Global Ammonia Value Chains to Europe: A techno-economic evaluation

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Abstract:
As hydrogen research began to catch up with various political aspirations and promises, the technological gaps in realizing the global hydrogen supply chain, built for several purposes, became increasingly apparent. Challenges such as those associated with the technological implementation of hydrogen storage, liquefaction, transport, and re-gasification came into question. For the short- and mid-term implementation of hydrogen, many hydrogen-derived fuels emerged as solutions to the current technological and economic hurdles in the hydrogen supply chain. Most prominently, ammonia presented itself as a key candidate for specifically long-distance or cross-continental hydrogen transport in regions such as Europe, a region that is expected to rely on energy imports to meet future demand. Despite growing interest, significant uncertainties remain across the ammonia global value chain. Particularly regarding production and transport pathways, port storage infrastructure, bunkering operations, and matching policy and regulations between the producing and receiving countries or regions. This study presents a framework by integrating a techno-economic evaluation of various ammonia supply chains delivering to Europe with other qualitative criteria into a multi-criteria analysis framework. Several representative ammonia supply chain pathways are defined to represent diverse exporting regions, production technologies, transport distances, and port-level configuration. The techno-economic analysis is conducted to estimate the energy requirements, cost indicators, and greenhouse gas emissions associated with key stages of the ammonia value chain. The results are further integrated in an MCA analysis together with other indicators such as port readiness level, technological maturity, scalability potential, and geopolitical risks. The MCA highlights the trade-offs between economic competitiveness, environmental performance, and strategic feasibility when comparing the different supply routes. By combining both approaches, this research aims to provide a comprehensive framework for evaluating ammonia´s role as a hydrogen carrier in Europe.

Keywords:
Techno-economic; Ammonia; Supply Chain; Multi-Criteria; Europe.

1. Introduction

Regarding ammonia as an energy vector and an energy source results in many adjustments along its supply chain, upstream, midstream, and downstream. All supply chain stages are projected for a reconstruction based not only on scale but also on cleanliness. Cleanliness here refers to the carbon dioxide (CO_2) associated with any energy vector, not only ammonia. This can be represented as the carbon emissions of production, transport, or application. Achieving an efficient, reliable, and affordable energy source without compromising one factor or the other is challenging. An added challenge accompanying the decarbonization wave is the need to secure a reliable, affordable, and low-carbon energy source. There is so much room for more research concerning low-carbon hydrogen-based fuel, such as ammonia. Although ammonia has a well-established global supply chain, expanding its end-use application will require expanding every building block of the supply chain. And since its proposed extended application falls under decarbonizing goals, some technologies will need to be retrofitted and studied further for possible room for improvement. Ammonia is already heavily used in the chemical industry, with around 70% of production directed toward the production of nitrogen-based fertilizers [1]. And the rest goes towards its use in the manufacture of pharmaceuticals and textiles, its direct use as a refrigerant, and its use in the manufacture of explosives. The proposed end-uses include its use as an energy storage medium, energy vector (for renewables and hydrogen), and within the power, industrial, and mobility sectors as a fuel. Recent political developments and shortcomings in hydrogen are directing research and economic attention towards ammonia. This led to increased research interest in the fuel, especially in low-carbon production technologies such as electrochemical, photochemical, and photocatalytic processes, as well as carbon capture technology integrated with conventional ammonia production methods. Political support is essential for supporting the growth of low-carbon technologies. This study investigates the potential supply of ammonia to Europe through the evaluation of the levelized cost of ammonia (LCOA) and greenhouse gas (GHG) emissions associated with the fuel upon its arrival at one of the major European import ports. The LCOA is calculated through a techno-economic analysis applied to multiple countries. This study takes a different approach in which the LCOA is conducted for each stage of the ammonia supply chain to Europe separately. The same applies to estimating GHG emissions. There is very little scientific research that discusses a breakdown of the LCOA when considering the supply chain as a whole. The study aims to contribute to filling in this research gap, which is in need of immediate attention, in order to avoid falling behind any type of political push towards an ammonia boom. In other words, to learn from the mistakes made at the very beginning of the hydrogen economy.

1.1. State of the art

Given Europe's past, current, and projected future as a major energy importer, and the role ammonia can play in many relatively new sectors, Europe is proposed to be one of the largest importers of ammonia worldwide. In 2024, the World Bank reported that Europe imported 2.4 Mt of ammonia [2]. The highest imports were from Russia, Trinidad and Tobago, Algeria, and Egypt. Therefore, an accurate depiction of the cost of ammonia and associated emissions at import port is an important matter to discuss. As it only affects Europe's economy but rather all of the countries it relies and will rely on for long-term energy supply.

