Texas' Role in the Future Global Demand for Hydrogen

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- Exporting hydrogen from Texas, including additional transportation costs, can be cost competitive with domestic hydrogen production in Germany.
- With the existing commercial infrastructure, transporting hydrogen as ammonia is more cost effective than transporting liquid hydrogen. Without extraordinary effort, cost parity is unlikely before mid-century.
- The incremental growth in shipping cost with distance is small enough to make a distributed hydrogen economy promising.

Introduction

Future decarbonized economies will still include sectors that will be hard to electrify. Some countries such as Japan and Germany, that are targeting net-zero emissions by 2050 and 2045 respectively, are counting on hydrogen to play a key role in their respective energy strategies. Many others are also beginning to see hydrogen as a form of energy security and are launching agreements to facilitate hydrogen use and trade networks. As hydrogen demand around the world increases, leading hydrogen-producing countries, such as the US, stand to gain by developing a global hydrogen export strategy.

The US, and in particular, the Texas Gulf Coast region, has vast experience in the global energy trade. In 2020, the United States exported an average of 3 million barrels of oil a day and within the next decade, Texas is expected to reach an export capacity of 7 million barrels of oil a day.[1] In 2021, the US surpassed Qatar and Australia to become the top liquified natural gas (LNG) exporter in the world.[2] Average US LNG exports are expected to be 12.1 Bcf/day in 2023, a 14% increase compared to 2022.[3] While the majority of US energy exports have been fossil-based, it is possible that parts of the existing LNG infrastructure and institutional knowledge could be leveraged for additional types of energy export, such as liquefied hydrogen or hydrogen carriers such as ammonia.

Texas currently produces about a third of domestically consumed hydrogen, more than 3 million metric tons annually. Most of this hydrogen is produced from methane via steam

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[1] https://www.thenation.com/article/environment/texas-gulf-coast-lng/

[2] https://www.eia.gov/todayinenergy/detail.php?id=50598

[3] https://www.eia.gov/todayinenergy/detail.php?id=55741

methane reforming (SMR) and used in oil and gas refining and fertilizer production. However, there is high interest in the future of clean hydrogen in Texas and many new clean hydrogen projects have been proposed in the state[4], including plans to build a "Hydrogen City": an integrated hydrogen production, storage, and transportation hub located on the Gulf Coast. If all goes to schedule, Hydrogen City will commence operations in 2026, starting with 2 GW of electrolyzer production capacity paired with two storage caverns and with plans to expand to produce more than 2.5 million tons of green hydrogen annually. The off-takers for this hydrogen are still being determined, but options being explored include fuel switching for power plants, feedstock for green ammonia, aviation and rocket fuel, and export.[5] Previous research has examined the infrastructure needs and costs for establishing a hydrogen economy for domestic consumption in Texas. [6]

However, current cost and technological readiness challenges within the clean hydrogen production chain are barriers to scaling. The unsubsidized cost of clean hydrogen is currently high relative to hydrogen produced using conventional production methods. Additionally, global export capabilities are limited or non-existent and there is currently only one prototype vessel capable of transporting liquid hydrogen (LH2). However, ammonia is already a globally traded commodity and so its transport requirements are well understood. These barriers create a causality dilemma: without significant demand or the ability to access the demand, investments in economies of scale carry considerable risk; however, economies of scale are necessary to reduce costs and create economic viability.[7] On the other hand, conventional production of hydrogen is likely to get more expensive with increasing CO_2 prices in Europe and increasingly high and volatile natural gas prices.

Billions of dollars of global investments are seeking to reduce the cost of clean hydrogen through economies of scale, research, and development. For example, China is investing more than $7 billion in hydrogen truck development[8] and the US *Infrastructure Investment and Jobs Act* included $8 billion[9] for the development of clean hydrogen hubs to support the *"*production, processing, delivery, storage, and end-use of clean hydrogen, including innovative

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[4] https://www.utilitydive.com/news/texas-clean-energy-bechtel-solar-hydrogen-construction/638739

[5] https://www.prnewswire.com/news-releases/green-hydrogen-international-announces-hydrogen-city-texas--the-worlds-largest-green-hydrogen-production-and-storage-hub-301494988.html

[6] E. Beagle, M. Lewis, B. Pecora, J. Rhodes, R Hebner. "Model to Inform the Expansion of Hydrogen Distribution Infrastructure", International Journal of Hydrogen Energy, 22 July 2023

[7] https://irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf

[8] https://energy.utexas.edu/sites/default/files/H2%20Roundtable%20Speaker%20Slide_Master_FINAL_releasable.pdf

[9] U.S. Department of Energy. "DOE Launches Bipartisan Infrastructure Law's $8 Billion Program for Clean Hydrogen Hubs Across U.S." 6 June 2022. https://www.energy.gov/articles/doe-launches-bipartisan-infrastructure-laws-8-billion-program-clean-hydrogen-hubs-across

uses in the industrial sector". In addition, the Inflation Reduction Act,[10] signed into law in September 2022, offers tax credits for hydrogen production that meets certain carbon emissions standards. This tax credit is tiered with the lowest emitting facilities eligible for up to \$3.00/kg H_2.

