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Optimizing the supply chain for green hydrogen and derivatives: A case study from Australia to Germany including inland transport considerations

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ABSTRACT

The TrHyHub project examines the production of green hydrogen and derivatives, particularly ammonia, and their global transport from Western Australia to Germany via the Port of Rotterdam. This techno-economic analysis, which was conducted using an in-house simulation tool that incorporates a genetic optimization algorithm and covers the entire Power-to-X (PtX) supply chain, demonstrates that excellent conditions in Western Australia enable the effective generation of hydrogen from wind and solar power. By 2030, delivery costs for ammonia, methanol, and liquid hydrogen are projected to be below 225 EUR/MWh, with potential reductions for ammonia to 100 EUR/MWh by 2050. Inland transport costs below 3 % of the total costs can typically be achieved by inland waterway or rail transport. For the direct use of ammonia, methanol, and liquid hydrogen, inland waterway transport is the most cost-effective national distribution method, underscoring the importance of access to inland waterways for off-taker sites. Further research on multimodal inland transport is essential, focusing on less well-connected demand sites and the last mile. Future studies should monitor PtX product imports into Germany and Europe, emphasizing sustainability and ecological footprint alongside economic factors.

1. Introduction

Hydrogen is estimated to cover 4–11 %, respectively 4000 to 15,000 TWh, of the global final energy consumption by the year 2050 and already 473 TWh of hydrogen might be traded globally in 2030 [1]. For Germany a Hydrogen demand of 56–93 TWh in 2030 is estimated by the German National Hydrogen Council [2]. By 2050, renewable hydrogen is expected to cover 10 % of the EU's energy needs, contributing significantly to decarbonization efforts [3,4]. Multiple studies indicate that only a few EU countries, including Germany, are dependent on molecular hydrogen imports. It is therefore possible that the EU will be able to meet most of its direct hydrogen needs domestically. However, the European Union is expected to import hydrogen derivatives, especially ammonia and methanol [5–7]. The EU's hydrogen import policy, part of its REPowerEU Strategy, aims to import 10 million tonnes of renewable hydrogen annually by 2030. This is supported by the 'Fit for 55′ package and the Hydrogen and Decarbonized Gas Market Package, which set binding targets and develop infrastructure. This policy demonstrates the EU's commitment to integrating imported hydrogen into its energy mix while ensuring alignment with climate goals [3,4,8,9]. It is stated that importing hydrogen derivates by ship can be more cost efficient than producing it domestically using imported or locally produced hydrogen [5,10]. Moritz et al. provide a comprehensive overview of various studies and papers that examine the costs associated with the production and global transport of hydrogen and hydrogen derivatives [10]. Whereas some studies investigate the global transport costs, insight is mostly lacking regarding inland transport to concrete off-takers sites. A few works consider inland transport by truck, tanker vessels or train for liquid hydrogen, conducted by Busch et al., Rapp et al. and Borsboom-Hanson et al., while only a study by Fraunhofer IEG considers inland transport of ammonia and methanol in Germany [11–14]. The TrHyHub project is investigating the development of an PtX supply chain, with a particular focus on ammonia, between the Oakajee region in Western Australia, the Port of Rotterdam, and exemplary demand sites in Germany. As part of the Western Australian government's Renewable Hydrogen Strategy introduced in 2019,

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Oakajee is positioned as a potential major producer and exporter of green hydrogen. The goal is to conduct a comprehensive feasibility study for the large-scale export of green hydrogen in the form of derivatives. To this end, a techno-economic analysis and optimization of the value chain was carried out, based on the findings of a location analysis and evaluation of the regulatory framework. The analysis revealed that the location of the production site in Western Australia presents excellent conditions for hydrogen generation through the integration of wind power and ground-mounted solar power. The following work presents the results of a techno-economical cost analysis based on an extensive analysis of the Western Australian location regarding the renewables generation potential and a holistic simulation-based optimization of the PtX generation and supply pathway. Including the oversea transport as well as the inland transport options for exemplary demand sites spread over Germany, emphasizing the feasibility and cost structures for 2030, 2040, and 2050. The findings highlight the potential for cost-effective imports of green-hydrogen-based ammonia, methanol and liquid hydrogen to Europe, while underlining the importance of optimizing inland transport methods.