There are multiple ways to define a supply chain, depending on the field and angle of study. An example of an ammonia supply chain structure is presented in Figure 1. First comes the ammonia production block, associated with upstream, followed by the transportation of ammonia, which can be indicated as a midstream block of the supply chain, and the end-use block immediately after, which is commonly associated with end-use. This is a typical and simplistic description of a supply chain. The downstream segment for end-use applications has been excluded from this study. Due to the wide variety of applications. The transportation block is limited to a single mode of intercontinental transport, namely, using Liquefied Petroleum Gas (LPG) tankers, aligning with the design of this study.

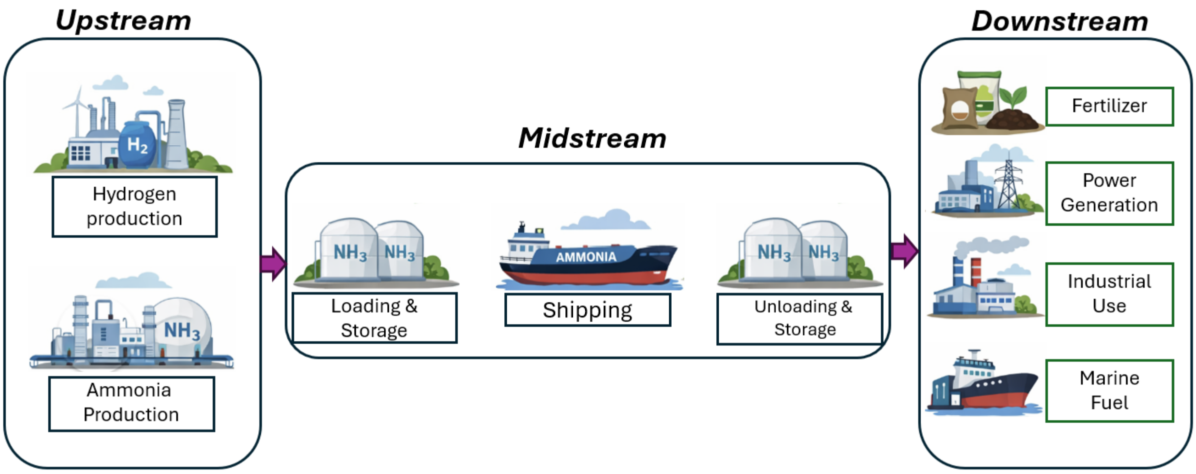

Figure. 1. *A simplistic breakdown of an ammonia supply chain.*

80% of globally produced ammonia is produced through steam reforming of natural gas without carbon capture technology, resulting in the assignment of “gray” color to the output ammonia [2]. The ammonia color association, with respect to production rather than safety, is neither regulated nor mandated; it is used for “marketing” purposes. However, this marketing ploy has found its way into scientific and regulatory contexts due to its ease of use. As mentioned, it's neither regulated nor mandated. For the purposes of this study, the following colors have been assigned to reflect specific ammonia production technologies as observed in the surveyed reports, papers, and press releases. The most common colors are:

- Black/Brown: ammonia produced from acquiring hydrogen from coal gasification.
- Gray: ammonia produced from acquiring hydrogen from steam methane reforming without the use of CCUS.

- Blue: ammonia produced from acquiring hydrogen from steam methane reforming with the use of CCUS.
- Green: ammonia produced from acquiring hydrogen from water electrolysis powered by renewable energy (RE).

Depending on a country's electricity grid mix, an electrolysis and Haber-Bosch process (HBP) powered by the grid can be classified as low-carbon ammonia. Following the colors of hydrogen, this ammonia is assigned the color orange. Also, been observed in literature to be denoted by yellow. Pink ammonia is a product of water electrolysis powered by nuclear energy. Red is a substitute color assigned to the previously mentioned production technology. A lack of an ammonia production color standard and carbon emission associating terminology leads to confusion upon relaying information within the industry, the scientific, and regulatory realms. Which in turn makes finding the appropriate information more difficult.

1.2. Supply chain description

The boundaries of this study were built based on the supply chain design. Only the upstream and midstream of the supply chain are considered. However, this classic definition is broken down into further blocks. The first block is the production block, where hydrogen, nitrogen, and ammonia are produced. Hydrogen production technology depends on the color, while nitrogen production is achieved using air-separating units (ASUs) and ammonia synthesis via HBP. The production block is followed by the storage of ammonia at port and its consequent loading on the seaborne carriers. The tankers then transport the ammonia from the export port to one of the import ports in North-East Europe. The final block in this study is the unloading and storage of ammonia at import ports. According to global ammonia trade flows, some of the largest ammonia-importing European countries are Belgium, Germany, and the Netherlands [3]. The ports of Antwerp, Wilhelmshaven, Rostock, and Rotterdam were consequently selected for this study based on their current ammonia import capabilities and the planned expansion projects pertaining to ammonia and other low-carbon hydrogen-based fuels [4,5]. A total of 12 routes were selected to represent imports from Africa, North America, South America, the Gulf, and Asia-Pacific [6] The routes coincide with standing European deals with the exporting countries. The routes are presented in Table 1 below.