Hydrogen is slated to grow from being primarily a localized product to a global commodity. It is estimated that the global demand for low-carbon hydrogen will reach 530 MMT/year by 2050, with 150 MMT/year (28% of all demand) traded via maritime routes.[11] Many countries have announced projects and signed preliminary agreements to develop low-carbon hydrogen export. In early 2022, Australia sent a shipment of liquified hydrogen to Japan as part of the Hydrogen Energy Supply Chain pilot project.[12] In August 2022, Canada and Germany announced an agreement to trade hydrogen.[13] The EU's REPowerEU plan's ambition is to import 10 million tonnes of renewable hydrogen by 2030, in addition to producing 10 million tonnes domestically.[14] Many regions, including the Middle East, Africa and North America, are potentially well-suited to produce low-carbon hydrogen for export. Suitable regions typically have high resource availability (renewable potential, natural gas, CO_2/H_2 storage geology), which also leads to reduced production costs, and hence, export to other countries may be economically viable as well as favorable to help the EU meet their goals. Conversion and transport costs can make up as much as 67% of the delivered cost of seaborne hydrogen.[15] Thus, identifying low-cost production regions and short transport routes will be critical for economically supplying future hydrogen demand for trade. While not included in current export agreements, the US, particularly Texas,[16] shares many of the characteristics of other export regions, including low cost and high potential for renewable electricity production as well as existing ports and hydrogen infrastructure.

Scope

This white paper looks to create a first-cut analysis of the potential for Texas to serve as a hydrogen export hub. Due to cost and capacity restrictions, transporting hydrogen in a gaseous form overseas is likely unfeasible. Thus, the two most promising hydrogen forms for long distance transport are liquefied hydrogen and ammonia. The analysis specifically considers a

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[10] https://www.congress.gov/117/plaws/publ169/PLAW-117publ169.pdf

[11] https://www.woodmac.com/press-releases/major-energy-exporters-race-to-lead-in-global-hydrogen-trade/

[12] https://www.austrade.gov.au/international/invest/investor-updates/australia-exports-world-s-first-shipment-of-liquified-hydrogen-to-japan

[13] https://theconversation.com/new-hydrogen-alliance-offers-canada-an-opportunity-to-export-ammonia-to-europe-189517

[14] https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en

[15] https://www.woodmac.com/press-releases/major-energy-exporters-race-to-lead-in-global-hydrogen-trade/

[16] https://www.energypolicy.columbia.edu/wpcontent/uploads/2021/08/GreenHydrogen_CGEP_Report_111122.pdf

comparison of transporting liquefied hydrogen vs. ammonia and considers a transport case study exporting hydrogen from Texas to Germany, with conclusions applicable to other transport corridors.

Current maritime hydrogen capabilities and analysis assumptions

Maritime hydrogen transport at a commercial scale is essentially non-existent. There are a very limited number of ships capable of storing and transporting hydrogen for international trade. Kawasaki's Suiso Frontier is capable of transporting about 89 metric tons of liquid hydrogen.[17] The Gaia, a concept ship developed by C-Job Naval Architects alongside LH2 Europe, has a capacity of 37,500 m^3 or nearly 2,700 metric tons of liquid hydrogen[3,18] and is anticipated to begin hydrogen deliveries by 2027. Building upon the technology developed for the Suiso Frontier, Kawasaki has announced plans to develop a large, liquefied hydrogen carrier capable of transporting approximately 11,000 tonnes of hydrogen (160,000 m^3) with commercial operation expected in the mid-2020s.[19]

The long-distance transport of hydrogen via ammonia is also being considered. Ammonia is already a globally traded commodity, thus transport and storage at scale are well known and commercially available.[20] However, some of the downsides of ammonia transport are its toxicity and flammability.[21]

Analysis/Methods

In this analysis, process supply chains for transport of LH2 and ammonia are developed to compare costs and technical parameters between the two commodity transport forms. Further, the costs of hydrogen delivery are compared in the specific context of a supply chain exporting hydrogen produced in Texas to Germany.

