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Energy efficiency of future hydrogen-based fuel supply chain routes for Germany's maritime demand

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The share of renewable electricity generation has been growing steadily over the past few years. However, not all sectors can be fully electrified to reach decarbonization goals. The maritime industry, which plays a critical role in international trade, is such a sector. Therefore, there is a need for a global strategic approach towards the production, transportation, and use of synfuels, enabling the maritime energy transition to benefit from economies of scale. There are potential locations around the world for renewable generation, such as hydropower in Norway, wind turbines in the North Sea, and photovoltaics in the Sahara, where synfuels can be produced and utilized within the country as well as exported to demand hubs. Given that a country's domestic production may not fully meet its demand, a scenario-based analysis is essential to determine the feasibility of supply chains, pillaring on the demand and supply for the respective sector of utilization. Our work demonstrates this methodology for the import of hydrogen and derived ammonia and methanol to Germany from Norway, Namibia and Algeria in 2030 and 2050, utilizing the pipeline- and ship-based transport scenarios. Thereby, the overall supply chain efficiency for maritime applications is analyzed based on the individual supply chain energy consumption from production to bunkering of the fuel to a vessel. The analysis showed that the efficiency of import varies from 44.6% to 53.9% between the analyzed countries. Furthermore, a sensitivity analysis for green and blue hydrogen production pathways is presented along with the influence of qualitative factors like port infrastructure, geopolitics etc. As an example, through these analyses, recommendations for supply from Norway, Algeria, and Namibia at the Port of Wilhelmshaven within a supply chain are examined.

KEYWORDS

synfuels, scenarios, import efficiency, maritime transport, pipeline infrastructure, hydrogen geopolitics

1 Introduction

Maritime transport accounts for 80% of the total volume of global trade (IEA 2023a). International Shipping which drives the global trade, accounts for approximately 2% of global energy-related carbon dioxide (CO_2) emissions (IEA 2023b). Moreover, to achieve the net-zero greenhouse gas (GHG) emissions target for international shipping by 2050, as established by the International Maritime Organization, the implementation of multiple decarbonization measures is necessary (IMO 2024). Hydrogen-based fuel supply chains shall significantly influence the course of this transition. Other relevant aspects in the transition are fleet readiness, fuel availabilty and adoption of IMO guidelines for alternative maritime fuels. According to Clarkson's Green Technology Tracker (Gordon 2024), the proportion of alternative-fuel capable vessels has been folowing an increasing trend, with 41% of the tonnage ordered in the first quarter of 2024 being alternative fuel capable. Orders were placed for a total of 310 alternative dual-fuel ships, including 109 LNG dual-fuel ships, 49 for methanol, 42 for LPG, 15 for ammonia, and four for hydrogen. In the scenario of deployment of hydrogen and its derivatives, ammonia and methanol are the two proposed alternative maritime fuels based on environmental and economic life cycle considerations. Hydrogen, on the other hand, could be a promising fuel for small, medium-size, and short-range ships (Kanchiralla et al., 2024; Raucci et al., 2023).

Germany has set an ambitious target of up to 10 GW electrolysis capacity by 2030; however, domestic production alone will not be sufficient to meet its hydrogen demand, meaning substantial amounts will need to be imported (Dertinger et al., 2022). Following this, the total future demand of hydrogen derivatives, including ammonia and methanol, in Germany in 2030 and 2050, will also exhibit import requirements. Many studies have addressed the techno-economic aspects of global supply chains of these fuels. Song et al. (2022) presented comparative study of energy efficiency of the maritime supply chains for hydrogen, ammonia, methanol, and natural gas with energy efficiency of 62.31% for ammonia, 65.67% for methanol and 47.78% for hydrogen. Ammonia and methanol showed potential to replace LNG due to lower energy losses and efficient long-distance transport. Hydrogen requires efficient BOG handling systems to increase competitiveness. They concluded that these energy carriers could transport renewable energy across seas, but further analyses are needed. Although, the efficiency presented in this paper was for a majorly natural gas-based production pathway without CCS.

Noh et al. (2023) analyzed the environmental impact through LCA for compressed gaseous hydrogen, liquid hydrogen, LOHC and Ammonia, specifically focusing on ship-based transportation. Notably, all the above-mentioned derivatives are converted back to compressed gaseous hydrogen, forming the boundary condition of the methodology. They reported energy efficiency of supply chain for a shipping distance of 100 km ranges to be between 41%–57%. However, as the transport distance increases to 10,000 km efficiency decreases to 18%–22%.

Previous investigations of the energy efficiency of hydrogen and derivatives transport, reported value ranging from 42%–65% (including green, blue, grey pathways of hydrogen production) (Al-Breiki and Bicer 2020b; Ishimoto et al., 2020; Noh et al., 2023; Song et al., 2022; Staudt et al., 2024). However, there remains a gap in the literature concerning the maritime transport and utilization of these fuels, particularly in understanding the direct use of ammonia and methanol as maritime fuels, as well as the associated bunkering operations and infrastructure. This study leverages the existing pipeline infrastructure between Norway and Germany to demonstrate a near-future 2030 scenario, and also a 2050 scenario, where the construction of new pipeline may be considered. Staudt et al. (2024) lays focus on import, contrasting with other studies that primary focus on transport without considering the specific demand of importing countries or supply ambitions of exporting countries. The study covers synthetic ammonia and methanol however, their analysis is limited to the supply chain processes after hydrogen production. Sens et al. (2024), Rahmat et al. (2023) focused on use of ammonia or methanol as transport vectors of hydrogen and their land based utilization. This paper demonstrates a potential for directly utilizing ammonia and methanol as alternative maritime fuel, thereby bridging the aforementioned gaps. It also accounts for bunkering operations for the specific port of Wilhelmshaven.

When considering economic feasibility, studies have assessed the cost of hydrogen transportation and utilization in sectors such as heavy duty transport, aviation and steel manufacturing (Ishimoto et al., 2020; Ratnakar et al., 2021; Sens et al., 2024). It has been found that supply chains of compressed gaseous hydrogen exhibit the lowest overall supply costs, particularly when transported via pipelines directly to filling stations. Liquid hydrogen supply chains are less cost-effective due to substantial capital expenditures and energy demands for liquefaction, although LH_2 storage could benefit from well-stablished LNG technologies. Meanwhile, liquid organic hydrogen carriers have the highest supply costs due to the high energy demands for dehydrogenation and their limited hydrogen carrying capacity (Sens et al., 2024). However, in the context of maritime transport, dehydrogenation is not utmost necessary, as fuels such as ammonia and methanol can be utilized directly. Schorn et al. (2021), estimate levelized costs for importing methanol from Saudi Arabia to Germany or importing hydrogen to Germany and producing methanol locally. It was reported that for both options imports costs were 25–30 €/GJ in 2030. However, they do not look into the energy efficiency of the processes involved in the supply chain, nor consider different hydrogen production pathways.

Green hydrogen production costs are expected to decrease from a reference 5.3 € per kg in 2020 to 4.4 € per kg by 2030 and further to 2.7 € per kg by 2050 (Frieden and Leker 2024). Despite anticipated cost reductions, Europe is still projected to incur the highest hydrogen production costs. This underscores the necessity of exploring import options, although in most instances, the development of new infrastructure will be required. Dinh et al. (2024) have demonstrated that for newly built infrastructure of hydrogen and ammonia transport, pipelines are most economical for short distances up to 500 km, whereas LH_2 tankers are more economical for distances exceeding 2,000 km and with a generation capacity of 2,500 MW. However, a technical assessment of using existing pipeline infrastructure, as well as demand-supply based shipping routes with a clear focus on maritime fuels is missing from existing literature. Consequently, this paper seeks to address this gap from a 2030 and 2050 time horizon perspective.

Chen et al. (2025) analyzed the levelized cost approach to evaluate the H_2 shipping costs on eight potential international routes. Analysis considered transport of LH_2, methanol, liquid ammonia, DBT and MCH and concluded that methanol has the lowest hydrogen shipping cost, followed by ammonia, LH_2, DBT, and MCH. Moreover, the results also show H_2 shipping costs on the Australia-East/Southeast Asia and West Africa-Europe routes are comparatively competitive than those on the Australia-Europe, South America-Europe, Middle East-East Asia, and Middle East-Europe routes. Furthermore, it is reported by Schuler et al. (2024) that the potential shipping costs of ammonia and Fischer-Tropsch fuels are to be the least expensive option when compared to liquid hydrogen. While shipping costs constitute a rather small part of the overall energy supply cost in the importing country, studies are needed to identify the most efficient energy carrier derived from renewables. Consequently, a scenario-based approach is essential to recommend import from a particular geographical region.

Therefore, different import scenarios, with three potential production locations, namely Norway, Namibia and Algeria, are studied in this paper. In light of this background, the objective of the work presented here is to investigate the supply chain efficiency of maritime fuels i.e. gaseous hydrogen, ammonia and methanol, considering the production, storage, transport and bunkering stages of the fuel supply chain. Ammonia and methanol constitute established globally traded chemicals, available for transport on a large scale via shipping fleets and harbor infrastructure. Compressed gaseous hydrogen, on the other hand, can be transported via pipelines, which are typically constructed for large capacities. Existing natural gas pipelines could also be repurposed after implementing rigorous inspection protocols to mitigate safety and material embrittlement risks (DENA & Gassco AS 2023; Dertinger et al., 2022).