Table 1. *Ammonia supply chain routes*

Route ID	Export Port	Export Country	Import Port	Import Country
G1	Oran	Algeria	Antwerp	Belgium
G2	Yanbu	Saudi Arabia	Antwerp	Belgium
G3	Houston	USA	Antwerp	Belgium
G4	Ain El Sokhna	Egypt	Rotterdam	Netherlands
G5	Ruwais	UAE	Rotterdam	Netherlands
G6	Port of Açu	Brazil	Rotterdam	Netherlands
G7	Casablanca	Morocco	Wilhelmshaven	Germany
G8	Balikpapan	Indonesia	Wilhelmshaven	Germany
G9	San Gregorio Bay	Chile	Wilhelmshaven	Germany
G10	Oran	Algeria	Rostock	Germany
G11	Houston	USA	Rostock	Germany
G12	Port of Dampier	Australia	Rostock	Germany

1.3. Bibliometric study

A bibliometric study was conducted using Scopus to identify relevant literature for this research and to assess the status of research on ammonia value chains in energy engineering. Hence, this study was limited to English-language publications in the energy field. The research was conducted as portrayed in Figure 2. There are 27,360 publications related to " ammonia ". There are a few peaks in publication numbers between the 1990s and 2025; the most significant peak was in 2024. Figure 3 shows the active years of research on ammonia. Publications have more than doubled from the first hydrogen roadmap in 2019. And as the on-ground hydrogen reality began to sink in, "ammonia"-related publications started to gradually increase. Country-associated publications is observed to not coincide with the top ten ammonia export countries but rather with the ammonia import countries. Adding the keyword "value chain" reduces the number of publications to 163. Out of the 163 publications, only 26 cover "techno-economic" related studies. On observing national policies and roadmaps, ammonia has little standalone roadmap; rather, it's mentioned in the context of decarbonizing industries, carbon neutrality, and hydrogen utilization. That is in addition to its traditional mention within agricultural and chemical contexts. A similar approach was observed within scientific publications. Therefore, the decision was made to expand the search to include mentions of “ammonia AND hydrogen”. Figure 4 shows the most common keywords related to ammonia. “Hydrogen” is not one of the strongest keywords associated with ammonia. This highlights a research gap that needs to be addressed by the scientific community to avoid lagging behind the industry’s needs. The keywords with the highest occurrences are more focused on ammonia’s end-use as a fertilizer. Given that supply chain and value chain are used interchangeably, both keywords were added to the search as follows: “ammonia AND hydrogen AND value chain AND techno-economic” OR “ammonia AND hydrogen AND supply chain AND techno-economic.” That resulted in 71 publications. The 26 publications yielded by the previous bibliometric search, which was limited to techno-economic assessments of ammonia supply chains, were all included in the 71 publications. Figure 4 shows the main sponsors, journals, and countries. China, followed by the US, has the highest number of publications and, hence, the largest number of research sponsors. Contrary to the keyword-association findings, the journals Hydrogen Energy, Fuel, and Cleaner Production are among the top five journals for ammonia-related publications. Another result that highlights the research gap within the ammonia economy. The gathered literature was examined for the TEA, GHG emissions, and MCA approach and application. Relevant data were collected to build the TEA and GHG framework for this study.