Data

Export Demand Forecasts

Both near- and long-term scenarios for Texas to serve as a hydrogen export hub were considered. The US Clean Hydrogen Strategy and Roadmap[22] sets a target for 10 MMT/year of clean hydrogen demand in 2030, with approximately 5 MMT of that demand designated as

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[17] https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20191211_3487

[18] https://www.autoevolution.com/news/this-futuristic-ship-will-be-able-to-deliver-green-fuel-for-400k-hydrogen-cars-188072.html#

[19] https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20220422_3378

[20] https://www.iea.org/reports/ammonia-technology-roadmap/executive-summary

[21] https://www.iea.org/reports/the-future-of-hydrogen

[22] https://www.hydrogen.energy.gov/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

'additional demands.' The team assumed that those additional demands are export demands and Texas produces 30% of this amount for export (scaled based on Texas's current fraction of total US hydrogen production). In this scenario, Texas would export 1.5 MMT/year hydrogen to Europe, fulfilling approximately 15% of the EU's 2030 clean hydrogen import demand. For the long-term (2050) demand estimate, the annual hydrogen export demand from Texas is 10 MMT of hydrogen export each year, as estimated by the McKinsey Houston Hydrogen Hub report.[23]

Export Ships

Due to the nascent stage of the global hydrogen trade, there is no significant international hydrogen market. However, several companies have released announcements and have plans to develop and build commercial scale shipping vessels for transport of liquefied hydrogen. International agencies, like the IEA, also have projections and expectations for the development of future hydrogen infrastructure, which were used to inform the hydrogen transport vessel capacity in this study.

Liquid hydrogen

For long distance transportation of hydrogen, particularly overseas, transporting hydrogen in gaseous form is unfeasible due to its low energy density and thus high per unit costs. Transporting liquid hydrogen (LH2), which can have twice or more the volumetric energy density of compressed gaseous hydrogen,[24] could be economical, particularly if new technologies and vessels are developed to transport large volumes. However, the additional steps in the liquefaction process (and their associated energy consumption and costs) must be considered, as they add to the final delivered price of transported hydrogen. Figure 1 provides a graphical representation of the supply chain elements considered in the analysis for the liquid hydrogen transport process.

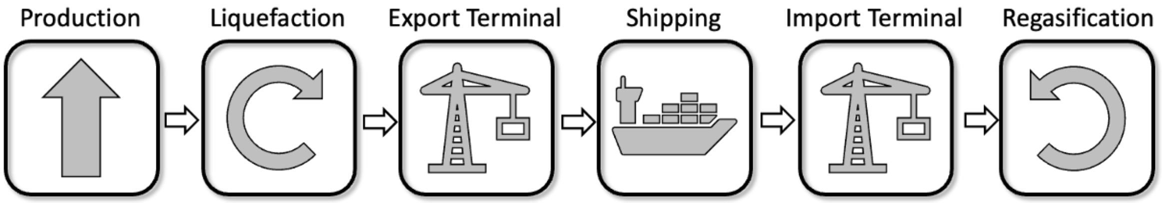

Figure 1. Supply chain diagram showing the considered processes and steps for liquid hydrogen export and import.

Ammonia

It is also possible to transport hydrogen overseas as ammonia due to its higher volumetric energy density – about 50% higher than LH2. Additionally, because ammonia is currently a

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[23] McKinsey Houston Hydrogen Hub Report

[24] M. Aziz, A. Tri Wijayanta, and A. Bayu Dani Nandiyanto, "Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilization" *Energies* 2020, 13, 3062; doi:10.3390/en13123062

globally traded commodity, vessels for its transport are already commercial. However, there are also additional steps required in converting between hydrogen to ammonia that add costs to the whole supply chain as well as higher costs of producing carbon-free ammonia, as considered in this study, compared to conventional production. Figure 2 provides a graphical representation of the supply chain elements considered in the analysis for the ammonia transport process.

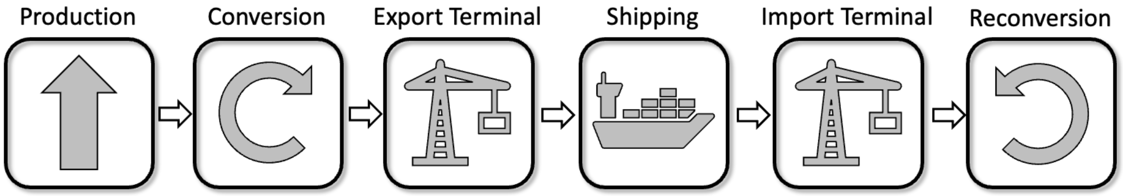

Figure 2. Supply chain diagram showing the considered processes and steps for ammonia production, export, and import.