2. Material and methods

The first part of the techno-economic analysis is based on a simulation of the supply chain starting from the renewable electricity (RE) power generation in Western Australia, the ammonia (NH_3), methanol (MeOH) or liquid hydrogen (LH_2) production in Oakajee and the subsequent PtX transport to the Port of Rotterdam. Ammonia and methanol are the most commonly discussed hydrogen derivatives for import applications. The most significant advantage of ammonia and methanol is the existence of infrastructure and direct use cases. NH_3 benefits from established global trade networks and port infrastructure, reducing the need for costly new infrastructure. The ammonia production process (Haber-Bosch) is well-established and can be adapted to use green hydrogen, enabling large-scale production and transport of renewable energy. Germany plans to prioritize NH_3 as hydrogen derivate imports for direct industrial applications such as fertilizer production and maritime fuels, with the objective of minimizing energy losses arising from the process of reconversion to pure hydrogen. In 2023, imports accounted for 87 % of the EU's total MeOH demand, primarily utilized by chemical industries. It is being discussed that future green MeOH imports could be facilitated by leveraging existing LNG terminals and shipping routes. Additionally, MeOH is designated as a hydrogen derivative for direct industrial applications, including plastics and synthetic fuels. In contrast, LH_2 has the advantage that the regasification necessitates less energy and fewer technical steps compared to the reconversion of NH_3 and MeOH. However, the global lack of cryogenic infrastructure represents a significant challenge. LH_2 import may find application in specific sectors such as aerospace or high-purity industrial processes by the year 2030. The following supply chain analysis was concentrated on these three hydrogen derivatives [15–18].

Fig. 1 shows the system layout of the ammonia supply chain analyzed. Since the basic system layout for the production and export of LH_2 and MeOH is identical to that for NH_3, with the exchange of individual system components (e.g. synthesis/liquefaction, carbon capture and storage instead of air separation unit), only the layout of the NH_3 supply chain is explained below. European regulations for renewable fuels of non-biological origin (RFNBO) [19] are considered, ensuring that the green hydrogen production utilizes electricity generated by dedicated onshore wind and photovoltaic (PV) plants with geographical and temporal correlation. The water supply for the electrolysis is based on seawater, which must be desalinated prior to use. The desalination technology under consideration is reverse osmosis. Alkaline electrolysis was considered for hydrogen production due to the expected scale of several gigawatts. The hydrogen is then compressed and subsequently fed directly into the ammonia synthesis process. Nitrogen (N_2) for the ammonia synthesis is produced by an air separation unit (ASU). If more hydrogen is produced by the electrolysis than is consumed directly by the ammonia synthesis, it can be stored in an intermediate hydrogen storage facility (underground pipe pressure storage). The stored hydrogen can later be used to supply the ammonia synthesis in times of low hydrogen production, as the synthesis (or liquefaction process) cannot be operated in a dynamic range comparable to the fluctuations in renewable electricity and hydrogen production. The NH_3 produced is stored in NH_3 tanks that are part of the export terminal.

The target production and export of ammonia is set at 3 Mtpa, prompting an investigation into the optimal system layout that minimizes ammonia supply costs. Consequently, the system layout depicted in Fig. 1 has been transformed into a technical simulation model, which performs annual simulations of representative years. Specific production time series of the respective sites are utilized for the wind and PV power generation. Each component of the system layout is modeled based on power curves, conversion efficiencies, and mass and energy balances. In the case of the synthesis/liquefaction processes regarded, the respective minimum partial loads must be considered in each timestep of the annual simulation. To calculate the supply costs, this model is integrated with an economic model that considers the costs associated with the components of the supply chain. This setup allows for the determination of costs for various combinations of installed wind, PV, electrolysis, synthesis, etc. capacities. To efficiently achieve this goal, an optimization algorithm is employed. The optimization algorithm can adjust selected decision variables with the objective of minimizing ammonia supply costs. The decision variables are listed below:

- Installed capacity of wind power
- Installed capacity of PV power
- Installed capacity of electrolysis
- Volume of intermediate hydrogen storage
- Rated capacity of ammonia synthesis
- Number of oversea tanker ships.