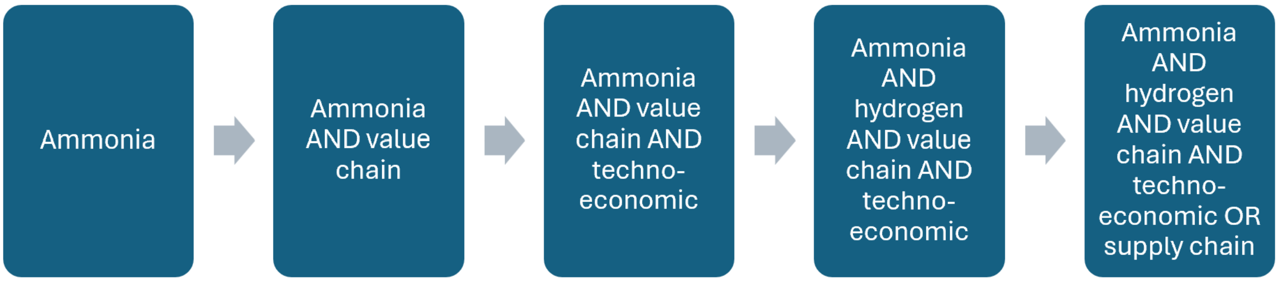

Figure. 2. *MCA ranking of gray, blue, green, and orange ammonia supply routes.*

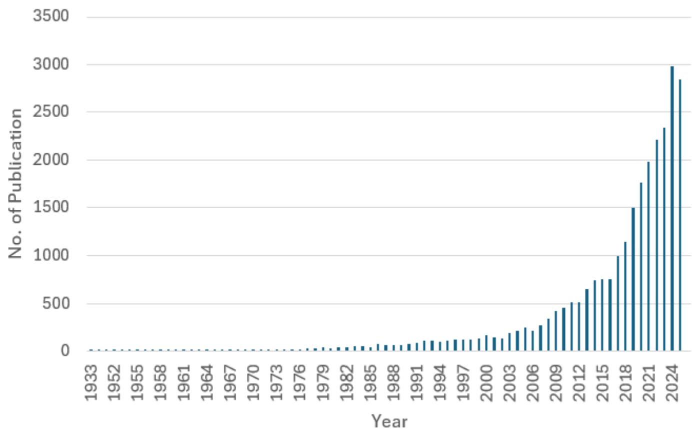

Figure. 3. *Ammonia-related documents found on the Scopus database (1933-2025).*

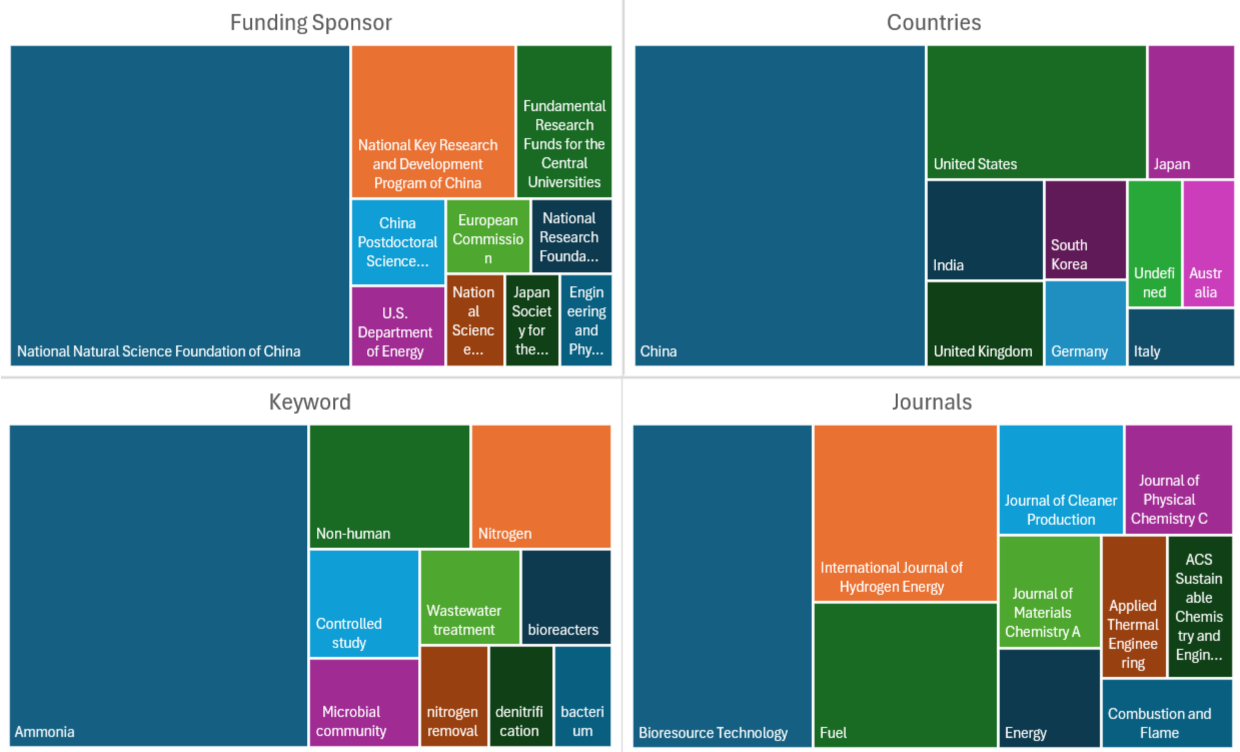

Figure. 4. *Ammonia-related documents found on the Scopus database (1933-2025).*

2. Techno-economic analysis

The total levelized cost of ammonia (LCOA) is calculated using equation (1) by summing the levelized costs at each stage of the studied supply chain. 'x' in equation (2) denotes the exporting country, 'f' the importing country, 's' the supply chain stage, and 'c' the country in which the stage is taking place. The supply stages are as follows: production, transport (shipping), export port, and import port for storage purposes. LCOA for each stage is calculated using equation (1), expressed in 2022 USD per ton of ammonia, where 'x' is the export country and 'f' the import country.

$$LCOA_{total,x\rightarrow f} = \sum LCOA_{s,c} \quad (1)$$

$$LCOA_{s,c} = \frac{(FCR_{s,c}\ x\ CAPEX_{s,c}) + OPEX_{s,c} + VFC_{s,c}}{annual\ NH_3\ production} \quad (2)$$

$CAPEX_{s,c}$ and $OPEX_{s,c}$ are the capital and operating expenditures for stage 's' in country 'c'. The $CAPEX_{s,c}$, are adjusted by the fixed charge rate ($FCR_{s,c}$), which is calculated using the weighted average cost of capital (WACC) and the project finance factor (ProFinFactor), both of which carry variables that are either country or technology-specific. $OPEX_{s,c}$ is estimated as a percentage of capital expenditures, while the variable fuel cost ($VFC_{s,c}$) accounts for the electricity, natural gas, or shipping fuel used at each stage.