In both cases (LH2 and ammonia), the hydrogen is assumed to be produced via electrolysis with a utilization of 57% to reflect low-carbon electricity availability. Currently, this method is the more expensive of the two primary commercially available low-carbon hydrogen production pathways (SMR + CCS and electrolysis), therefore conclusions that hold true for the more expensive pathway will hold true for less expensive hydrogen production as well. Additionally, all costs associated with conversion and shipping would be agnostic of the hydrogen production pathway.

Other relevant input values, including CAPEX, OPEX, and electricity and fuel use of each supply chain technology were taken from IEA data.[25] The analysis used an interest rate of 8% and an annuity rate of 9%. Assumptions for technology cost declines from 2020 to 2030 and to 2050 were taken from Brandle et al[26] and Wijayanta et al.[27]

As electricity is the primary feedstock and significant cost driver for electrolytic hydrogen production, the selection of electricity price to use in the model was a key model design choice. Table 1 gives the input electricity price assumptions for each of the analysis scenarios considered. Renewable electricity was assumed to be the feedstock for the hydrogen production component of the modeled supply chain while all other processes were subject to grid electricity prices.

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[25] https://www.iea.org/reports/the-future-of-hydrogen/data-and-assumptions

[26] https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2020/11/EWI_WP_20-04_Estimating_long-term_global_supply_costs_for_low-carbon_Schoenfisch_Braendle_Schulte.pdf

[27] https://www.sciencedirect.com/science/article/abs/pii/S0360319919315411

	Baseline		Low Electricity Price		Mid Electricity Price		High Electricity Price	
	Renewable Electricity	Grid Electricity	Renewable Electricity	Grid Electricity	Renewable Electricity	Grid Electricity	Renewable Electricity	Grid Electricity
2030	0.04	0.061	0.015	0.055	0.03	0.061	0.05	0.067
2050	0.03	0.066	0.01	0.059	0.025	0.066	0.04	0.073

Table 1. Input electricity price assumptions ($/kWh) for analysis scenarios. Renewable electricity prices taken from NREL ATB 2023[28] representative of projected wind and solar costs; grid electricity prices taken from EIA AEO 2023[29] projections for industrial electricity prices in the West South-Central region, which includes Texas.

Results

The additional costs (costs added to the hydrogen production costs) of transporting hydrogen via maritime routes were calculated based on (1) carrier type (liquefied hydrogen and ammonia) and (2) distance. Figure 3 shows the estimated levelized transport costs for both LH2 and ammonia for various distances. The additional costs for transport as liquefied hydrogen are nearly twice as much as transport as ammonia, on a $/kg H_2 basis, across all transport distances in 2030. Levelized hydrogen transport costs increase slightly as distance increases, increasing by 14% and 31% for liquefied hydrogen and ammonia, respectively, for a travel distance increasing from 1000 to 9800 km in 2030. For reference, the 9,800 km transport distance is approximately the length of the transport route between Texas and Germany. These increases are due to the longer times needed for each ship to travel the distance, resulting in less hydrogen that can be transported overall each year. However, when considering the capital investments needed for all stages of the process, the levelized cost is impacted only slightly. This implies that once the required infrastructure is put in place the transportation distance is minor and increasing transportation corridors by significant distances does not significantly impact the cost.