In this analysis, hydrogen is produced either via electrolysis powered with renewable energy, referred to as green hydrogen, or via Steaming Methane Reforming (SMR) coupled with Carbon Capture and Storage (CCS), referred to as blue hydrogen (Ustolin et al., 2022). This hydrogen is subsequently transported in gaseous form via pipelines from Norway, whereas from Namibia and Algeria, hydrogen derivatives, namely ammonia and methanol, are produced in these countries and then transported to Germany via ship. Both ammonia and methanol can be utilized as maritime fuels without reconversion to hydrogen. Simultaneously, the extensive pipeline infrastructure currently operational in Norway and Germany has been proposed as a potential means for transporting compressed gaseous H_2.

2 Demand and supply

This chapter describes the expected demand for 2030 and 2050 of hydrogen and hydrogen-based fuels-ammonia and methanol-in Germany, and presents the three possible supply options considered, namely from Norway, Namibia and Algeria.

2.1 Demand in Germany

The transport sector's hydrogen demand worldwide is projected to be the second most significant after the industry sector. Maritime and aviation sectors will depend on synfuels for decarbonization, with a total of approximately 450 TWh by 2050 in the EU27+UK. Consequently, in 2050, the demand for synfuels in Germany's transport sector could reach 60 TWh. Conversely, the total demand for gaseous hydrogen in Germany could increase to between 150–580 TWh by 2050 (Ausfelder et al., 2024).

The potential hydrogen (and its derivatives) demand across maritime sub-sectors in Germany is projected to reach 5 TWh by 2030 and 114 TWh by 2045. Currently, an equivalent of approximately 20 TWh of energy per annum is bunkered at German ports. The majority of this energy, accounting for nearly 70%, is utilized by international ocean-going vessels, followed by inland shipping at 15% and national maritime shipping at 13% (Zerta et al., 2023).

Based on studies by DENA (2024); EE Energy Engineers and TÜV NORD EnSys GmbH (2023), the ammonia demand is estimated to be 0.7 Mt/year in 2030 and 2.32 Mt/year in 2050 and the methanol demand, 0.8 Mt/year in 2030 and 4 Mt/year in 2050. These values indicate probable fuel demand in Germany; from these probable values, low and high demand indicating a pessimistic and optimistic scenario, are considered. Based on these, eight total scenarios have been assumed namely low (considering 80% of the mean expected demand) and high (considering 120%) for both fuels and the 2030 and 2050 timeframe, as presented in Table 1.

2.2 Supply options

Norway, Namibia and Algeria are introduced as three supply chain options for hydrogen-based maritime fuels to be imported to Germany.

2.2.1 Supply from Norway

In 2021, Norway had laid out its hydrogen roadmap to establish large scale green and blue hydrogen production facilities. Low-carbon hydrogen is prioritized to cater for two end-use sectors: maritime transport and energy-intensive process industries (Skjærseth et al., 2023). Norway can potentially produce approximately 25 million tons of blue hydrogen for export needs as of 2019 estimates (Quitzow and Zabanova 2024).

There is an existing natural gas infrastructure between Norway and Germany, and according to the European Hydrogen Backbone Infrastructure map, there are plans to utilize part of these pipelines to transport hydrogen by 2030.

2.2.2 Supply from Namibia

Namibia possesses significant potential for renewable energy generation. The country experiences approximately 3,000 h of sunlight annually, with annual solar irradiation values ranging between 2,200–2,400 kWh/m^2, which exceed the average for the African continent. In contrast, wind power potential is geographically limited to specific regions with higher onshore wind capacity factors. In the vicinity of Lüderitz, an annual electricity yield of approximately 2,800 MWh per installed MW of wind power can be anticipated. Consequently, Namibia aims to establish itself internationally as a production site for green hydrogen (GIZ 2022). The nation's strategy to produce synfuels at scale, with a target of 10–15 million tonnes per year hydrogen equivalent by 2050, coupled with relatively lower shipping costs within the African continent, renders Namibia an attractive location for export to the European market. Plans are underway for the development of three hydrogen valleys: in the southern region of Kharas, the central region encompassing Walvis Bay port and the capital Windhoek, and the northern region of Kunene. To meet ammonia demand in the fertilizer industry and potentially in the maritime sector as a fuel, Namibia is exploring the export of synthetic ammonia in the short term and synthetic methanol in longer-term scenarios (Ministry of Mines and Energy Namibia 2022).

TABLE 1 Demand scenarios of ammonia and methanol for the maritime sector in Germany.

Fuel type	Demand in 2030		Demand in 2050	
	Low (t/year)	High (t/year)	Low (t/year)	High (t/year)
Ammonia (demand for maritime sector)	560,000	840,000	1,856,000	2,784,000
Methanol (demand for maritime sector)	640,000	960,000	3,200,000	4,800,000

The national hydrogen strategy of Namibia presents estimations of the costs of production of green ammonia and methanol in their planned southern hydrogen hub, to be built around the Luderitz port. In the case of ammonia, a cost of $420–460 USD/ton NH_3 is estimated by 2030, progressively decreasing in the future to $360–390 USD/ton NH_3 by 2040 and $320–350 USD/ton NH_3 by 2050. As for methanol, estimations of the cost of production using DAC as the CO_2 source are presented. These range from $670–850 USD/ton MeOH by 2030 (considering a DAC cost of $225 USD/ton CO_2) to $440–560 USD/ton MeOH by 2050 (with a DAC cost of $140 USD/ton CO_2) (Ministry of Mines and Energy Namibia 2022).

2.2.3 Supply from Algeria

Algeria possesses several assets that could position it as a regional and international player in hydrogen production. The country experiences approximately 2000–3,000 h of sunlight annually, with estimated annual solar irradiation of nearly 1700 kWh/m^2 in the northern regions and 2,263 kWh/m^2 in the southern regions. The government's renewable energy development strategy has determined to calculate green electricity production based on 70% photovoltaic solar power and 30% wind power, given the complementary nature of their load profiles. Algeria's geographical proximity to the European market, port infrastructure, and 1,200 km coastline facilitates export routes in the Mediterranean basin for hydrogen and its derivatives. The nation aims to export up to 40 TWh in the form of gaseous, liquid hydrogen and/or its derivatives to the European market by 2040 (Ministère de L'Energie et des Mines - Algérie, 2023).

Algeria's national strategy for the development of hydrogen (Ministère de L'Energie et des Mines - Algérie, 2023) estimated the cost of hydrogen production and transport to Germany via pipeline. This corresponds to around $0.98 USD/kg H_2 by 2040, which includes $0.76 USD/kg H_2 for hydrogen production based on renewable energy and $0.22 USD/kg H_2 for its transport via pipeline. The estimation considers the use of repurposed natural gas pipelines and a pipeline distance of 2,800 km (BloombergNEF 2020).

3 Scope and boundary conditions of the analysis

This research examines a system designed to supply alternative maritime fuels, specifically methanol and ammonia, to Germany, evaluating their supply chain efficiency. The analysis establishes the system's boundary conditions and defines the scope of the selected import pathway. While various import pathway combinations are currently under consideration and may be subject to future feasibility analyses, this investigation focuses on three probable supply chain options. These options are based on Germany's projected demand, the exporting country's hydrogen strategies, renewable energy generation capabilities, and transportation modes, including pipeline and ship. The analysis incorporates blue and green hydrogen based on the country of export. In the case of Norway and Algeria, a higher proportion of blue hydrogen in 2030 is considered, as there is a natural gas reliance in these economies. The ratios of blue to green hydrogen are derived from existing literature (Alvik et al., 2023; BMWK 2023) and can be found in Table 2. Assuming that geopolitical conditions are prone to change, which is further described in Section 5.5, a sensitivity analysis is conducted in the results section. The ammonia and methanol supply routes examined are as below:

- Import of hydrogen via pipeline from Norway to produce ammonia and methanol in Germany
- Import of ammonia and methanol via ship from Namibia
- Import of ammonia and methanol via ship from Algeria

Table 3 describes the boundary conditions relevant for transport and the country specific conditions. The hydrogen imported from Norway via pipeline could fulfill the total demand for gaseous hydrogen in Germany, which is estimated to be 1.5–3.3 Mt per year in 2030 and 10.5–17.4 Mt per year in 2050. It is then assumed that one-third of this demand will be met by imports from Norway (Alvik et al., 2023). The pipeline specifications are enumerated later in Table 7. The demand for ammonia presented in.

Table 1 is utilized to calculate the hydrogen redirected through the distribution pipelines from Schillig (point of arrival) to Wilhelmshaven (final destination). Considering the projected growth in ammonia and methanol demand within the maritime industry, this hydrogen is subsequently converted to ammonia in Wilhelmshaven (EE Energy Engineers & TÜV NORD EnSys GmbH, 2023).

As for Namibia and Algeria, both countries have above-average solar and onshore wind resources. This can be observed, for example, when comparing the capacity factors that can be obtained in both countries with world averages. For instance, the mean capacity factor expected to be obtained in solar PV plants in Namibia is 32% (Ministry of Mines and Energy Namibia 2022), while in Algeria it is 27% (Wolf et al., 2024). For reference, the world average for new solar PV projects in 2018, according to the IEA, was 18% (Cozzi et al., 2019). Similarly, for onshore wind plants, the mean capacity factor expected in Namibia is 40%

TABLE 2 Distribution of hydrogen production.