For each stage, the following assumptions are discussed. As this study aims to calculate LCOA imported and exported from different countries to provide an approximation of global supply chains to Europe, the analysis must account for country-dependent and technology-dependent factors. Across the literature surveyed in the most coherent TEA methodology closest to the goal of this research is the one presented by [7]. This study follows a similar LCOA calculation formula, however, the main inputs, namely, technical and economical variables, are collected based on either average assumptions or using cost estimating equations observed in the studied literature. Unlike [7], who depended on simulation results. Due to the limited and narrow amount of market-observed data and research regarding comparisons among global ammonia supply chains, the specific cost of debt and equity proposed by [7] was adopted. The authors introduced an add-on margin for each to account for project risk inputs while also accounting for country risk. Some technology-dependent factors were adjusted accordingly based on the technology used at each stage. This is a step away from the National Renewable Energy Laboratory's (NREL) Annual Technology Baseline (ATB) approach for LCOE calculation, which is heavily technology-dependent, since the approach is designed for LCOE calculation in the US [8]. Therefore, the chosen Weighted Average Capital Cost (WACC) calculation methodology, although more complex, accommodates country and technological diversity associated with import and export countries.

2.1. Ammonia production

The following assumptions were used to define the technical and economic parameters related to ammonia production across all colors and production/export countries involved in the analysis. A single production plant of 700,000 tNH3/a is assumed to have an operational capacity of 7884 h/y, corresponding to a capacity factor of 0,9. Annual hydrogen and nitrogen demand was determined from a stoichiometric standpoint, based on which, together with electricity demand values for each step within the production block, the overall energy demand of the ammonia production block was determined. The plant lifetime was taken to be 30 years with a 20-year depreciation period.

The effects of RE variability and part-load efficiency were not considered, as they are outside the scope of this study. Consequently, as well, an intermediate hydrogen storage or connectivity to the grid, with respect to green ammonia, to ensure overnight operation, is not taken into consideration. It's assumed that green ammonia is supplied with 100% RE during the operation period. Green, orange, and pink ammonia are assumed to employ a proton exchange membrane (PEM) electrolyzer for hydrogen production. The hydrogen plant CAPEX is taken as \$ 1,697/kW, a median value for 2022 [9]. While the CAPEX for the gray and blue hydrogen is estimated based on the equations presented by [10], as seen in equations (3) and (4) below. For the ASU and HBP cost estimating equations, equations (5) and (6), respectively, presented by the same paper, are utilized. The OPEX was taken to be 3,5% of CAPEX, which is an average of values reported in TEA literature (2-5%). The decision to use this approach for CAPEX and OPEX estimation was based on the literature survey conducted. CAPEX correlations were adopted from a US-based study and were first adjusted to USD 2022 using the chemical engineering cost index (CEPCI2022 = 816) [11]. The resultant CAPEX values fell within the observed corresponding ranges for each technology. Country-level CAPEX was then adjusted using the locational factor (LF) reported by [7]. The LFs were adopted from this [7], as it provides country-specific cost multipliers referenced to the U.S. (U.S. = 100%) within a harmonized 2022 economic dataset. Since the CAPEX correlations used in this work are also based on a U.S. cost basis and have been updated to 2022 values, the LF was directly applied as a scaling factor to account for regional cost differences.

$$CAPEX_{Gray\ H2} = 539\ \left(\frac{\frac{\$}{kg_{N2}}}{h}\right) \text{x}\ hourly\ H_2\ production \quad (3)$$

$$CAPEX_{Blue\ H2} = 1309\ \left(\frac{\frac{\$}{kg_{N2}}}{h}\right) \text{x}\ hourly\ H_2\ production \quad (4)$$

$$CAPEX_{ASU} = 6\ 777\ 000\ (\$) + 789\ \left(\frac{\frac{\$}{kg_{N2}}}{h}\right) \text{x}\ hourly\ N_2 capacity \quad (5)$$

$$CAPEX_{HBP} = 5\ 103\ 000\ (\$) + 4220\ \left(\frac{\frac{\$}{kg_{NH3}}}{h}\right) \text{x}\ hourly\ NH_3 capacity \quad (6)$$

$$CAPEX_{NH3,t,c} = \left(CAPEX_{H2,t} + CAPEX_{ASU} + CAPEX_{HBP}\right) \text{x}\ LF_c \quad (7)$$

CAPEX and OPEX used within this study do not cover the handling of cryogenic and electrolysis oxygen by-products. For green, pink, and orange ammonia production, the energy demand for hydrogen, nitrogen, and HBP is assumed to be fully met by electricity. The electric demand of the HBP and ASU processes for gray and blue ammonia is taken to refer to the energy demand of auxiliary components, while the thermal demand is covered by natural gas supply.