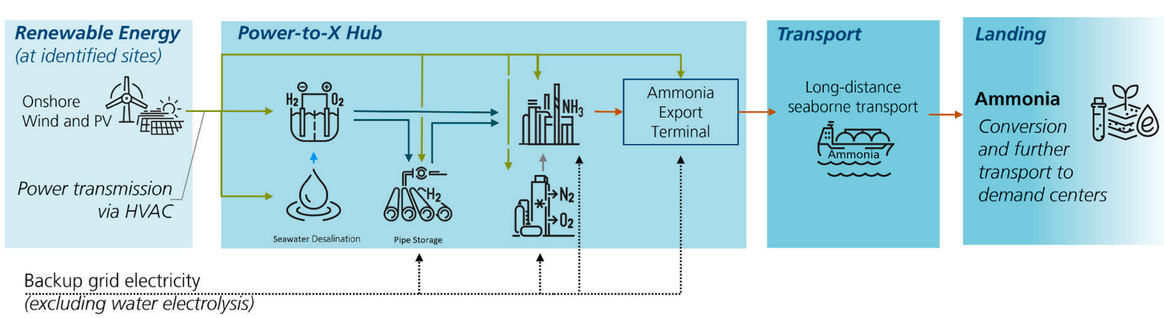

Fig. 1. System Layout of the ammonia supply chain from Oakajee, Western Australia, to Rotterdam. With the renewable energy generation and the Power-to-X Hub onsite at Oakajee, featuring an electrolysis plant, desalination unit, underground hydrogen pipe storage, air separation unit, ammonia synthesis, and an export terminal for overseas transport.

The economic model is used to determine the costs of producing and delivering hydrogen and PtX products. The economic model includes cost parameters such as specific investment costs and operating costs for all components of the supply chains. These values are based on literature references, manufacturer information, and expert knowledge. As the economic model is linked to the technical model, the results of the annual simulation of the system (e.g. component sizing, amount of PtX product produced, marine fuel demand, external power supply) are used in the economic model to calculate the costs of each PtX path. The levelized costs of the PtX products, *LCoPtX*, are calculated using the annuity method as follows [20]:

$$LCoPtX\left(\frac{EUR}{MWh}\right)=\sum_{i=1}\frac{CAPEX_i{}^*ANF+OPEX_i}{E_X} \tag{1}$$

$$ANF=\frac{WACC(1+WACC)^{n_i}}{(1+WACC)^{n_i}-1} \tag{2}$$

CAPEX are the investment costs for each component i of the supply chain, *OPEX* are the annual operating costs (fixed and variable), E_X is the total amount of PtX energy exported (in terms of the lower calorific value), and *ANF* is the annuity factor. The latter is calculated in equation (2) with *WACC* as the weighted average cost of capital and n as the technical lifetime specified for each component. Residual values of individual components at the end of the plant's service life are not considered in this study. The PtX costs in this analysis are given in costs per energy (EUR/MWh) based on the lower calorific value. This ensures comparability among the different PtX products.

The techno-economic model is built and simulated in the Matlab/Simulink based in-house toolbox H2ProSim, which has been developed specifically for hydrogen and PtX system analysis. A detailed explanation of the methodology used to identify RE potential areas and the techno-economic supply chain model can be found in the PtX Country Analyses study and the Power-To-X Colombia study by Fraunhofer ISE [21,22].

In order to analyze the costs for the inland transport of ammonia, liquid hydrogen and methanol, defined as the costs of transport from the point of import to the point of domestic demand, a detailed techno-economic model with temporal and spatial resolution for optimization was used. A detailed description of the model and parameters used can be found in Ref. [23]. The economic model for the transport costs calculation follows the same principles of the annuity method as described for the LCoPtX calculation. The model computes the shortest routes for non-pipeline transport modes, including roads, railways, and inland waterways, as well as the associated transport time. The objective of the techno-economic simulation and optimization is to minimize transport costs while satisfying customer demand. Factors influencing the inland transport cost calculation include capital expenditures (CAPEX), operational expenditures (OPEX), transport mode, lifetime, operating times, fuel consumption, and loading, unloading and transport times. For a summary of the most important parameters, see Supplementary Material A1. Initially, the shortest point-to-point route for each transport mode is determined using Python programming language and QGIS QNEAT3, an open-source geographic information system, along with transport infrastructure data (see Fig. 3). Subsequently, optimization calculations are performed for the three different transport modes to identify the lowest cost for each transport mode and PtX product transported. This optimization process can alter the storage dimensions, the number of ships/vehicles, and the number of loaded containers/tank wagons. Additionally, it optimizes the trade-off between higher transport volume per vessel and higher storage volume at the destination while ensuring the PtX product demand is met. The model approach for the inland transport also utilizes the in-house toolbox H2ProSim.