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[28] https://atb.nrel.gov/

[29] https://www.eia.gov/outlooks/aeo/

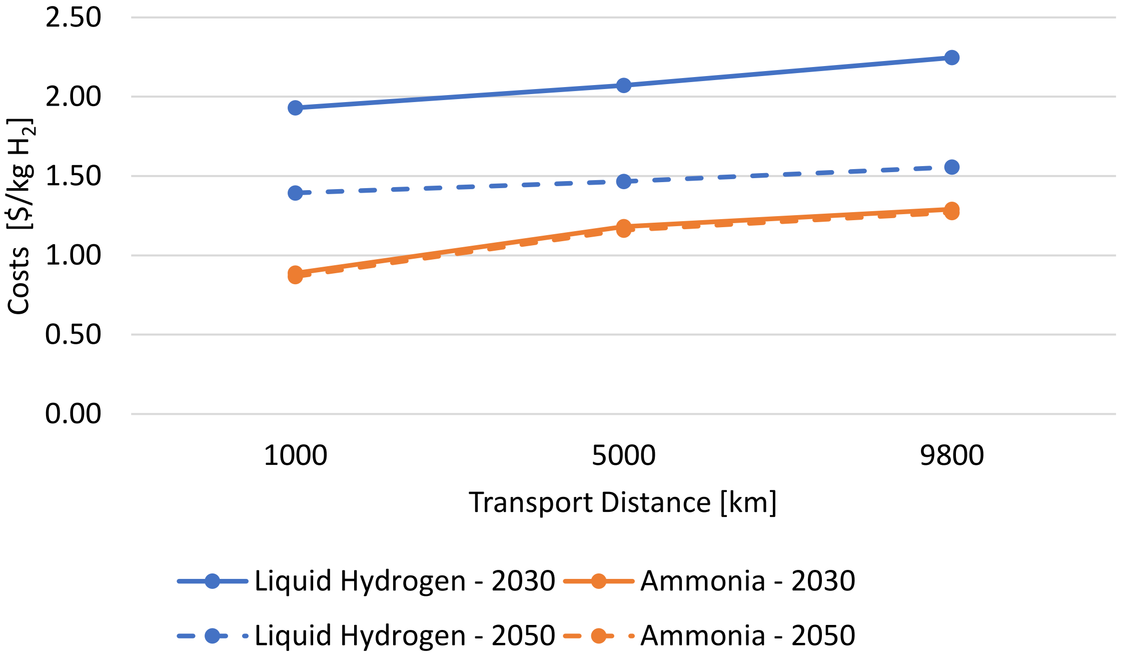

Figure 3. Additional costs for transport and any required conversion and reconversion of hydrogen as liquefied hydrogen or ammonia as a function of distance transported in 2030 and 2050.

The levelized transport costs for LH2 and ammonia are dominated by the capital costs of the port infrastructure at both ends of the journey. The physical transport of the hydrogen itself has a much lower impact overall as shown by the only slight increase in total transport costs relative to transport distance. Since ammonia is already commercially transported in global markets, there are less opportunities for cost reductions as technology is deployed and improved compared to LH2. As a result, LH2 cost declines between 2030 to 2050 are much greater than for transport as ammonia. However, even with cost declines the additional transport costs for LH2 are still greater in 2050 compared to ammonia.

Figure 4 shows the breakdown of the levelized cost of creating and transporting LH2 and ammonia via maritime transport to the receiving import terminal. Most of the costs associated with a liquid hydrogen transport process chain are due to hydrogen production (56% in 2030 and 55% in 2050 as shown in Figure 4). Approximately 44% of the delivered hydrogen price represents the price to transport the hydrogen. This breakdown indicates that regions with comparatively low-cost hydrogen production could have an economic advantage in transporting hydrogen to regions with higher local production costs.

Similarly, most of the costs (68% and 62% in 2030 and 2050, respectively) associated with an ammonia transport process chain are due to hydrogen production and conversion to ammonia, as shown in Figure 4. Reconversion costs at the import terminal account for 12% and 14% of the total cost in 2030 and 2050 respectively, meaning that if ammonia were the final used product (i.e., for fertilizer production) at the import destination, total costs would be reduced.