Hydrogen type	Share for 2030			Share for 2050		
	Norway	Namibia	Algeria	Norway	Namibia	Algeria
Blue	98%	0%	98%	20%	0%	0%
Green	2%	100%	2%	80%	100%	100%

TABLE 3 Country specific boundary conditions.

Boundary condition	Unit	Norway	Namibia	Algeria	References
Distance of transport (Pipeline length or Ship route)	km	950	11,000	3,400	SEA-DISTANCES.ORG (2024)
Average ambient temperature	°C	10	21	21	Climate Change Knowledge Portal (2021)

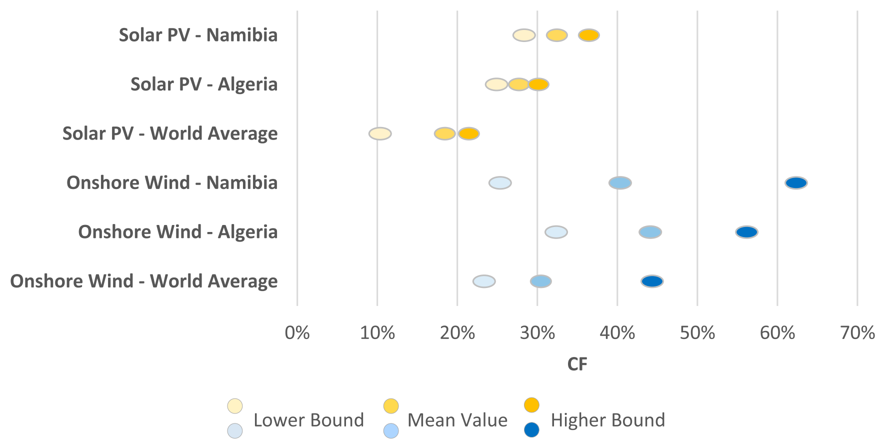

FIGURE 1
Solar PV and onshore wind capacity factors (CF) for Namibia and Algeria compared to world averages for 2018.

(Ministry of Mines and Energy Namibia 2022), while in Algeria it is 44% (Wolf et al., 2024). In contrast, the worldwide average for new projects in 2018 was 30% (Cozzi et al., 2019). Figure 1 graphically shows the lower bound, mean, and higher bound values of these capacity factors.

For the case of imports from Algeria, hydrogen transport to Germany via pipeline is another alternative that could be contemplated, with it being mentioned in the country´s national hydrogen strategy (Ministère de L'Energie et des Mines - Algérie, 2023). The Global Gas Report 2020 (BloombergNEF 2020) outlines a potentially cost-competitive import route via the Transmed pipeline, going from Algeria through the Mediterranean sea to Italy and reaching south Germany after a transport distance of 2,800 km. However, the additional transport requirement from south Germany to Wilhelmshaven would result in a low economic appeal of the import route. In this sense, IRENA suggests that pipeline transport is the most cost-efficient option for distances of up to 3,000 km, which would be exceeded in this case (IRENA 2022). This takeaway is also supported by analysis performed for the TransHyDE Project (Ausfelder et al., 2024), where it was stated that hydrogen imports from non-EU countries are less competitive compared to large-scale domestic production within Europe, especially when those imports are intended to be carried out via pipeline. Moreover, hydrogen exports in the form of methanol and ammonia via shipping are also outlined in Algeria´s national hydrogen strategy (Ministère de L'Energie et des Mines - Algérie, 2023). Therefore, the approach of considering their direct import shows potential, since these fuels could be deployed in alternative maritime transport.

In this analysis, a ship transport of hydrogen-derived fuels for maritime applications is considered, with the final destination of interest being the port of Wilhelmshaven. In 2019, a total of 29.29 million tons of cargo were handled at the port of Wilhelmshaven. This consisted of oil and its by-products carriers, chemical carriers, steel and by-products carriers, LPG, wood, and car carriers. Therefore, this port has been selected due to international carrier's bunkering requirements (Niedersachsen Ports 2020).

The storage of methanol and ammonia is assumed both at the import and export terminals. Furthermore, for both of these fuels,

TABLE 4 Assumptions for import of methanol and ammonia.

Description	Country	2030 (% of total demand)	2050 (% of total demand)	References
Percentage of methanol demand covered per country	Norway	33.3%	33.3%	Alvik et al. (2023)
	Namibia	53.3%	33.3%	Ministry of Mines and Energy Namibia (2022) (Ministère de L'Energie et des Mines - Algérie, 2023)
	Algeria	13.3%	33.3%	
Percentage of ammonia demand covered per country	Norway	33.3%	33.3%	(BMWK, 2024; EE Energy Engineers & TÜV NORD EnSys GmbH, 2023; Zerta et al., 2023)
	Namibia	33.3%	33.3%	
	Algeria	33.3%	33.3%	

a 30 days storage capacity was assumed at the import terminal. Additionally, the maritime demand of ammonia in Germany is used to estimate the hydrogen needed via the inland distribution pipeline. Losses due to boil-off for ammonia, which is reliquefied, are considered for energy consumption calculations during its transport, loading and unloading and bunkering. Both ammonia and methanol are assumed to be transported in liquid state.

In both 2030 and 2050 scenarios, the percentage distribution for import is based on each importing country's availability of fuel data. For 2050, the demand has been split equally between countries in order to avoid biases in calculations. However, for 2030 this could not be considered because of the current strategies of the respective countries. The aforementioned assumptions were also formulated under the premise that the German government wants to guarantee a diversified supply of the country´s hydrogen and hydrogen derivatives imports, as outlined in the national import strategy adopted in July 2024 (BMWK, 2024). Additionally, in the case of the African countries, a comparison of their hydrogen production and export goals for 2030 was considered in order to define the shares of imports for the case of methanol (Ministère de L'Energie et des Mines - Algérie, 2023; Ministry of Mines and Energy Namibia 2022). This led to the observation that Namibia has a hydrogen production goal of 1 Mt of H_2 per year for 2030, while Algeria has a goal of 0.3 Mt of H_2 per year for the same time horizon. Therefore, it was assumed that, for 2030, 53.3% of Germany's methanol demand would be supplied by Namibia, while 13.3% would be supplied by Algeria, and the remaining 33.3% by Norway, as shown in Table 4.

In case of ammonia, the german maritime demand for both 2030 and 2050 is assumed to be equally distributed between 1) hydrogen imports from Norway for the domestic production of ammonia, and 2) direct imports of ammonia from Algeria and Namibia.

3.1 Supply chain system description

Hydrogen can be transported in various forms, including compressed gaseous hydrogen, liquid hydrogen, ammonia, methanol and liquid organic hydrogen carriers (LOHC). This analysis investigates two maritime synfuels derived from gaseous hydrogen, namely ammonia and methanol, from their respective supply chain perspectives. For the year 2030 and 2050, Figure 2 illustrates the boundary of the supply chain for each fuel, encompassing production, conversion, transport, storage, and bunkering.

The energy requirement for different stages of the supply chain is calculated for the years 2030 and 2050, with high and low supply scenarios from three exporting countries: Norway, Namibia, and Algeria, with the destination site being Wilhelmshaven in Germany. This includes the energy required for the production of hydrogen via both Steam Methane Reforming (SMR) with carbon capture and storage or water electrolysis, as well as the conversion, storage, transport via pipeline or ship, and bunkering of the fuels in the port of Wilhelmshaven. For transport from Norway, given the relatively shorter distance, pipeline transport of gaseous hydrogen is utilized, whereas for the transport of ammonia and methanol, ship-based transport is considered. For the ship-based supply chains, the duration of transport is determined by the speed of the carrier ship and the transport distance. Boil-off is generated by ammonia is stored and transported in a liquid state. It is assumed that the boil-off generated is reliquefied during transport, storage in ports, and bunkering operations. The storage capacity of ammonia and methanol produced in Namibia and Algeria is calculated based on the number of ships, the average ship speed, and the number of annual voyages. A 30-day storage period for ammonia and methanol at the port of Wilhelmshaven is assumed. Ammonia and methanol bunkering ships operate on marine gas oil (MGO) and very low sulphur fuel oil (VLS IFO) respectively.

The following supply chain routes, illustrated in Figure 2, have been evaluated in this analysis:

3.1.1 Supply chain 1: Norway to Germany transport of gaseous hydrogen and conversion to ammonia and methanol

Supply chain 1 considers the production of hydrogen utilizing both green and blue pathways of production at Mongstad in Norway. This refers to a combination of variable renewable energy and SMR with carbon capture and storage. The hydrogen is compressed and transported via a newly constructed pipeline from Mongstad to the Draupner platform in the North Sea. From Draupner to Schillig in Germany, it is transported via repurposed