2.2. Ammonia transport

For this study, large-ammonia transport is selected to be carried by a fully refrigerated LPG tanker with an ammonia cargo capacity of 65,000 t (≈ 96 000m3), at a capacity factor of 90%, and a ship speed of 16 knots (conservative speed). The tankers have a 25-year lifetime and a 20-year depreciation period. The distance between the ports was determined in nautical miles (add reference). Ships are assumed to make a total of 11 trips per year to deliver the produced ammonia. However, for larger distances, such as ammonia delivery from Chile, Indonesia, and Australia to Europe, it will require two ships. The distance is divided among two ships; however, the number of trips does not change. Fuel consumption is assumed to be steady along the voyage, covering both engine and transportation needs. Marine Diesel Oil (MDO), a common tanker fuel that accounts for around 30% of marine transportation consumption, was selected as the shipping fuel for this study. It's a low viscosity fuel, with a relatively low-sulphur content that requires minimal fuel treatment in comparison to heavy fuels. It's widely used and has an established, regulation-compliant baseline. The LCOA of ammonia transport depends on the ship capacity and the number of round trips per year.

2.3. Ammonia loading/unloading

The storage of ammonia at port, its loading on ships, unloading at import port, and consequent storage before direct use or transport are key factors that should be considered within the overall LCOA of ammonia. A thorough review was conducted to identify cost-estimating equations and/or averages used in scientific publications to estimate the CAPEX, OPEX, and fuel consumption of each building block in this stage. There was little literature that explicitly discussed these points. It has been decided to use the CAPEX estimate from [7]. The authors suggested a combined CAPEX for both the loading and storage together, and unloading and storage at the import port together as well. The estimate of 118 M$/tank is assumed for both export and import terminal logistics, including terminal infrastructure costs for loading, unloading, and storage, as well as all other auxiliary components. The energy consumption for these stages is also taken from the mentioned reference and validated by findings from the IEA´s G20 Hydrogen report [12]. In this study, it’s assumed that the electrical loads are covered by grid electricity [13]. For all transportation scenarios, the ship will spend 4 days per round trip, 2 days for loading and 2 days for unloading at ports (including port in/out time).

3. Greenhouse gas emissions

The GHG emissions for each stage of the supply chain are calculated based on the energy consumption, using country- and/or fuel-specific emission factors. Renewable energy is assumed to have zero associated GHG emissions. Therefore, GHG emissions from green ammonia depend on the GHG emissions of the shipping fuel consumed and on electricity consumption during loading, unloading, and storage at the import and export ports. All other colors include GHG emissions for each stage of the supply chain, depending on whether fuel, electricity, or both were consumed. The upstream GHG emissions for grid electricity and natural gas were taken from [7], due to data availability and concision with this study. While GHG emissions, MDO was assumed to be 3.26 kgCO2e/kgMDO [14]. Assuming equal fuel consumption for outbound and return journeys, the transport GHG emissions were calculated. Production GHG emissions for orange and pink were calculated based on energy-related emissions from electricity use. While blue and gray are from natural gas consumption and electricity use. Residual emissions from carbon capture and methane leakage during ammonia production, in addition to any indirect emissions from labor or equipment, were not taken into consideration. For loading, storage, unloading, and import storage, the GHG emissions are also associated with energy consumption. Ammonia has a global warming potential (GWP) of zero, making emissions associated with ammonia leakage along the chain zero [15].

4. Results and discussion

This section presents and interprets the results of the techno-economic and environmental assessment of the selected ammonia supply routes to Europe. The results are first examined individually for LCOA and emissions to highlight trade-offs between ammonia production pathways and exporting regions. Subsequently, these dimensions are combined within a structured multi-criteria analysis (MCA) framework to provide a comparative assessment of overall route performance.

4.1. LCOA

LCOA is used as the primary indicator of economic performance across the assessed supply routes. It represents the total cost of producing ammonia, loading it on seaborne carriers, transporting it, and storing it at the importing port. It's expressed on a per-tonne basis, enabling direct comparison between gray, blue, green, and orange, as well as geographic export and import locations. The country with the highest green LCOA is Egypt, $2.05/tNH3, and the lowest is Saudi Arabia, $0.9/tNH3.Egypt’s high cost is attributed to its relative economic assumptions, especially its Inflation rate and country risk premium, which stand at 13.9% and 7.69% in 2022, respectively. The same goes for orange ammonia, where the LCOA is $2732/tNH3 and $1018/tNH3 for Egypt and Saudi Arabia, respectively. For both green and orange ammonia the hydrogen production CAPEX is a major contributor to the final LCOA. The same high-low theme carries through to blue and gray LCOA. However, this time, grid electricity costs also played a role in the price differences between Egypt and Saudi Arabia. Overall, gray LCOA is the lowest followed by blue, green, and orange.