3. Results and discussion

Selected key input parameters for the simulation of the PtX production and supply chain are presented in Table 1. The base case scenario assumes that the plant will commence operations in 2030, utilizing current state-of-the-art data. Conversely, the more optimistic scenarios, scenario 2 and 3, anticipate significant cost reductions and technological advancements in 2040 and 2050. For these two scenarios only the ammonia supply chain was simulated. The CAPEX and LCOE reduction assumptions are based on the literature references listed in Table 1. Technological advancements, as presented in Table 1, were only considered for the ammonia synthesis part load and the electrolysis efficiency. The anticipated advancements are intended to provide sensitivity to the levelized cost of ammonia import in order to show the influence of the establishment of ammonia as a hydrogen derivative/energy carrier and the further development of electrolysis technology. However, it is important to acknowledge the inherent uncertainty associated with technological advancements of this nature.

The simulation results in Fig. 2 show the costs for generation and global oversea transport from Australia to Europe of 3 Mtpa ammonia, or the energy equivalent amount of liquid hydrogen and methanol. Depending on the final PtX product, feasible costs are below 225 EUR/MWh (lower calorific value) already in 2030, as shown in Fig. 2. The lowest costs with ~203 EUR/MWh (~1053 EUR/t) to export the target value of ammonia can be achieved with an installed wind power capacity of 5.5 GW and an installed PV power capacity of 6.8 GW, which accounts for about 50 % of the final costs. The corresponding installed electrolysis capacity amounts to 4.4 GW_{el}. The limited part load capability of the Haber Bosch synthesis, indicated with 80 % in Table 1, necessitates a large capacity of the intermediate H_2 storage, optimized to a storage volume of 925,000 m^3, and an overcapacity of RE plants in comparison to the electrolysis system by 18 %. A single point mooring buoy to fill the carriers is necessary to realize an export of 3 Mtpa of ammonia in 2030 and was considered in the technical and economical calculations. If ammonia cracking is considered at the import point (Port of Rotterdam), the process adds costs of ~22 EUR/MWh to the total supply chain costs. However, ammonia cracking is not currently commercially available.

As indicated in Fig. 2, the study shows potential to reduce the global transport costs of ammonia by half until 2050, specifically by reduced costs for RE and electrolysis systems, the reduction of the costs of equity and dept, as well as assumed technological improvements such as reduced specific energy demand of electrolysis and a lower part load limit of the ammonia synthesis. Industry engineering experts, consulted as part of the TrHyHub project, state, that increasing the operation window of the Haber Bosch synthesis down to a 10 % part-load limit can be achieved due to technical advances. A preliminary estimation indicates that this could potentially result in a reduction in ammonia supply costs of approximately 10 % (equivalent to approximately 20

Table 1
Key input Parameters in the base case (scenario 1; referring to be in operation in 2030) and for optimistic scenarios applied to the ammonia supply chain (2 & 3). Assumptions for cost reduction and technology improvements are limited to supply chain parameters listed.