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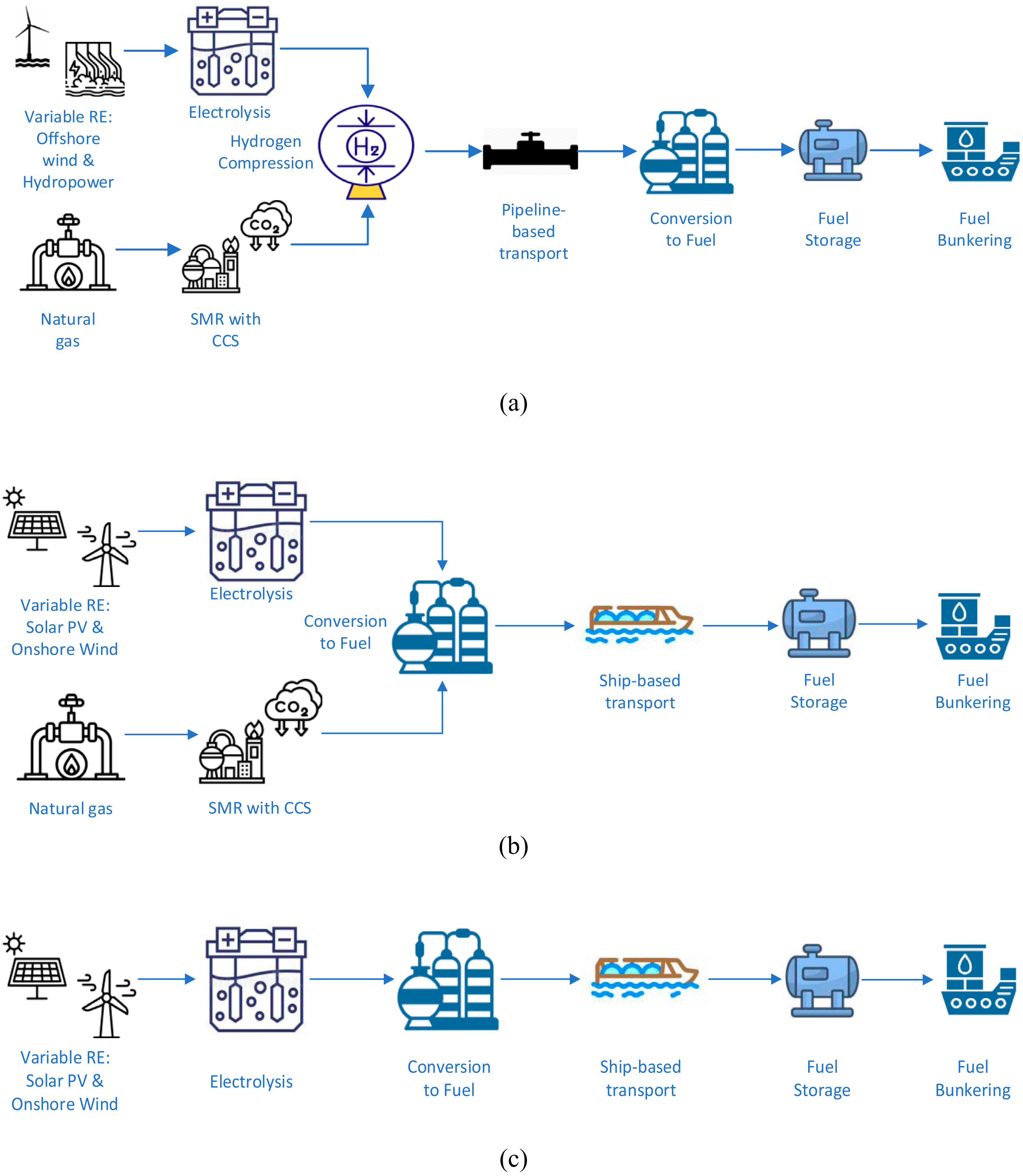

FIGURE 2
Schematic representation of the supply chains for: **(a)** Compressed hydrogen from Norway to Germany (2030 and 2050); **(b)** Synthetic ammonia and methanol from Algeria to Germany (2030); **(c)** Synthetic ammonia and methanol from Namibia (2030 and 2050) and Algeria (2050) to Germany.

natural gas pipelines. Upon arrival in Schillig, a portion of this hydrogen for maritime utilization is transported through the german distribution inland pipelines to Wilhelmshaven. In Wilhelmshaven, the hydrogen is converted to ammonia via the Haber-Bosch process, and methanol via CO_2 hydrogenation. The fuels are then stored and bunkered.

3.1.2 Supply chain 2: Namibia to Germany transport of synthetic ammonia and methanol

The port of origin is the Luderitz Port (in Namibia) and the destination the Port of Wilhelmshaven in Germany. Hydrogen is produced via onshore wind and solar PV-driven electrolysis, converted to methanol and ammonia, stored and

TABLE 5 Hydrogen production process parameters.

Parameter	Unit	Value	References
Electrolysis energy consumption 2030	kWh/kg H_2	50	U.S. DOE (2024)
Electrolysis energy consumption 2050	kWh/kg H_2	46	
Output temperature of H_2 (Electrolysis)	°C	50	Rahmat et al. (2023)
Output pressure of H_2 (Electrolysis)	MPa	3	
SMR + CCS energy consumption	kWh/kg H_2	49.5	Collodi et al. (02/2017); Ali Khan et al. (2021)
Output temperature of H_2 (SMR)	°C	412	
Output pressure of H_2 (SMR)	MPa	2.77	

TABLE 6 Parameters of the Haber-Bosch process and Air Separation Unit (ASU).

Parameter	Unit	Value	References
Haber Bosch process operating pressure	MPa	30	Valera-Medina and Banares-Alcantara (2020)
HB operating temperature	°C	500	
Temperature of N_2 (ASU Cryo)	°C	−170	
Pressure of N_2 (ASU Cryo)	MPa	0.5	
Energy consumption for N_2 separation (ASU Cryo)	MJ/kg NH_3	0.3	

transported via chemical carriers to Wilhelmshaven, where it is subsequently bunkered.

3.1.3 Supply chain 3: Algeria to Germany transport of synthetic ammonia and methanol

The port of origin is Arzew Port (in Algeria), while the destination port would be the Wilhelmshaven Port (in Germany). The hydrogen is produced via a mixture of natural gas with carbon capture and storage, solar PV, and onshore wind, converted to methanol and ammonia, stored, and transported via chemical carriers to Wilhelmshaven, where it is subsequently bunkered.

3.2 Production boundary conditions

The assumptions and boundary conditions for hydrogen production, as well as the parameters for the Haber-Bosch process for ammonia production are provided in Tables 5, 6 respectively. Green hydrogen production is assumed to be carried out with PEM electrolyzers. As for blue hydrogen, it was assumed to be produced via Steam Methane Reforming (SMR) coupled with Carbon Capture and Storage (CCS). The energy demand considered for this production pathway was derived from energy balance values from (Collodi et al., 2017; Ali Khan et al., 2021).

Methanol, on the other hand, was assumed to be produced via carbon dioxide hydrogenation with the CO_2 feedstock coming from a stream of flue gas produced in a conventional thermal power plant (Rahmat et al., 2023; Sollai et al., 2023). The feedstock, namely hydrogen and carbon dioxide, are compressed adiabatically to reach the reaction pressure of 6.5 MPa and heated isobarically to reach the reaction temperature of 230°C. After production, it is cooled to reach ambient temperature from the reaction outlet temperature of 55°C (Rahmat et al., 2023). Lastly, upon cooling it is assumed to be stored at atmospheric pressure and ambient temperature (MAN Energy Solutions 2024a).

In the case of ammonia, it is assumed to be produced via the Haber Bosch process (Valera-Medina and Banares-Alcantara 2020). Nitrogen is assumed to be derived from an Air Separation Unit (ASU). The feedstock nitrogen and hydrogen are then compressed and heated to the process requirements. Afterwards, the produced ammonia is distilled and stored in a cryogenic tank.

It is noteworthy that the targets for improvements in energy efficiency of electrolysis between 2030 and 2050 are outlined in the projections of the U.S. Department of Energy (U.S. DOE 2024). Thus, a lower energy consumption was considered for the 2050 scenarios as compared to the 2030 ones. Conversely, for the production of hydrogen via Steam Methane Reforming (SMR) coupled with Carbon Capture and Storage (CCS), no significant energy efficiency improvements were considered. This is attributed to the fact that both processes are already highly developed and optimized, as evidenced by a Technology Readiness Level (TRL) of 9, reported in sources such as (Kearns et al., 2021; Muron et al., 2024; Pinsky et al., 2020).

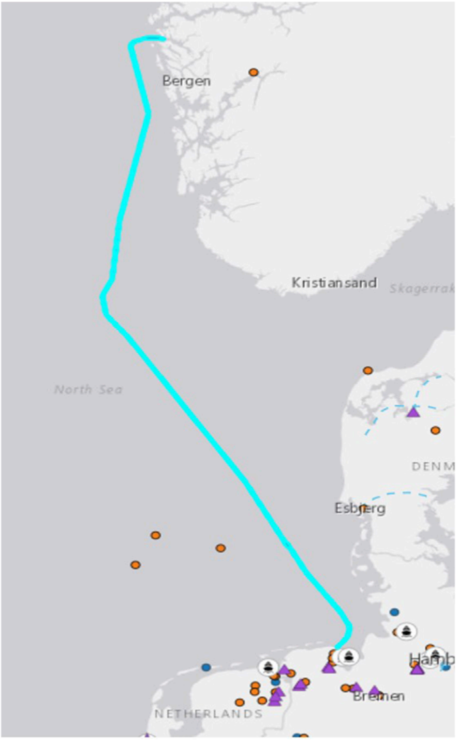

FIGURE 3
Hydrogen backbone pipeline (van Rossum et al., 2022).

3.3 Fuel transport boundary conditions

The transport route from Norway to Germany is shown in Figure 3: the backbone pipeline with a length of 950 km and a further 30-km pipeline for inland distribution within Germany.

Table 7 presents the characteristics and specifications of the pipeline considered for the transport of gaseous hydrogen. Fuel transport via ship is considered to be done by ammonia and methanol tankers. For this analysis, one sample tanker for ammonia and two for methanol (one for 2030, and another with higher cargo capacity for 2050) are considered. Their main characteristics, relevant to energy demand calculations, are presented in Table 8.