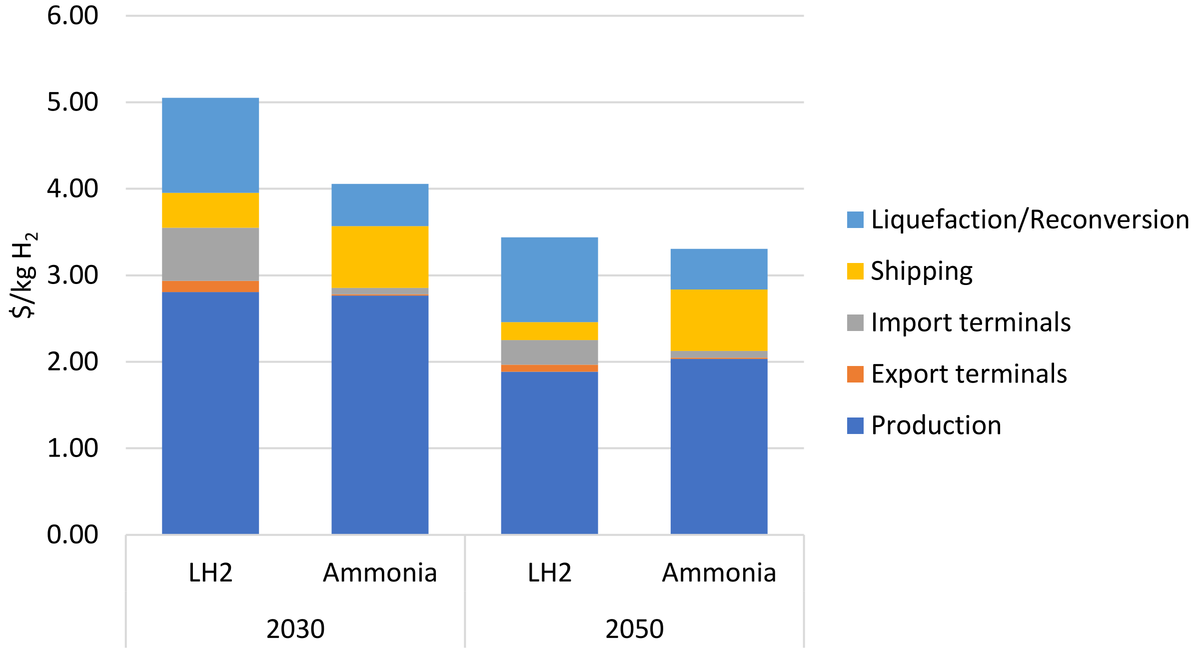

Figure 4. LCOH for distribution of costs for liquid hydrogen and ammonia export process chain from hydrogen production through delivery at import terminal for 2030 and 2050 assuming a 9800 km transportation distance. Note: costs do not include transport from import terminal to end-use facility.

Ammonia shipping vessels are assumed to be fueled with heavy fuel oil, which accounts for the high cost of ammonia shipping compared to LH2, which is fueled by hydrogen boil off. While this represents the fuel used in ammonia transport today, the development of ammonia-powered ships is at about the same degree of technical maturity as that of hydrogen powered ships.[30]

In 2030, the results show that the total delivered hydrogen price for liquefied hydrogen will be more than ammonia for all distances ($5.05/kg H_2 compared to $4.06/kg H_2 for liquified hydrogen and ammonia respectively for the 9800 km transit). However, towards 2050 as electrolytic hydrogen production costs decline, the costs of ammonia and liquefied hydrogen begin to converge ($3.44/kg H_2 for liquid hydrogen and $3.31/kg H_2 for ammonia).

Texas to Germany Export Scenario

Many countries are looking to import clean sources of energy. Recent efforts for decarbonizing the energy system in the EU and its member states were published in the EU Green Deal[31] and the RePowerEU plan,[32] published in May 2022. According to this plan, the EU seeks to produce

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[30] https://www.canarymedia.com/articles/sea-transport/the-race-is-on-to-build-the-worlds-first-ammonia-powered-ship

[31] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[32] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

10 MMT of hydrogen domestically and import the same amount from abroad by 2030. Germany, as the largest consumer of energy in the EU, forecasts a domestic demand for green hydrogen between 2.7 and 3.3 MMT in 2030.[33] The directive focuses on hydrogen generated by an electrolyzer fueled with electricity from renewable sources only.

Historically, the EU has imported energy and the newest plans continue relying partially on imports. One reason is a limited production area due to a high population density and a lower-quality renewable energy potential, particularly when compared to other parts of the world. However, areas in Northern Africa and Australia have access to cheap and abundant renewable electricity and therefore can produce cheap hydrogen. The US has not yet published interest in joining the global hydrogen market even though regions, such as Texas, have potential as a low-cost clean hydrogen producer and have existing hydrogen infrastructure and institutional knowledge. Recent global events, such as Russia's invasion of Ukraine and the resulting energy embargos, have driven up electricity and natural gas prices in Germany. Electricity prices increased from \$36/MWh in 2019 to over \$200/MWh in the summer of 2022.[34] Thus, depending on future developments, it might be more economical to focus on importing cheap hydrogen from abroad.

A single round trip from the Texas Gulf Coast to an import terminal in Germany would take approximately 31 days assuming a 48-hour hydrogen loading time, 14-day travel time each way, and 48-hour unloading time. Assuming the vessel could convey about 11,000 tonnes of liquefied hydrogen or 53,000 tonnes of ammonia, a single vessel can complete this route 12 times each year and deliver 0.13 MMT liquefied hydrogen or 0.64 MMT ammonia annually. Assuming the 2030 demand scenario of delivering 1.5 MMT of hydrogen each year, the trade route would need approximately 12 liquefied hydrogen vessels or 14 ammonia vessels. For the 2050 demand scenario delivering 10 MMT of hydrogen each year, an estimated 80 liquefied hydrogen vessels or 90 ammonia vessels are needed. However, future higher capacity ships would necessitate fewer overall trips.

For hydrogen imports to Germany to be economical, the delivered price of hydrogen transported from Texas must be less than the price to produce hydrogen domestically. Given that the cost of buying electricity makes up a significant share of the total produced cost, the differential in electricity prices between Texas (with low prices) and Germany (with high prices) yields conditions where importing is less expensive than domestic production. Figure 5 compares the delivered cost of hydrogen in 2030, as either liquefied hydrogen or ammonia, for varying input electricity prices, with the cost of domestic production in Germany for varying electricity prices.

