MAGPIE

SMART GREEN PORTS

Gaps and developments

Ammonia supply chain for future demand



D3.7 – GAPS AND DEVELOPMENTS AMMONIA SUPPLY CHAIN FOR FUTURE DEMAND

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Abbreviations

AEM	Anion Exchange Membrane (electrolyzer)
AiP	Approval in Principle
ATR	Autothermal Reforming
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CII	Carbon Intensity Indicator (IMO)
EOR	End of Run
FC	Fuel Cell
FID	Final Investment Decision
GHG	Greenhouse gas
ICE	Internal Combustion Engine
IFO	Intermediate Fuel Oil
IGF Code	International Code of Safety for Ships using Gases or Other Low-flashpoint Fuels
IMO	International Maritime Organization
IRENA	International Renewable Energy Agency
LCA	Life Cycle Analysis
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LPG	Liquefied Petroleum Gas
MDO	Marine Diesel Oil
MENA	Middle East and North Africa
MGO	Marine Gas Oil
MJ	Megajoule
MKI	Milieu Kosten Waarde (Environmental Cost Indicator)
MKW	Milieu Kwaliteits Waard (Environmental Quality Value)
MSC	Maritime Safety Committee (IMO)
MT	Metric Tonne
MW	Megawatt
NM	Nautical Mile
PEM	Proton Exchange Membrane (electrolyzer)
PSA	Pressure Swing Adsorption technology
PSV	Platform Supply Vessel
PtX	Power to X (Conversion of renewable electricity to chemicals)
RES	Renewable Energy Sources
SCR	Selective Catalytic Reduction
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyzer Cell
SOR	Start of Run
TEU	Twenty-foot Equivalent Unit (cargo capacity for container)
TTF	Title Transfer Facility (European gas benchmark)
VLSFO	Very Low Sulfur Fuel Oil

Executive Summary

The adoption of low-emission fuels in European ports could significantly advance Europe on its path to net zero emissions. As hubs for global trade and centers of both energy supply and demand, the impact of decarbonizing the port ecosystem can go far beyond its geographical area. Low-emission ammonia could play a significant role, but only if the supply chain is understood and gaps are identified and closed. This report is a stepping stone on that journey.

Through evaluation of ammonia sources, routes to market and future off-takers, we have mapped the supply chain, with a focus on the Port of Rotterdam as a case study. Our analytical models and interviews with key stakeholders have identified the gaps and developments that we have explained through the report.

Our findings indicate, across most identified gaps, regulation is the defining enabler. It remains the fundamental pre-requisite to establish an ammonia supply chain, but only if designed effectively. Both 'facilitating' and 'incentivizing' regulation is needed, but should be carefully considered with market participants. Overly prescriptive regulation, particularly for a fast-developing technology, risks hindering innovation and slowing progress. Greater consideration could be given to prioritizing the incentivization of low-emission fuels, compared to energy saving technologies, in order to accelerate progress toward the ultimate objective of zero-emission fuels.

We also found that while the promise of commercial-scale low-emission fuels, such as green ammonia, is important, it can both support and impede progress. Although this long-term goal is essential, transitional solutions—such as blue ammonia—should also be encouraged to help drive near-term advancement.

1. Introduction

There is unlikely to be a single low-emission fuel of the future, and ammonia is well-placed to play a significant role. Its competition faces challenges: biofuels face constraints in sustainable feedstock availability, liquefied hydrogen remains a nascent technology, methanol is a carbon-based vector, and green methanol is widely forecast to be more expensive than green ammonia.

However, ammonia has its own challenges to address, notably its toxicity and the challenge of scaling up low-emission production. Demonstration projects and well-designed regulation remain key to expanding the proven, yet high-emission, value chain of today. We will explore this below.

1.0 Report methodology

The purpose of this document is to map the value chain of ammonia from source to end use as a low-emission energy vector, highlighting gaps and developments that must be addressed. The ambition is to accelerate a breakthrough in the supply and use of ammonia within ports.

Analytical models and expert interviews will form the basis of sections on supply and demand. Expert interviews are used for sections on operations and infrastructure. Findings and knowledge disseminated will feed into Work Package 9: Masterplan for European Green ports and Work Package 5, Demo 4: Ammonia bunkering demonstration. This report will be revisited in a second phase during months 48-54 of MAGPIE.