	Scenario 1 (Base Case; 2030)	Scenario 2 (2040)	Scenario 3 (2050)
LCOE Wind (EUR/MWh) [24]	40	35	25
LCOE PV (EUR/MWh) [24]	35	25	15
CAPEX Electrolysis (EUR/kW) [25–27]	1000	750	500
Specific Energy Demand Electrolysis (kWh/kg) [28–30]	50	48	46
Minimal Part Load Synthesis (%) [31–33]	80	25	10
WACC (%)	8	6.5	5

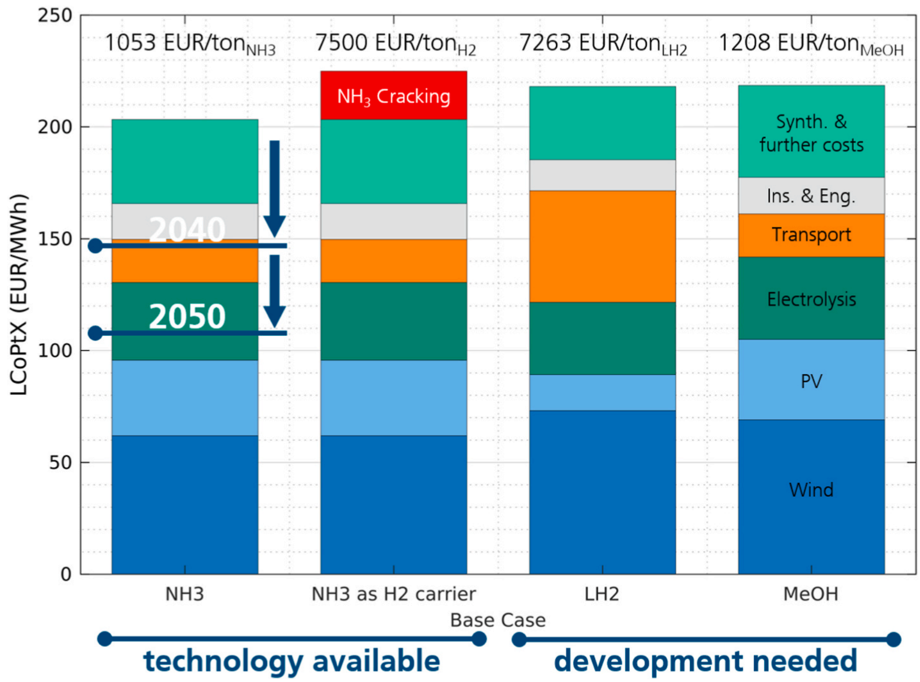

Fig. 2. Levelized costs of power-to-X products for generation in Oakajee, Western Australia and transport to the port of Rotterdam for the year 2030 and estimations for 2040 and 2050 (ammonia only). The levelized costs of the PtX product, LCoPtX, are subdivided into costs for wind power plants, photovoltaic plants, electrolysis, oversea transport, installation and engineering, and synthesis plus additional components. If ammonia is utilized as H_2 carrier, additional costs for the ammonia cracking at the import port occur.