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[33] https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6

[34] https://www.smard.de/en/strommarkt-aktuell/alle-artikel

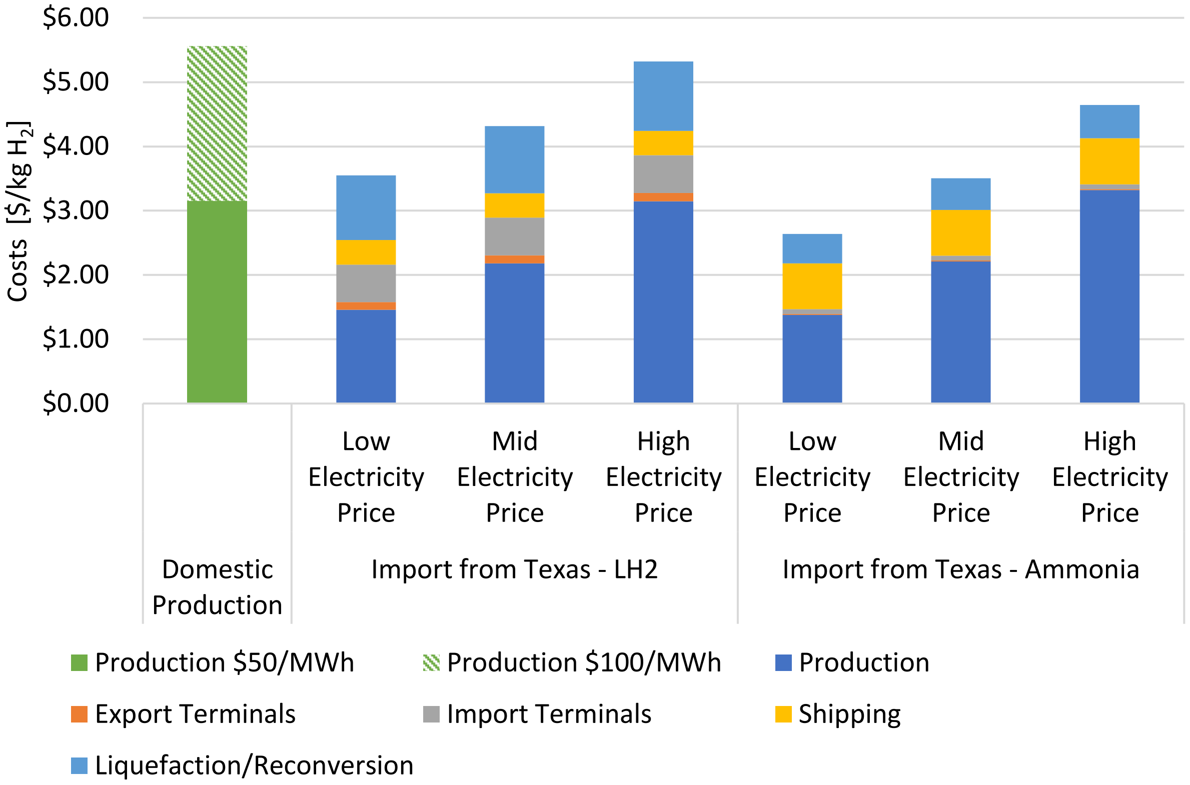

Figure 5. Comparison of delivered hydrogen cost ($/kg H_2) in 2030 in the form of liquid hydrogen or ammonia (production and transportation) for varying input electricity price scenarios in Texas. The electricity price assumptions for each of the considered scenarios can be found in Table 1.

The assumed electricity price, as the main input cost for hydrogen production and liquefaction/reconversion, significantly impacts the final delivered price of hydrogen. Even in the high electricity price scenario, imported LH2 and ammonia is competitive with the high electricity price ($100/MWh) scenario of domestic hydrogen production in Germany. For low domestic electricity prices ($50/MWh), imported ammonia is competitive at low electricity prices but not at mid or high electricity prices. For low domestic electricity prices ($50/MWh), imported LH2 is not competitive at any of the considered electricity price scenarios. However, in the longer term, importing as LH2 becomes competitive with domestic production and with importing as ammonia, as shown in Figure 6.