Additionally, for the value chains with transport via ship, the loading and unloading of ammonia and methanol to and from the tanker vessels need to be considered. Consequently, assumptions regarding pump flow rate, hydraulic head and efficiency of the pump are made according to literature data, all of which are shown in Table 9.

3.4 Bunkering boundary conditions

In the context of maritime, the process of fueling ships is known as bunkering. The analyzed supply chains incorporated a ship-to-ship bunkering process. In support of this assumption, successful instances of ship-to-ship bunkering processes have already been documented for both ammonia (GCMD 2024) and methanol (Hand 2024). Additionally, the ship-to-ship approach stands out for its exceptional adaptability, enabling fuel transfer operations to occur at sea without requiring the recipient vessels to enter port facilities (ABS 2024). This flexibility represents a significant advantage in the maritime fueling landscape.

Furthermore, it facilitates high bunkering rates and volumes, which is particularly significant when considering the large-scale deployment of ammonia and methanol-driven fleets anticipated in the coming years (Raucci et al., 2023). Therefore, a single ship would have the ability to perform multiple bunkering operation within one bunkering cycle, allowing for more efficiency and flexibility on maritime shipping operations (ABS 2024). All of these factors collectively suggest the viability and potential implementation of this bunkering strategy for both fuels examined.

Table 10 presents the key characteristics of the bunkering ships selected, as well as of the bunkering processes themselves. In the case of the ammonia bunkering ships, the vessel's width, heel mass, and boil-off gas temperature are included precisely because they are relevant for the fuel boil-off calculation. This is not the case for the methanol bunkering ship, however, as no boil-off is considered. Consequently, the parameters are not presented.

4 Research methodology

A scenario-based approach is employed as the research methodology in this work. It entails the provision of optimized suggestions in the form of an output, relying on input variables that could be a function of time frame, demand and supply ambitions (for example, low and high demand values), and capacity to produce, transport, and store the traded item. This approach yields suggestions of a suitable supply chain route for the import of fuel considering low and high demand brackets, supply possibilities in the view of production capacities of hydrogen (blue, green), transport via pipeline and ship, storage at port, and bunkering vessels for the years 2030 and 2050 as time frames. The initial step involves identifying the specific fuel routes based on the exporting country's hydrogen strategy. Following this, the input and output parameters of the selected fuel transport routes are modeled, linking them with the end usage specifications (bunkering) to evaluate the efficiency of the overall supply chain. Furthermore, the uncertainties of the future, which might lead to a different share of blue and green hydrogen supply, are covered by performing a sensitivity analysis.

The following sub-chapter provides a detailed description of the compressed hydrogen, ammonia and methanol supply chains considered in this paper, along with their energy requirements and system boundaries.

4.1 Production

The energy required for hydrogen production in the exporting country is calculated for both the SMR + CCS and water electrolysis pathways. The energy requirements to produce hydrogen using SMR + CCS and electrolysis are mentioned in Table 5.

The power required is then calculated based on the amount of hydrogen required to meet the demand of ammonia or methanol. As the production pathway is split between SMR and electrolysis, the individual power requirements for each can be calculated.

TABLE 7 Pipeline boundary conditions.

Pipeline parameters	Unit	Backbone pipeline	Distribution pipeline	References
Length	km	950	30	Hydrogen Backbone Pipeline
Operating pressure	MPa	10	10	(Kuczyński et al., 2019; Tsiklios et al., 2022)
Inner Diameter	m	1.2	0.25	
Roughness factor of weld steel pipe material	mm	0.045	0.045	

TABLE 8 Methanol and ammonia tanker characteristics.

Tanker	Parameter	Value	Unit	References
Ammonia	Effective cargo capacity	23,600	m^3	Own assumption
	Fuel consumption	0.78	t/h	Own assumption
	Energy density of fuel – VLS IFO	41,500	MJ/t	Daling and Kristin Rist (2020)
	Ship mean speed	11	kn	Own assumption
Methanol – 2030	Effective cargo capacity	15,400	m^3	Own assumption
	Fuel consumption	0.6	t/h	Own assumption
	Energy density of fuel - Marine diesel	42,190	MJ/t	Wu and Bucknall (2016)
	Ship mean speed	11	kn	Own assumption
Methanol – 2050	Effective cargo capacity	46,000	m^3	Own assumption
	Fuel consumption	1.4	t/h	Own assumption
	Energy density of fuel - Marine diesel	42,190	MJ/t	Wu and Bucknall (2016)
	Ship mean speed	12	kn	Own assumption

4.2 Conditioning and conversion

Hydrogen conditioning: Following its production, pipeline transport necessitates an increase in pressure to match the pipeline's operational requirements. To achieve this, a central compression facility is positioned at the pipeline's origin point. The requisite work done for this process is described in the Transport Section 4.3.

From the hydrogen produced, methanol and ammonia are synthesized in both Algeria and Namibia as per the quantities described in Table 4.

As a metric to assess the energy efficiency of the methanol synthesis process, the power-to-fuel efficiency was calculated using Equation 1 (Rahmat et al., 2023).

$$\eta_{PtF} = \frac{LHV_{Methanol} * \dot{n}_{Methanol}}{P_{Methanol\,synthesis}} \tag{1}$$

where, η_{PtF} is the power-to-fuel efficiency, $LHV_{Methanol}$ is the lower heating value of methanol per mole, $\dot{n}_{Methanol}$ represents the molar methanol flow rate and $P_{Methanol\ synthesis}$ is the total power (MW) input for methanol production.

4.3 Transport

Pipeline and ship-based transport is evaluated in this subsection for the transport of hydrogen and its analyzed derivatives.

4.3.1 Pipeline-based transport

To estimate the pressure loss due to pipeline transport, the Darcy-Weisbach equation was employed. For each compression station, including the main compression in Norway and recompression stations along the pipeline length, the compression work of a multistage compressor was calculated.

Equation 2: Compression work done (López-Paniagua et al., 2020):

$$w = -\frac{1}{\eta} R T_1 \frac{k}{k-1} n\left(r^{\frac{k-1}{k}} - 1\right) \tag{2}$$

Where w is the specific work, η is the efficiency of the compressor, R is the ideal gas constant, T_1 is the inlet gas temperature, k is the polytropic constant, n is the total number of compression stages, and r is the compression ratio.

TABLE 9 Parameters of pumps used for loading and unloading the carrier ships.

Parameter	Value	Unit	References
Loading and unloading flow rate (Ammonia)	2,934	m^3/h	Yang and Lam (2023)
Loading and unloading flow rate (Methanol)	12,000	m^3/h	(Al-Breiki and Bicer 2020a; Al-Breiki and Bicer 2020b)
Hydraulic head (Ammonia)	10.00	m	Own assumption. Estimated to be equal to the draught of the ship
Hydraulic head (Methanol)	9.61	m	
Pump efficiency	80	%	Al-Breiki and Bicer (2020b)

4.3.2 Ship-based transport

Based on the daily production rates of methanol and ammonia in Namibia and Algeria, as well as storage capacity considerations, the appropriate type of carrier ships for their transport was determined. Table 8 presents the characteristics of the tankers pertinent to ship fuel consumption and voyage energy requirements. The number of carrier ships required were calculated using the Equation 3. Whereas the number of voyages per year was calculated based on Equation 4.

$$No.\,of\,ships\,required = \frac{V_{Methanol\,per\,day} * voyage\,duration}{V_{Methanol\,per\,ship}} \tag{3}$$

$$No.\,of\,voyages\,per\,year = \frac{V_{Methanol\,per\,year}}{V_{Methanol\,per\,ship}} \tag{4}$$

Where $V_{Methanol\ per\ day}$ represents the volume of methanol produced per day, $V_{Methanol\ per\ ship}$ the volume of methanol transported per ship, $V_{Methanol\ per\ year}$ the volume of methanol produced per year and the voyage duration is the sum of the round trip.

In the case of ammonia, the energy required to reliquefy boil-off gas generated during ammonia transport via ship is calculated using Equations 5–7.

$$Evaporation = \frac{Q}{\Delta H_{vap}} \tag{5}$$

$$Boil-off\,ratio = \frac{Mass\,of\,ammonia_{evap}}{Mass\,of\,ammonia_{stored}} \tag{6}$$

$$Energy\,to\,cool\,BoG = mC_p\Delta T + \Delta H_{cond} \tag{7}$$

where Q refers to the heat ingress, ΔH_{vap} is the latent heat of vaporization, m is the mass of ammonia, C_p is the specific heat capacity, ΔT is the temperature difference and ΔH_{cond} is the latent heat of condensation.

The specific fuel consumption (SFC) is obtained either from the Clarkson database or the engine specification datasheet depending on the availability of data. Given the fuel consumption of the ship, the distance travelled for voyage and the speed of the ship, the energy required per kg of ammonia or methanol (MJ/kg) transported is calculated using Equation 8.

$$Transport\,energy\,consumption = \frac{SFC * LHV\,of\,fuel\,used * voyage\,duration}{Mass\,of\,Ammonia/Methanol\,transported\,per\,voyage} \tag{8}$$

4.4 Loading and unloading cargo

The loading and unloading energy requirements P for ammonia and methanol on the carrier ships are calculated using Equation 9, considering the assumptions presented in Table 9.

$$P_{load/unload} = \frac{q * \rho * g * h}{3.6 * 1000000 * \eta_{pump}} \tag{9}$$

where, q is the volumetric flow rate (m^3/h), ρ is the fuel density (kg/m^3), g is the gravitational acceleration (m/s^2), h is the differential head (m) and η_{pump} is the efficiency of the pump used.