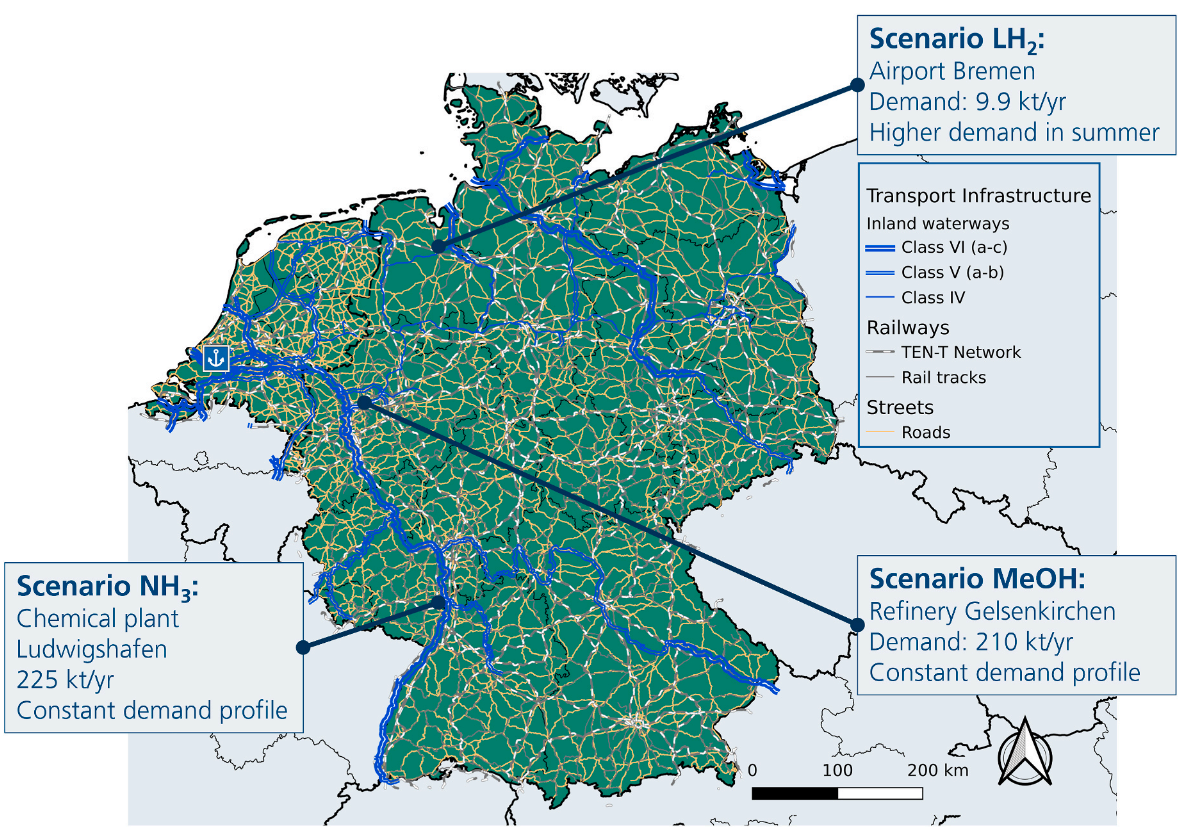

Fig. 3. The study on the inland transport costs of ammonia, liquid hydrogen, and methanol from the Port of Rotterdam focused on three possible off-taker sites in Germany. For the target location of the ammonia import, a chemical plant in Ludwigshafen was chosen. Methanol is delivered to a refinery in Gelsenkirchen, and the airport of Bremen is used as an exemplary customer for liquid hydrogen. The map illustrates the infrastructure network of all three inland transport modes (truck, rail, and inland tanker vessels) considered in the calculations.

EUR/MWh). For the supply of liquid hydrogen observed costs amount to 218 EUR/MWh, with a significant portion attributed to liquefaction with 16 EUR/MWh and long-distance transport with 50 EUR/MWh. Methanol supply costs are noted at 219 EUR/MWh, primarily driven by the expenses of 20 EUR/MWh associated with direct air capture (DAC) for CO_2 production. Additionally, DAC units have high power requirements, necessitating increased wind and PV energy input and slightly increased installed capacities with 6.1 GW and 7.3 GW compared to the NH_3 supply chain. While the technology for ammonia production is already available at an industrial scale, further development is required for the production and transport of liquid hydrogen and methanol. Currently, commercial transport vessels for liquid hydrogen do not exist, although conceptual designs have been proposed by manufacturers, with large-scale commercial vessels potentially available by 2040. The production capacity of liquefaction plants also needs substantial scaling, as the required liquefaction capacity would exceed the present global installed capacity. For methanol, the primary challenge lies in obtaining CO_2 from DAC, which is presently limited to small-scale operations and incurs high costs. To make green methanol production economically feasible, both an upscaling of DAC plants and a reduction in associated costs are necessary. The costs obtained for the import of hydrogen derivatives are comparable to the results generated in the PtX Country Analysis [21], which employs the same modeling approach and modeling toolbox, H2ProSim. In comparison to the comprehensive overview presented by Moritz et al. [10], the cost of importing NH_3 and MeOH, as obtained in this analysis, is approximately 5–15 % higher. This discrepancy can be attributed to more conservative cost assumptions for the DAC (500 EUR/t_{CO2}) and the offshore ship transport ($50*10^6$ EUR/ship).

For inland transport of NH_3, MeOH and LH_2, three off-taker locations were considered with specific demand profiles (Fig. 3). Additionally, Fig. 3 depicts the considered inland transport infrastructure network. For the NH_3 scenario an ammonia import demand of 25 % of the current annual production volume at the site was expected, with 225 kt/yr. The LH_2 scenario demand profile is based on the number of annual departures of short and medium-haul aircrafts to represent a possible LH_2 demand profile of an airport, with 9.9 kt/year. In the MeOH scenario, 75 % of a refinery's current annual production volume, equivalent to 210 kt/year, was used to represent a possible MeOH demand profile.