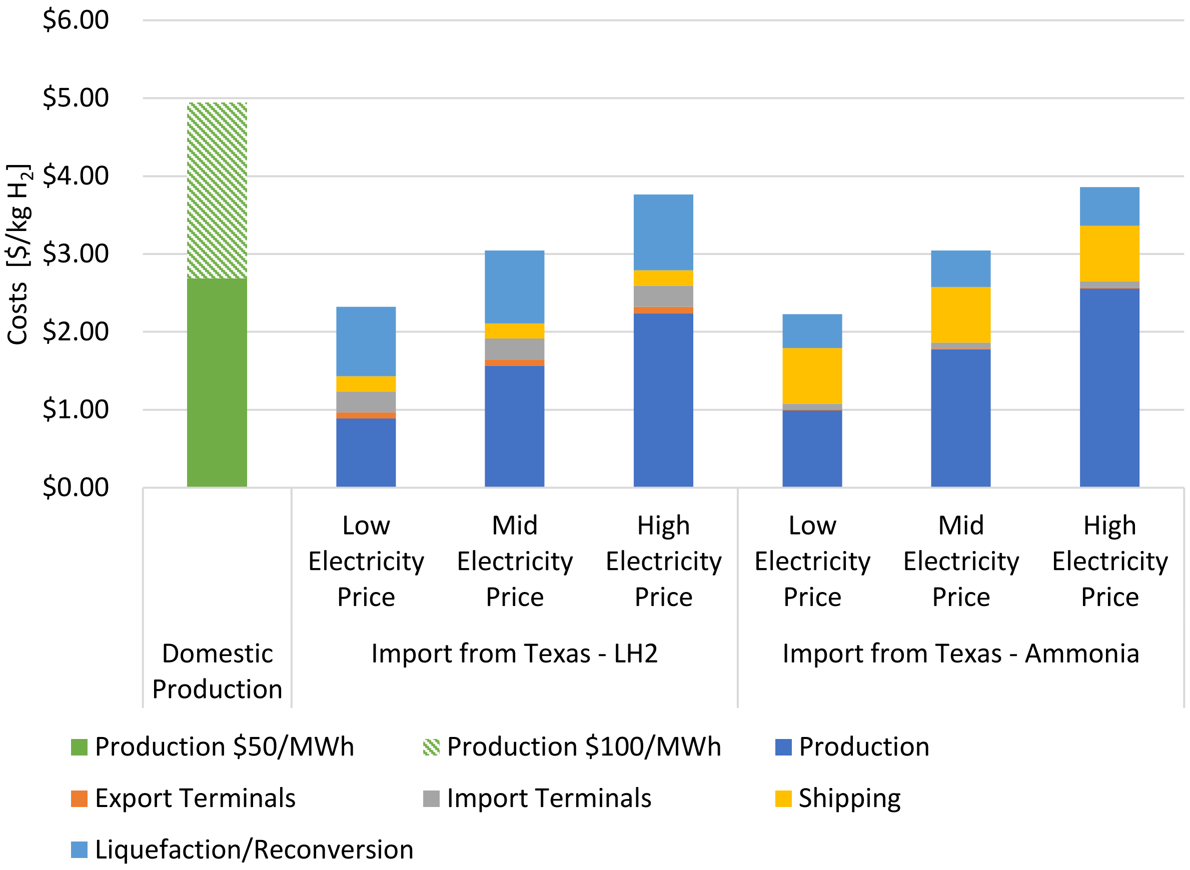

Figure 6. Comparison of delivered hydrogen cost ($/kg H_2) in 2050 in the form of liquid hydrogen or ammonia (production and transportation) for varying input electricity price scenarios in Texas. The electricity price assumptions for each of the considered scenarios can be found in Table 1.

Conclusions

With its existing hydrogen infrastructure, low renewable electricity prices, and precedence as an energy exporting hub, Texas has many characteristics that make it well suited as a potential hydrogen export hub and the region could position itself as a major player in the growing global hydrogen market while also serving to help regions like Germany and the EU meet their ambitious hydrogen import targets. This analysis found that, even considering conversion and transport costs, importing hydrogen in its liquid form or as ammonia could be economical to deliver to Germany and thus, by extension, other regions facing similar challenges. In 2030, LH2 and ammonia could be delivered to Germany for $5.05/kg H_2 and $4.06/kg H_2, respectively. With expected technology improvements and associated cost declines, these costs decrease in 2050 to $3.44/kg H_2 and $3.31/kg H_2 for LH2 and ammonia respectively. Domestic hydrogen production in Germany ranges from $2.70/kg H_2 to $5.56/kg H_2 for assumed electricity prices between $50/MWh and $100/MWh, which means there are conditions in which importing hydrogen from Texas to Germany is economical.

Future Work

The current model considers transporting ammonia with ships that are fueled with heavy fuel oil. A further analysis that looks at the required low-carbon fuel usage and associated costs for an ammonia shipping case would be illustrative to better capture the needs of a fully decarbonized hydrogen export system. Additionally, the current model does not include a temporal dimension, which is important for consideration of the hydrogen production and storage profiles. The demonstrated impacts of the electricity price and the full load hours from this model justify running a temporally resolved system level optimization model for hydrogen production and use. Another important aspect to consider in future modeling would be the impact of the new clean hydrogen production tax credits in the United States on the delivered hydrogen price. As hydrogen imported into Europe would be required to meet all the EU’s renewable fuel directive requirements, proper temporal modeling of hydrogen production in relation to renewables’ availability would further enhance the study.