Heat transfer through the loading pipe (q_{energy}), as analyzed by (Al-Breiki and Bicer 2020a), is given by Equation 10:

$$q_{energy} = \frac{2\pi kL\left(T^o - T^C\right)}{2.3\,log_{10}\left(\frac{D+2t_h}{D}\right)} \tag{10}$$

where, k is the thermal conductivity, D is the inner diameter of the pipe, L is the length of the pipe, t_h is the insulation thickness, T° is the ambient temperature, and T^c is the fuel temperature. Boil-off gas generated during the loading process (Al Ghafri et al., 2022) is estimated with Equation 11 (Al-Breiki and Bicer 2020a):

$$BoG_{loading/unloading} = \frac{t_{q_{energy}} + \left(HC_T + C_pM_H\right)\left(T^H - T^C\right)}{\Delta h_{vap}} \tag{11}$$

where, $t_{q\ energy}$ is either the loading or unloading time, HC_T is the tank heat capacity, C_p is the fuel isobaric specific heat capacity, M_H is the mass of the heel retained at the starting of loading or unloading, T^H is the temperature of heel and T^C is the temperature of the fuel.

4.5 Storage

The energy required for ammonia boil-off gas reliquefaction is calculated using Equation 7. Whereas, methanol, upon production in Namibia and Algeria, is stored in a tank with a volume of 80,000 m^3, considering a maximum used storage volume of 98% (Al-Breiki and Bicer 2020b). The number of storage tanks at the export terminal is determined based on the total voyage duration (accounting for round trips and 1 day of stay at port for both import and export terminals).

TABLE 10 Bunkering ships and processes – parameters and assumptions.

Parameter	Bunkering ship	Value	Unit	References
Bunkering Ship Fuel Type	Ammonia (2030)	MGO		Caterpillar 3516B-HD Engine
	Ammonia (2050)	VLS IFO		MAN Energy Solutions (2024b)
	Methanol	MDO		Yanmar (2020)
Bunkering Ship Fuel Consumption	Ammonia (2030)	0.4	m^3/h	Own assumption
	Ammonia (2050)	1.1	m^3/h	Own assumption
	Methanol	0.2	m^3/h	(Wu and Bucknall 2016; Yanmar 2020)
Bunkering Ship Transported Fuel Volume	Ammonia (2030)	4,800	m^3	Own assumption
	Ammonia (2050)	24,000	m^3	Own assumption
	Methanol	6,200	m^3	(The Engineering Toolbox 2008; Yanmar 2020)
Bunkering ship mean speed	Ammonia (2030)	6.5	kn	Own assumption
	Ammonia (2050)	13.0	kn	Own assumption
	Methanol	9.0	kn	Own assumption
Draught of ship/Height of cargo manifold above waterline	Ammonia (2030)	6	m	Own assumption
	Ammonia (2050)	10	m	Own assumption
	Methanol	6.50	m	Own assumption
Width of ship	Ammonia (2030)	16	m	Own assumption
	Ammonia (2050)	26	m	Own assumption
Heel mass	Ammonia (2030)	5	%	Own assumption
	Ammonia (2050)	5	%	Own assumption
Boil-off gas temperature	Ammonia (2030)	−29	°C	Al Ghafri et al. (2022)
	Ammonia (2050)	−29	°C	
Distance for bunkering trip - 2030	All	50	NM	Own assumption
Distance for bunkering trip - 2050	All	200	NM	Own assumption

The dimensions of the storage tanks for ammonia are calculated based on the ammonia demand for each scenario, maintaining a diameter-to-height (D/H) ratio of 0.75. The heat transfer coefficient from the tank is assumed to be 0.32 W/m^2K (Morgan 2013). This heat transfer into the tank results in the generation of boil-off gas. Subsequently, the energy consumption required to cool the boil-off gas is calculated.

4.6 Bunkering

This paper examines ship-to-ship bunkering of both ammonia and methanol. The heat flux for the selected two bunker vessels is calculated utilizing the surface area of the cargo storage tanks. This heat flux generates boil-off gas in the case of ammonia, which is subsequently reliquefied. The analysis considers one bunker cycle, commencing from the point of loading until the bunker vessel completes the bunkering operation of all the fuel (excluding heel mass) and returns to the loading station. It is noted that the quantity of boil-off gas, for the case of ammonia, varies at each stage of the process. The energy consumption for the bunkering stage is calculated using Equation 12.

$$P_{bunkering} = P_{vessel\,loading\,and\,unloading} + P_{vessel\,fuel\,consumption} \tag{12}$$

P_x implies energy consumption (MJ/kg) in each step of bunkering process.

The overall efficiency (η) of the import options in % is calculated using Equations 13, 14.

$$\eta_{cH_2\,to\,NH_3\,pipeline\,supply\,chain} = \frac{LHV_{NH_3} * \dot{n}_{NH_3}}{P_{H_2\,production} + P_{H_2\,compression} + P_{cH_2\,transport} + P_{NH_3\,production} + P_{NH_3\,storage} + P_{NH_3\,bunkering}} \quad (13)$$

Where LHV is the lower heating value, $\dot{n}$ is the molar flow rate, and P represents the power consumption of the different stages of the supply chain.

$$\eta_{f\,ship\,supply\,chain} = \frac{LHV_f * \dot{n}_f}{P_{H_2\,production} + P_{f\,synthesis} + P_{f\,transport} + P_{f\,storage} + P_{f\,bunkering}} \quad (14)$$

Where f stands for fuel (ammonia or methanol).

5 Results and discussion

The results are presented as per the methodology, considering low and high demand scenarios for both ammonia and methanol. These scenarios have been derived from.

Tables 1, 2 for the years 2030 and 2050. The summation of energy use of the different components of the supply chain constitutes the total energy input. The supply chain efficiency is defined as the ratio of the energy content of delivered fuel (LHV) in the form of ammonia and methanol to the total energy consumption covering all the considered stages of supply chain: production, conditioning, transport, storage and bunkering. It is important to note that because of the losses associated with electrolysis and SMR with carbon capture and storage, the energy consumption for the hydrogen production stage has a significantly high share in all three import options. In particular, it accounts from 75% to 82% of the total energy consumption of the supply chain.

The power-to-fuel efficiencies obtained in this study for 2030 range between 51.23% in Namibia and 51.65% in Algeria, while in 2050 they increase to 54.73% for both countries, primarily due to the anticipated improvement of electrolyzer efficiency. This aligns well with the 52.4% and 54.7% figures found by (Rahmat et al., 2023) when considering a VDB kinetic model and a GRF model respectively. On the other hand, the energy consumption calculated for the Haber- Bosch process and Air separation unit (ASU) is 2.05 MJ/kg NH_3. This value is slightly lower than the one reported in Staudt et al. (2024) (2.5 MJ/kg NH_3) owing to the differences in process conditions. Namely, that hydrogen is delivered in a compressed state. This difference in energy consumption is taken in to account in the conditioning stage of the supply chain.

5.1 Import from Norway

Figure 4 illustrates the energy consumption for each stage of Supply Chain 1 on the primary y-axis and the supply chain efficiency on the secondary y-axis. The individual energy consumption (in MJ/kg fuel) of various supply chain stages is represented below, whereinthe production stage consumes the highest amount of energy. The hydrogen production is a mixture of blue and green pathways, as stated in Table 2.

Energy consumption during the transport stage of hydrogen via pipeline encompasses both backbone and inland distribution networks. Initial energy consumption occurs due to the compression of hydrogen to the operating pressure of the pipeline. The pressure losses resulting from the pipeline transport of gaseous hydrogen are compensated with recompression stations, contributing to further energy consumption. Based on the pressure loss calculation and the total length of the pipeline, it was determined that three recompression stations are required to compensate for the frictional losses. Finally, the energy consumption associated with the bunkering process is dependent upon the varying bunkering requirements for both 2030 and 2050.

The overall efficiency of the supply chain is approximately 48% and 51% in 2030 and 50% and 53% in 2050 for ammonia and methanol respectively. The increase in overall efficiency between 2030 and 2050 is primarily attributed to improvements in the electrolyzer efficiencies (50–46 kWh/kg hydrogen) and minor improvements in the storage energy consumption. This increase in efficiency is achieved despite the increase in energy consumption due to the transport of hydrogen via pipeline. Energy requirements for the transport of hydrogen via pipeline increase for a fixed diameter pipe, while pressure losses increase with higher flow rates.

Bunkering energy consumption, on the other hand, depends on the capacity of the bunker ship. During the bunkering process, the boil-off gas for the ammonia supply chain is calculated to be 0.04 and 0.10 kg/s for bunkering ships 1 and 2 respectively as indicated in Table 9. For methanol, as there is no boil-off gas, the energy consumption results from the fuel usage of the bunkering ship only. The utilization of the bunker ship increase from low to high demand scenarios. This results in the reduction of energy consumption per kg of bunkered fuel.

5.2 Import from Namibia

An examination of the methanol supply chain reveals that, the most significant contributor to the energy demand, after hydrogen production, is CO_2 capture for methanol synthesis. The stage encompassing methanol production and storage is expected to maintain a consistent level of specific energy consumption, regardless of whether demand scenarios. This stability is attributed to technologically mature process and a high degree of optimization (Sollai et al., 2023).