The LCOA of transport depends on the ship CAPEX and the distance between the export and import ports. This results in the lowest LOCA for transport being between the port of Casablanca, Morocco, and Rostock, Germany, $30.85/tNH3. The highest LCOA is between Port of Dampier, Australia, and Antwerp, Belgium, $87.55/tNH3. The lowest ranges of LCOA are delivered from ports in North Africa, the US, Canada, and Brazil. The highest ranges are associated with ports in Asia-Pacific countries to all import ports in Europe, averaging at $80.68/tNH3. In addition to ammonia delivery from the UAE to Germany, averaging around $ 70/t NH3.

The LCOA for loading and storage follows the same trend as the LCOA for production, with the highest in Egypt and the lowest in Saudi Arabia. The main contributors to this LCOA are grid electricity costs and inflation rates. Whereas unloading and storage, Germany holds the lowest LCOA, \$80.6/tNH3 across all ports, and Antwerp, Belgium, the highest, \$95.44/tNH3.

4.2. GHG emissions

The GHG emissions are assessed to evaluate the environmental performance of the considered ammonia supply routes. Emissions are quantified per-tonne ammonia basis and include contributions from feedstock extraction or electricity generation, ammonia synthesis, loading and storage, transport to Europe, and unloading and storage at the export port. The results highlight the extent to which low-carbon ammonia options compare to conventional methods. For example, GHG emissions of green ammonia production are the lowest, when set at zero, followed by blue ammonia at 1.2 tCO2e/tNH3, gray ammonia at 2.7 tCO2e/tNH3, and orange ammonia at 5.8 tCO2e/tNH3. Orange ammonia is associated with the highest GHG emissions because of the electricity grid mix and the high electrical load required by the PEM electrolyzer. Transportation-associated emissions are dependent on the distance between the ports. Similar to the LOCA of transportation trend, GHG transportation emissions are highest from the Port of Dampier, Australia, and the lowest between Oran, Algeria, and Antwerp, Belgium, at 0.02 tCO2e/tNH3. With respect to emissions from loading and storage, the Quebec port in Canada has the lowest emissions at 0.11 tCO2e/tNH3, compared with the Port of Dampier in Australia at 0.69 tCO2e/tNH3. Whereas, for unloading and storage, the port of Antwerp has the lowest associated emissions, 0.44 tCO2e/tNH3, and German ports have the highest at 1.3 tCO2e/tNH3. Overall, for this study, the GHG emissions of loading and storage are much lower than those for unloading and storage because of the difference in electrical load.

4.3. Multi-criteria analysis

To support a holistic comparison of ammonia supply routes, an MCA is applied to integrate economic, environmental, and supply-related considerations into a single evaluation framework. It combines delivered LCOA, GHG emissions, political risk score, and shipping distance using a simple weighted-sum approach, enabling consistent ranking. All criteria were normalized to a 0-1 scale, with higher normalized values indicating preferable performance. Based on these normalized indicators, weighted aggregated scores were calculated for each alternative. The analysis was conducted both within each ammonia supply route pathway and color. Political stability is represented by the 2022 political stability indicator from the World Bank’s Worldwide Governance Indicators (WGI) [16], which captures country-level risks related to instability. Figure 4 presents the MCA ranking of gray, blue, green, and orange ammonia supply routes to Belgium, Germany, and the Netherlands. The higher the ranking, the better the supply route is in comparison to the others. The LCOA and GHG emissions were assigned the highest weighting, followed by political risk and shipping distance.

The results show, with respect to Europe, gray, blue, and green ammonia from Saudi Arabia is the most favorable imported through Antwerp, Belgium. This is attributed to its low LCOA and GHG emissions compared to all other routes for these colors. For orange ammonia, supply from the UAE to Rotterdam is more favorable than from Saudi Arabia to Belgium because of slightly better GHG emissions and political stability. The least favorable route for gray and blue ammonia supply to Europe is their export from Egypt. This contradicts current and previous hydrogen and ammonia production deals between the two countries. This is credited to Egypt’s economic and political assumptions in 2022. Indonesia’s exports of orange and green ammonia perform quite poorly in the MCA. The reason behind green ammonia’s bad performance is its relatively high LCOA and GHG emissions, as well as the large shipping distance. For orange ammonia export, the main contributor is the high GHG emissions associated with its grid electricity and the shipping distance as well.