The results of all scenarios for the inland transport indicate that waterway transport by vessel is cheapest for the considered demands of NH_3, MeOH and LH_2. For transport of NH_3 from the Port of Rotterdam to Ludwigshafen (Scenario NH_3) levelized costs of ammonia transport (LCOA) of 2.6 EUR/MWh (lower calorific value) is feasible, which relates to 1.3 % of the import costs, defined as the total supply chain costs up to arriving at the import port. Looking at MeOH, transport to Gelsenkirchen at 1.3 EUR/MWh is possible, equivalent to 0.75 % of import costs. Liquid hydrogen transport to Bremen via inland tanker vessel accounts for 5.3 EUR/MWh or 0.18 EUR/kg_{H2}, equivalent to 2.4 % of import costs. For comparison: According to the European Hydrogen Backbone, pipeline transport of gaseous hydrogen is estimated to require a tariff of ~0.95 EUR/kg_{H2} in 2030 to recoup total investments [34]. In general, the model simulation indicates that inland waterway vessel transport requires significant PtX product storage at the demand location. This is due to the necessity of achieving low costs, which in turn requires a high utilization factor of the vessels. Each vessel has a transport capacity of up to 10,000 m^3. Additionally, the model does not consider supply chains with multiple stops or multimodal transport.

Especially inland waterway transport shows a significant cost reduction per MWh for medium and high demands compared to small demands of NH_3, from 14.6 to 2.6 EUR/MWh, as highlighted in Fig. 4. For modest demands, here 9 kt/yr, the most cost-effective transport option is by rail, with costs of 7.7 EUR/MWh. The inland tanker vessels utilization is too low at modest demands, the initial investment costs cannot be offset. Truck transport on the other side is no longer technically or economically viable for high demands, an unrealistic high

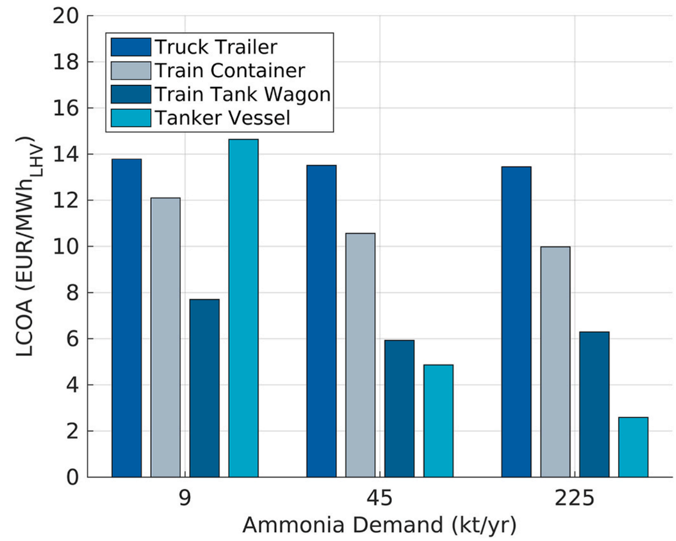

Fig. 4. Levelized Inland transport costs of ammonia (LCOA) as a function of the transport mode and the annual demand of ammonia. Depending on the demand, the cheapest transport mode changes from train tank wagons at 9 kt/yr to tanker vessels at 45 and 225 kt/yr.

number of 31 daily deliveries would be necessary. For the transport of medium annual quantities, here 45 kt/yr, railway as well as tanker vessels are a valid choice, with LCOA of 5.9 and 4.9 EUR/MWh. Comparable results have been obtained and presented by Fraunhofer IEG and Busch et al. [11,14]. For NH_3 and MeOH, the Fraunhofer IEG analysis considers tanker vessels to be the cheapest inland transportation option, while for liquid hydrogen, according to Busch et al., the use of rail is initially the most economical transportation method. However, once the rail capacity is depleted, employing tanker vessels becomes the most cost-effective alternative.