Regarding the methanol shipping process, there is a substantial reduction in its contribution to the supply chain energy consumption when comparing the 2030 and 2050 scenarios as shown in Figure 5. In particular, the specific energy consumption decreases from a maximum of 2.317 MJ/kg methanol (for the low demand scenario) to 1.637 MJ/kg methanol. This reduction is attributable to economies of scale, as the utilization of a larger carrier for transporting increased quantities of fuel results in a lower specific energy consumption.

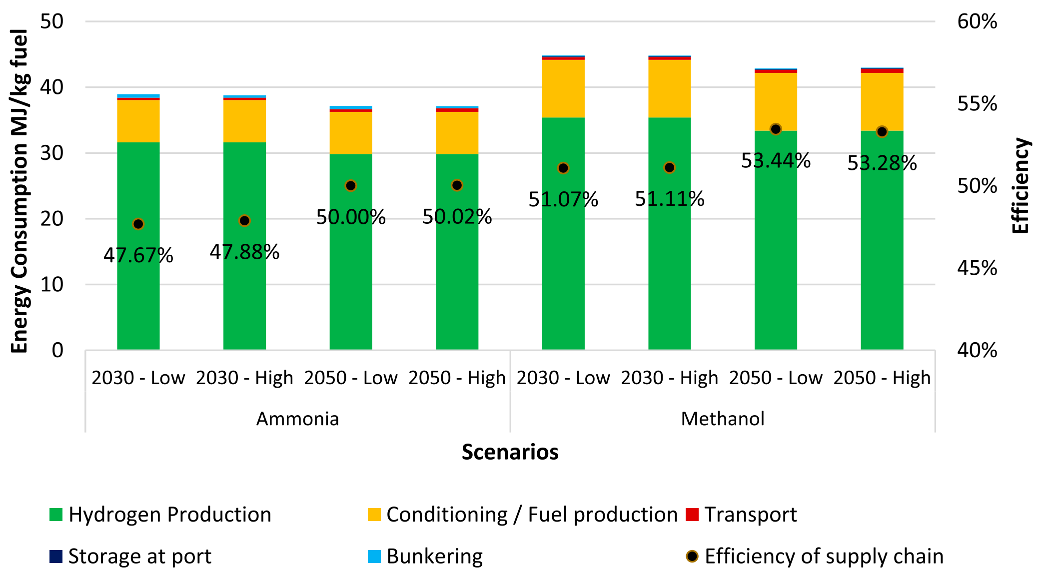

FIGURE 4
Energy consumption and efficiency of supply chain 1 – Norway.

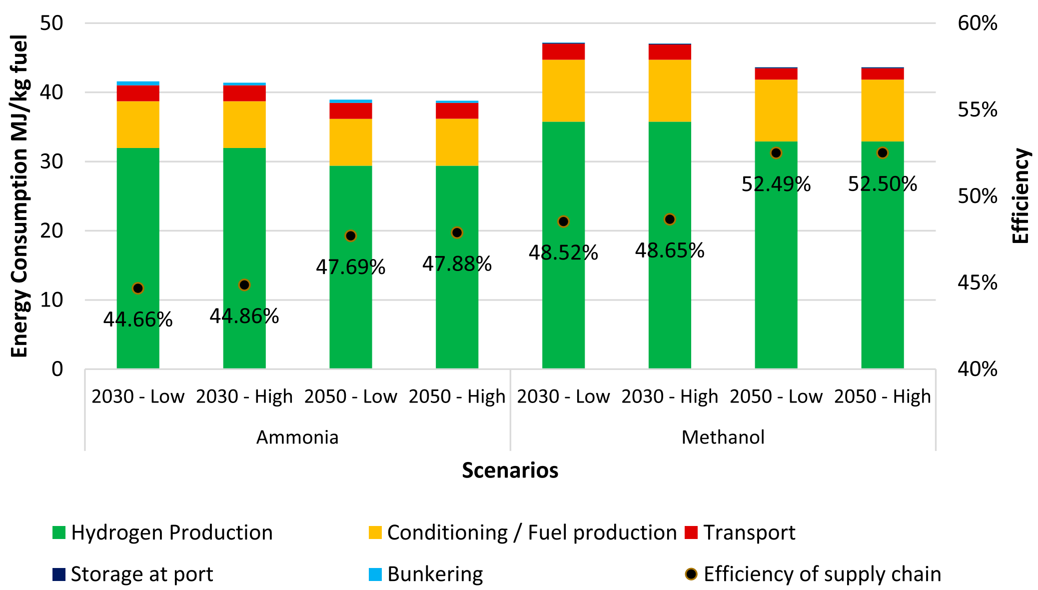

FIGURE 5
Energy consumption and efficiency of supply chain 2 – Namibia.

5.3 Import from Algeria

The analysis of the methanol supply chain in Algeria reveals that the energy consumption for hydrogen production in 2030 is slightly lower compared to Namibia (35.40 MJ/kg methanol versus 35.76 MJ/kg methanol) as shown in Figure 6. This can be primarily attributed to two factors: firstly, the Algerian scenario incorporates a substantial proportion of blue hydrogen (98%), which is not the case for Namibia. Secondly, SMR processes exhibit marginally higher energy efficiency relative to the projected figures for water electrolysis (Collodi et al., 2017).

The observed patterns in CO_2 capture, methanol production, shipping, and bunkering exhibited consistent trends across various demand scenarios and temporal horizons, aligning with the findings from Namibia's supply chain analysis. Notably, the specific energy consumption for shipping was much lower compared to the Namibian case, which can be attributed to the significantly reduced voyage distance required. Nevertheless, the difference in the efficiency from both routes i.e. Namibia and Algeria ranges

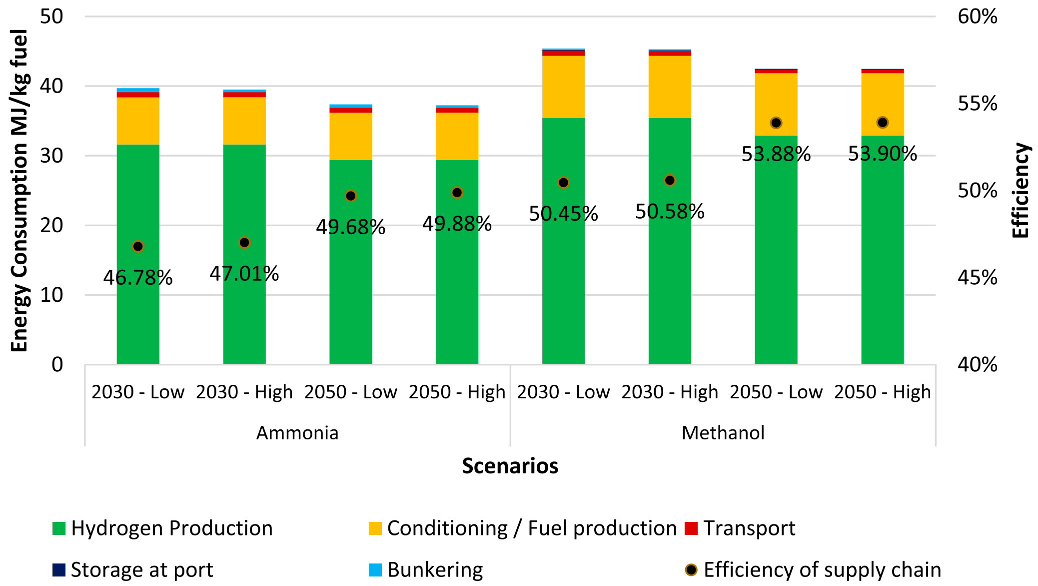

FIGURE 6
Energy consumption and efficiency of supply chain 3 – Algeria.

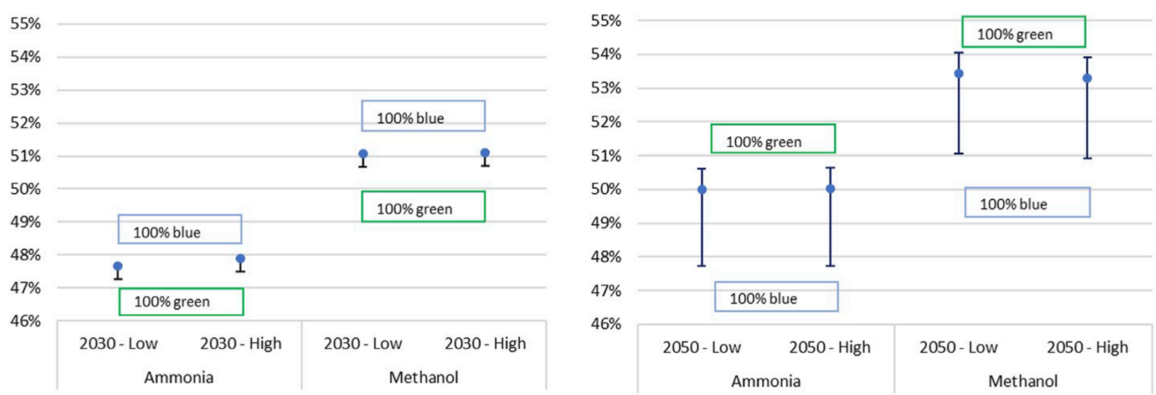

FIGURE 7
Sensitivity analysis of the energy efficiency of supply chain 1 (hydrogen import from Norway) in 2030 (left) and 2050 (right) considering a blue hydrogen only and green hydrogen only supply chain.

from a minimum of 1.39% to a maximum of 1.93% when comparing the same scenarios. This is aligned with the results reported by (Staudt et al., 2024), who found a reduction in efficiency of 1%–2% for a 7,000 km difference in shipping distances between analyzed routes.