With respect to the port of Antwerp, supply from Saudi Arabia outperforms other routes except in orange ammonia, where the shortest route, from Algeria, is more favored. For Rotterdam, supply from the UAE outperforms all others across all colors, with the highest score in orange ammonia supply. For the Wilhelmshaven port, supply from Morocco outperforms that from the Asia-Pacific and South America for gray and blue ammonia. It loses, however, competitiveness to supply from Indonesia in the other colors. Overall scores for Wilhelmshaven remain low across all colors in comparison to Antwerp and Rotterdam. Finally, the port of Rostock supplies from the US is strongest across all colors, except orange, where supply from Algeria outperforms it. This

Overall, the results indicate that routes to Antwerp and Rotterdam consistently outperform those to German ports, driven by a favorable combination of shorter transport distances, lower costs, and associated emissions. While some variations exist across the colors of ammonia, routes from Saudi Arabia and the UAE emerge as the most robust routes across multiple scenarios. Solidifying current and planned investments made by European countries in the Gulf.

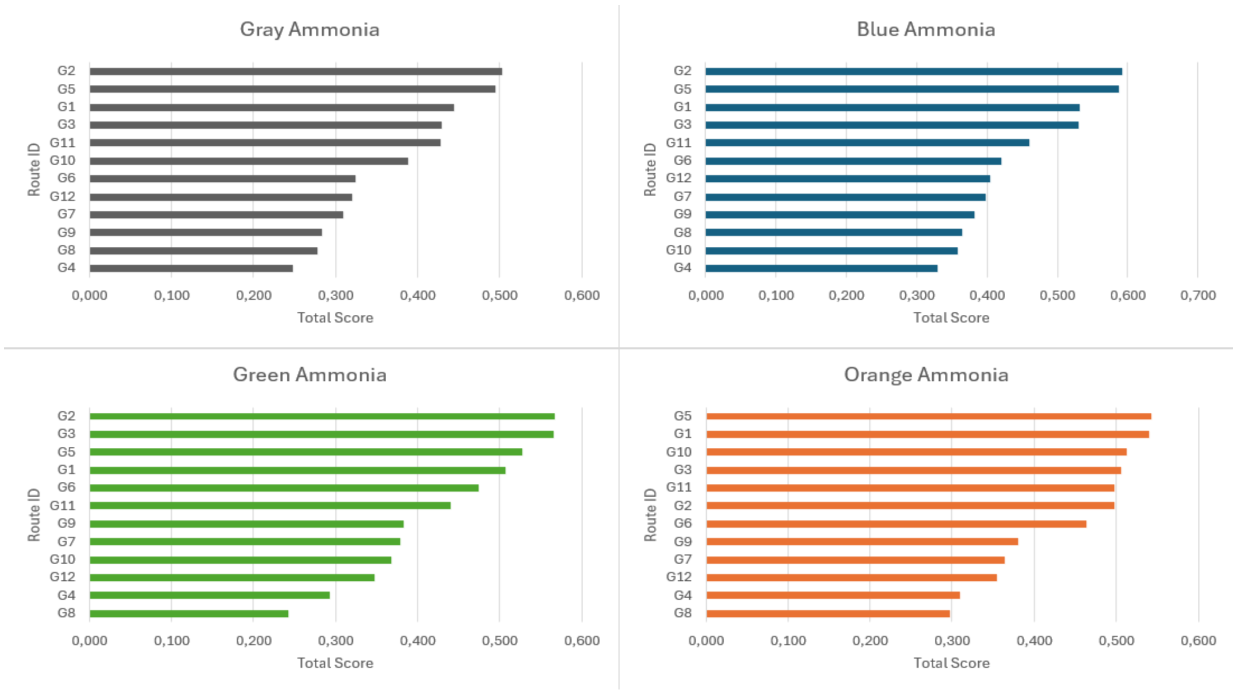

Figure. 4. *MCA ranking of gray, blue, green, and orange ammonia supply routes.*

5. Conclusion

This study demonstrates that the LCOA for imports into Europe is best evaluated by breaking down the supply chain into distinct building blocks. A key limitation remains the availability and consistency of data. Results indicate that orange ammonia exhibits the highest overall LCOA, followed by green, blue, and gray ammonia, with production costs driven primarily by hydrogen CAPEX and fuel use. Transport costs are influenced by distance and shipping CAPEX, while storage, loading, and unloading costs largely depend on storage CAPEX, with limited data available on terminal infrastructure (loading and unloading arms). GHG emission estimates in the literature are predominantly simulation-based and require further development on a supply chain scale to capture technological diversity and scale. Emissions are mainly determined by fuel type and consumption, with orange ammonia showing the highest emissions due to grid emission intensity and high electrical production load. That is followed by gray and blue ammonia, while green ammonia is assumed to have zero direct emissions in line with regulatory conventions. Finally, MCA indicates that Gulf countries and the US have a competitive advantage with respect to blue and gray ammonia due to fuel availability and relative political and economic stability. Its important to point out that this research was conducted based on data from 2022. Current political unrest will alter results. Another finding from the MCA is the favor of the ports of Antwerp and Rotterdam across all colors over German ports. This finding coincides with the planned low-carbon hydrogen and ammonia deals among European countries and African, Guld, North American, South American, and Asia-Pacific countries.

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