Inland waterways in Europe offer significant potential for freight transport, but their effectiveness varies across countries due to geographic and infrastructure limitations. While Germany has a well-developed inland waterway network, the situation differs in other European countries. Along with Germany the Netherlands is a major contributor to EU inland waterway transport, together accounting for almost three-quarters (71 %) of the EU's total inland waterway transport in 2023 with 116.4 billion tonne-kilometres. While in France, despite having a network that includes the Seine, Croatia and Poland, the transport contribution decreases between 10 and 27 % from 2022 to 2023, it increases by 11 and 12 % in Romania and Bulgaria. In Italy, only the Po contributes to inland waterways transport with only 0.1 billion tonne-kilometres [35,36].

While Germany's inland waterway system is well-developed, continuous improvements are necessary to maintain its efficiency and adapt to future challenges, also in other European countries. Many European waterways suffer from insufficient infrastructure due to lack of appropriate maintenance and investment. Adaption to climate change is a necessity, infrastructure improvements are needed to address the increasing frequency of extreme low and high flow situations, which can disrupt waterway traffic. The European Commission aims to promote and strengthen the competitive position of inland waterways in the transport system, facilitating their integration into the intermodal logistics chain [37,38].

Scaling the inland transport infrastructure for larger amounts of PtX energy carriers faces key bottlenecks in capacity, infrastructure readiness, and cost efficiency. For example, existing ammonia rail traffic (1.5 Mt/yr) already strains Germany's rail network. Many rail routes remain diesel-dependent, conflicting with decarbonization goals for green transport. 71 % of Germany's freight transport is handled by trucks, but as seen in the results discussed for PtX products, road transport should only be an exception for small quantities and short-distance requirements. Regarding the inland waterway transport, tanker vessels currently move ammonia in regions like the Rhine-Main-Danube network, but most EU ports lack ammonia bunkering facilities for inland vessels. In Germany, too, the inland methanol terminals are not yet equipped to support distribution on a large scale. In order to address the aforementioned and further challenges, the implementation of coordinated EU infrastructure upgrades, standardized safety protocols, and incentives for intermodal integration may prove beneficial [39–42].4 Conclusions.

Global import of renewable energy to Europe in the form of ammonia, liquid hydrogen, or methanol will be possible for around 200 EUR/MWh in the near future. Waterway transport via tanker vessel reduces costs by up to factor 5 compared to railway or truck transport of ammonia, methanol, and liquid hydrogen from the port of Rotterdam to various off-taker locations in Germany. This emphasizes that sites with access to waterway harbors are favored, though individual demand profiles, locations and infrastructure availability define the optimal inland transport option.

Compared to import costs of hydrogen and its derivates, the inland transport costs account for below 3 % in optimized calculations. In all of the examined scenarios, inland waterway transport proved to be the most economical mode of transport. Altogether costs for RE represent nearly 50 % of the total supply chain costs. Electrolysis covers over 15 % of the total costs. It is feasible to achieve future cost reductions through the implementation of global scale-up and technological improvements. The assumptions employed in this study indicate that a reduction in the total supply chain costs associated with ammonia imports by 50 % by 2050 is a realistic target. The recent increase in maritime transport costs can be offset by the favorable wind and PV potential in locations such as Western Australia, particularly given Germany's projected dependence on imported PtX energy carriers in the future, as previously discussed.

Further research is necessary on the subject of multimodal inland transport. In addition, demand sites with inadequate transport infrastructure connections should be considered. This requires an examination of the so-called "last mile". Furthermore, it is advisable to track the development of the import necessity of PtX products into Germany and Europe, and to conduct comprehensive analyses in future studies. Besides the economic analysis, sustainability and the ecological footprint of the whole supply chain as well as the challenges regarding the toxicity and the environmental hazards of ammonia should play a significant role.

CRediT authorship contribution statement

Tobias Eißler: Writing – original draft, Investigation, Data curation, Conceptualization. **Ulf Groos:** Writing – original draft. **Marius Holst:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Patrick Deringer:** Methodology. **Lucas Edenhofer:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Friedrich Mendler:** Writing – review & editing. **Christopher Voglstätter:** Writing – original draft. **Robert Szolak:** Writing – review & editing, Project administration, Funding acquisition.

Declaration of interests

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2025.04.163.

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