5.4 Sensitivity analysis for 100% blue hydrogen and 100% green hydrogen scenarios

To complement the previously presented scenarios, a sensitivity analysis is conducted for 100% blue and 100% green hydrogen supply chains for both 2030 and 2050 in Norway and Algeria. Namibia is not included in this sensitivity analysis, as the country does not plan to produce blue hydrogen.

In the case of supply chain 1- Norway to Germany, when considering a 100% green hydrogen scenario, the energy efficiency in 2030 decreases by approximately 0.40% for ammonia and 0.41% for methanol (lower whisker bars on the left side of Figure 7), while for 2050 it increases by 0.61% and 0.63% respectively (upper whisker bars on the right side). This is due to electrolyser efficiency improvements that are expected to occur between 2030 and 2050.

This observation is further corroborated by the results of the 100% blue hydrogen scenario: in 2030, the supply chain efficiency increases marginally (by 0.01%) for both ammonia and methanol, while in 2050 it decreases by approximately 2.28% in the case of ammonia and 2.36% in the case of methanol (lower whisker bars on the right side of Figure 7).

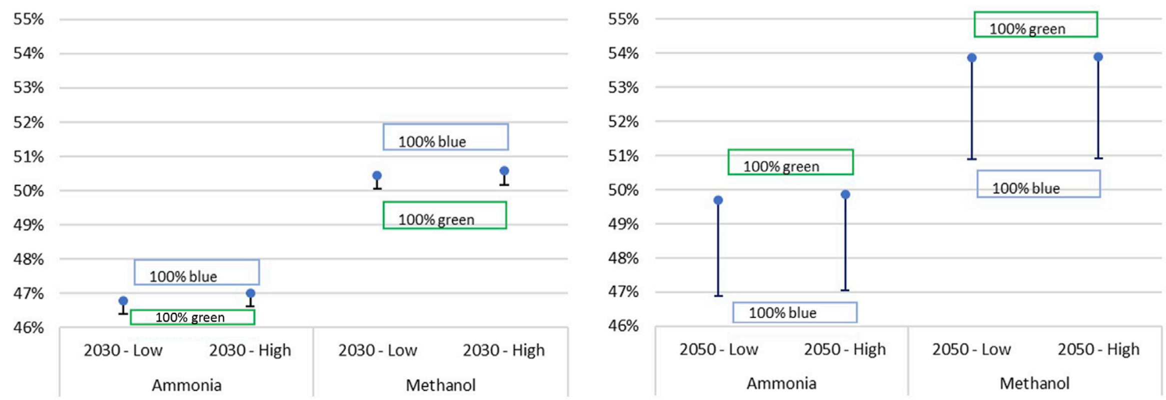

FIGURE 8
Sensitivity analysis of the energy efficiency of supply chain 3 (ammonia and methanol import from Algeria) in 2030 (left) and 2050 (right) considering a blue hydrogen only and green hydrogen only supply chain.

A comparable phenomenon is observed in the case of supply chain 3- Algeria to Germany, wherein considering a 100% green hydrogen scenario, the energy efficiency in 2030 decreases by approximately 0.38% for ammonia and 0.40% for methanol (lower whisker bars on the left side of Figure 8). For the year 2050, supply chain efficiency remains constant, as a 100% green scenario had previously been considered. In contrast, for the 100% blue scenario, efficiency increases marginally (by 0.01%) for both ammonia and methanol in 2030, while for 2050 it decreases by 2.80% and 2.98% respectively (lower whisker bars on the right side of Figure 8).

5.5 Qualitative factors and their influence

In the contemporary global context, geopolitics of hydrogen is pivotal for realistic implementation of maritime decarbonization not only from a resource perspective (critical minerals) but also from availability and supply side. The allocation of risk to address innovative financing (auctions, public-private risk-sharing) must extend beyond Europe to catalyze global alignment of supply and demand Furthermore, efforts to investigate how US-China competition, critical-minerals supply chains, and regional trade blocs shape hydrogen governance will deepen understanding of emerging energy geopolitics (Quitzow and Zabanova 2024). Similarly, analysis by (Pflugmann and De Blasio, 2020) indicates that countries are likely to take specific roles in future renewable hydrogen market based on their resource availability and infrastructure building potential. As a result, future geopolitical realities of countries in Europe and South-East Asia might remain as energy importers. On the other hand, there shall be an emergence of new export driven nations, such as Australia and North Africa.

Filling the regulatory voids in areas like fuel containment and quality, materials and manufacturing, safety systems etc. demands targeted research and experiments. This includes studies on material ageing under hydrogen exposure to large-scale leak and fire tests. The findings will result in precise prescriptive rules and functional requirements for the next revision of IGF Code, enabling safe and widespread adoption of hydrogen across the maritime sector.

The deployment of ammonia and methanol as alternative maritime fuels is constrained by technological and port infrastructure bottlenecks. One key challenge is the need for new or upgraded bunkering infrastructure, as majority of port facilities are not designed to handle the specific storage, transfer, and safety requirements associated with these fuels. Additionally, the port infrastructure also requires to be equipped to handle the volumes of fuel imported. While it is true that some ports have experience managing them for industrial purposes, adapting this expertise to the maritime sector still requires the creation of dedicated fueling terminals, as well as the implementation of robust safety systems (Boyland 2024). Furthermore, the lack of standardized and adopted international guidelines and operational procedures also complicates the harmonization of practices across ports, potentially impending the global adoption of these fuels. For instance, the IMO has developed interim guidelines for the use of ammonia and methanol as alternative maritime fuels, but these are yet to be officially enforced and adopted (IMO 2025).

(Nunes 2025) reviewed the role of renewable methanol's in reducing emissions, concluding that the potential of renewable methanol depends on its compatibility with existing infrastructure, its capacity to recycle carbon dioxide, and its adaptability to diverse feedstocks for production. This puts renewable methanol as a transitional solution towards a low-carbon future.

6 Conclusion

This analysis aims to evaluate import routes based on technical efficiency for establishing future trade relations. Additionally, it shall provide insights for shipping companies considering the trade routes presented in this research. Based on the results, it is concluded that the supply chain relying on pipeline-based transport of hydrogen demonstrated a lower energy consumption per kilogram of fuel (ammonia or methanol) compared to the ship-based transport. The overall supply chain efficiency of producing ammonia and methanol from Norway-imported hydrogen via pipelines is higher when compared with transport via ship from both Namibia and

Algeria, indicating the potential attractiveness of inland production. Consequently, continuous, large-scale transport of hydrogen from Norway to Germany could provide new opportunities for the domestic production of future maritime fuels.

As observed from the results, the technical efficiency of import varies from 44.6% to 53.9% between the analyzed countries. Hence, it is concluded that it is not a constraining factor to import the considered fuels via pipeline and ship. Although an economic analysis could provide further insights towards the implementation of the presented supply chain options.

It is noteworthy that in 2030, the disparity in supply chain efficiency is attributed to the hydrogen production methods, specifically between the green and blue pathways. A higher proportion of blue hydrogen originates from Norway and Algeria compared to Namibia. Consequently, this results in a reduced supply chain efficiency for maritime fuels produced in Namibia. For 2030, it is advisable to consider import options from Norway and Algeria, as their average supply chain efficiencies are highly comparable, where the average ammonia supply chain efficiency of Norway is 47.77% and Algeria 46.89%. And for methanol, the average supply chain efficiency of Norway is 51.09% and Algeria 50.52%.

By 2050, especially in high demand scenarios, import of ammonia and methanol from Algeria is competitive to production of those fuels in Germany. However, the extended maritime transportation route from Namibia results in a comparatively low overall supply chain efficiency. Import recommendations derived from this analysis indicate that green ammonia and methanol demonstrated comparable energy efficiency for transport from Namibia in 2050.

Furthermore, this analysis paves way for assessment of international fuel trade strategies by highlighting that the current seaports can be converted to future renewable fuel hubs thereby inland waterways could also benefit. Hence, a broader sectoral relevance can be envisaged upon economic assessment of such a pathway. Additionally, the intermittent nature of solar and wind energy demands large-scale storage, while transportation infrastructure for these types of fuels is also indispensable to fulfill worldwide energy needs. The demand and transport capacities of these fuels, along with energy security, also play a role in determining the need for storage capacities. Therefore, storage infrastructure is decisive for trading these fuels between demand and supply locations. Through this paper, we addressed the port storage requirements and its impact on bunkering operations.

Joint declaration of interest and project development among countries for alternative maritime fuels can also distribute the financial risks and capability of governments to intervene in market mechanisms to ensure sustainable, economically stable and equitable supply chains.

In the future, it is expected that ammonia and methanol would gain share as global alternative maritime fuels and/or alternative energy carriers, to transport renewable energy by sea from countries with high renewable energy generation potential to countries with high energy demand. Therefore, a comprehensive economic analysis is needed to extensively analyze the viability of the maritime supply chain for these energy carriers, which will be further explored in future studies.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YD: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review and editing. JM: Validation, Visualization, Writing – original draft. SK: Project administration, Writing – review and editing. LB: Supervision, Writing – review and editing. SE: Funding acquisition, Supervision, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

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