydrogen demand, but with notable differences in performance, efficiency, and system behavior.

Table 4: Simulation results of the scenario S-2045 (high demand).

Supply Policy	**form**	**Import (LH_2 / NH_3) (tons)**	**Unloading Times (min/mean/max) (hours)**	**Demand Bremen / Other (tons)**	**Storage level at hub (min/mean/max) (tons)**
fixed-interval	LH_2	414,888	14.0 / 14.2 / 24.0	381,620 / 801,424	0 / 357 / 500
	NH_3	733,089	135.0 / 139.5 / 145.0		
demand-based	LH_2	552,157	14.0 / 14.47 / 28.0	386,562 / 841,700	190 / 491 / 500
	NH_3	641,242	147.0 / 157.8 / 171.0		

Under the fixed-interval policy, a total of 414,888 tons of liquid hydrogen and 733,089 tons of ammonia are imported, while under the demand-based strategy liquid hydrogen imports increase to 552,157 tons, compared to 641,242 tons of ammonia. This indicates that as demand rises, demand-based policies increasingly rely on liquid hydrogen, likely due to its more favorable operational characteristics, such as shorter unloading times and continuous availability. The unloading times confirm these operational benefits. For liquid hydrogen, the average unloading duration remains very low under both policies (14.2 hours for fixed-interval and 14.47 hours for demand-based), with maximum times of only 24 and 28 hours, respectively. Ammonia, in contrast, takes significantly longer to unload, with average times of 139.5 hours under the fixed-interval policy and 157.8 hours under the demand-based strategy. However, even these extended durations remain lower than in earlier demand scenarios (S-2030 and S-2035), which may reflect improved throughput conditions and reduced congestion due to system optimization under higher utilization. Despite the substantial volumes handled, hydrogen demand is successfully fulfilled in both policies, with Bremen receiving over 380,000 tons and other regions over 800,000 tons. This confirms the scalability of the infrastructure. Hub storage levels reveal further contrasts: while the fixed-interval approach witnesses complete depletion at times (minimum: 0 tons), the demand-based policy maintains a more robust buffer, with a minimum level of 190 tons and near-capacity averages. This again underlines the superior reliability and responsiveness of the demand-based approach, especially under high-demand conditions, in ensuring consistent supply without risking shortages. Overall, the results suggest that liquid hydrogen becomes increasingly favorable in high-demand environments, due to its rapid unloading times and its ability to support dynamic, demand-triggered supply strategies. Meanwhile, ammonia continues to play a significant complementary role, despite its higher processing and unloading times. The results reinforce the conclusion that demand-based supply strategies offer more resilient performance, provided the system can support the logistical complexity associated with their implementation.

3.4 Discussion

Across all scenarios, the hub's maximum storage capacity (500 tons) is reached regardless of the policy. However, the minimum storage level drops to 0 under the fixed-interval policy in scenarios S-2035 and S-2045, indicating periods of potential undersupply. In contrast, the demand-based policy maintains a buffer, keeping storage above 190 tons in all cases. Mean storage levels are generally more stable and higher (~490–499 tons) under demand-based policy, which suggests better regulation of inflow and outflow, avoiding both overstocking and shortages. Unloading times are a key bottleneck metric. In Bremerhaven, the average unloading time is significantly higher under the fixed-interval policy in S-2030 (110 minutes) compared to only 23 minutes in S-2045 under the demand-based approach, reflecting improved efficiency with better planning. In Wilhelmshaven, unloading times are similarly reduced in future scenarios, with the demand-based policy achieving a consistently lower unloading duration, e.g., 160 minutes in 2045 vs. 142 minutes in the fixed-interval case. The observed increase in unloading times for vessels in scenarios S-2030 and S-2035 compared to S-2045 can be attributed to the relative immaturity and underutilization of the hydrogen infrastructure in the earlier scenarios. In 2030 and 2035, hydrogen demand is still moderate, leading to lower throughput at the ports and underuse of unloading equipment. This underutilization can result in inefficiencies such as longer wait times for vessels and less coordinated unloading processes. Additionally, under the demand-based supply policy, vessel arrivals are triggered by falling storage levels, which may occur sporadically in low-demand scenarios, causing clustering of vessels and increased average unloading times due to queuing. By contrast, in the 2045 scenario, the hydrogen demand is significantly higher, which leads to a more continuous and predictable flow of supply. This high utilization enforces better scheduling and coordination of vessel arrivals, ensuring that unloading equipment operates near capacity and with minimal downtime. As a result, unloading times are substantially reduced, particularly for liquid hydrogen, which benefits from faster handling processes. Moreover, it is assumed that by 2045, operational procedures and logistics strategies have been refined through experience, further contributing to the efficiency and speed of port operations.

It should be noted, however, that these conclusions are based on deterministic average values. Variance or confidence intervals were not included in the current analysis, which limits the ability to assess the robustness and reliability of the supply policies under uncertainty. While this is not a critical flaw, it does suggest that conclusions regarding the superior reliability of demand-driven policies should be interpreted with caution. The primary stochastic variation in the model is hydrogen consumption, where we have incorporated short-term (intra-daily) temporal demand fluctuations. This intraday variability, combined with the selected supply strategy, directly influences the storage levels, as shown in the results section. However, variability in vessel arrivals and other operational disruptions were not considered in the current model, as the aim of this study is a strategic feasibility analysis. Incorporating such stochastic elements is more relevant in short-term or operational feasibility studies, which are beyond the scope of this paper.

4 CONCLUSION

This paper presented a simulation-based analysis of hydrogen supply for the Bremen hydrogen hub, comparing two different ship-based hydrogen import routes through Northern German ports for different hydrogen transport forms, demand scenarios and supply policies. The results demonstrate that ammonia imports are advantageous in early and medium demand phases due to their flexibility and alignment with demand-based supply strategies. In contrast, liquid hydrogen imports become more suitable in high-demand scenarios, primarily due to significantly faster unloading times and their potential to support continuous supply without bottlenecks. In addition, demand-based supply policies prove more efficient overall, as they allow for better alignment between supply and storage needs, reducing the risk of supply shortages or overcapacity. The simulation also highlights the importance of balanced infrastructure development, especially with regard to port operations, storage management, and pipeline connections to regional consumers. For future work, we aim to refine the model by incorporating dynamic processing times for converting ammonia and liquid hydrogen into usable gaseous hydrogen. Additionally, pipeline throughput will be examined in more detail, as increasing hydrogen demand in the future will require scalable transport capacities to ensure a resilient and efficient supply chain.

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