The second phase of MAGPIE 3.4 updates the original ammonia supply chain assessment by incorporating the latest developments in ammonia production capacity, storage and bunkering infrastructure, vessel uptake, and the evolving regulatory framework. Particular attention is given to developments within the European Union, where policy initiatives and decarbonization targets are expected to play a key role in accelerating the adoption of ammonia as a marine fuel. The objective is to assess how the ammonia market and maritime sector have evolved since the initial study, identifying progress in supply chain development as well as the remaining challenges and gaps that need to be addressed to enable large-scale deployment of low-emission ammonia.

The report is split into four sections: supply, operations, infrastructure, and demand. How these sections interrelate on the value chain is visualized in Figure 1 below.

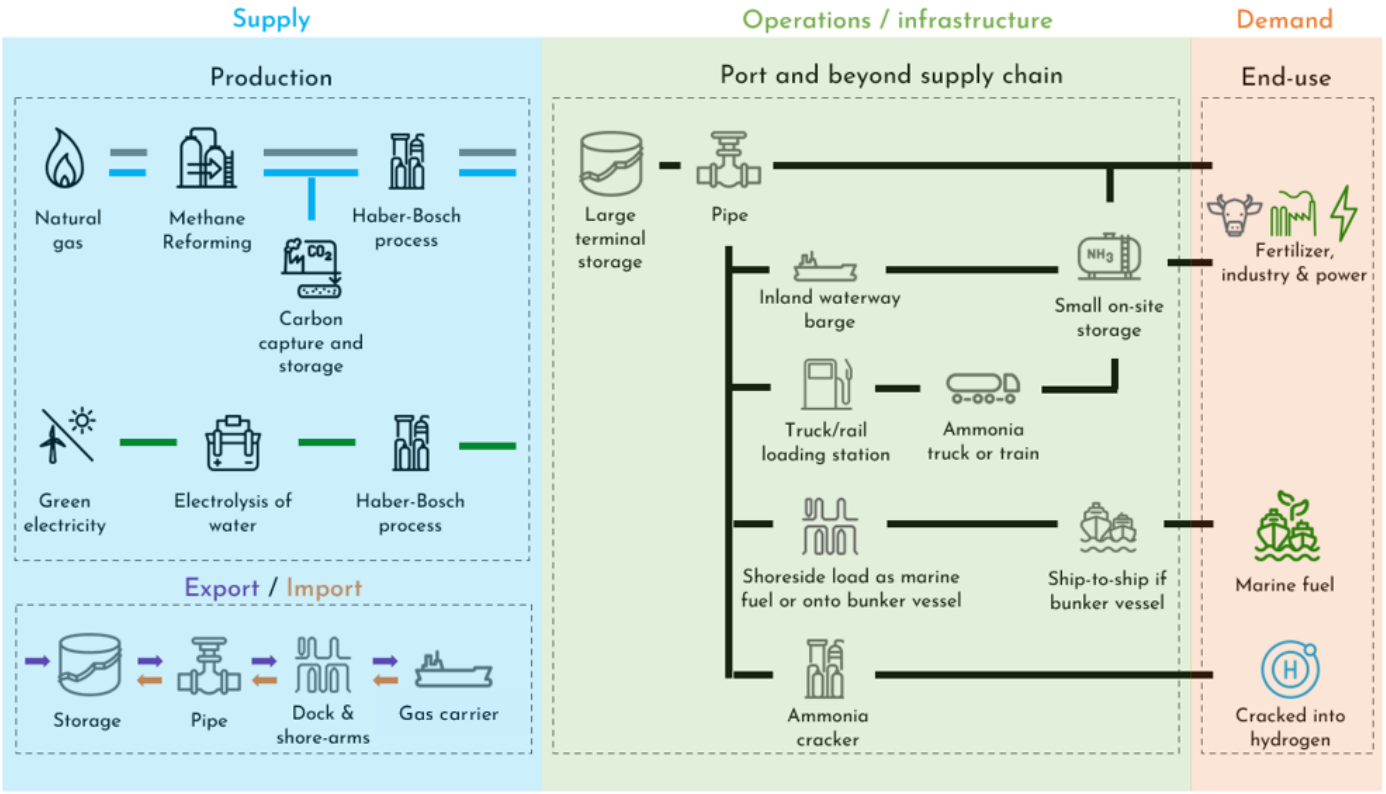


Figure 1: Simplified value chain diagram for ammonia [1]

1.1 Updates on Deliverable (2nd Phase)

This section outlines the changes made between the first phase of this deliverable (submitted in March 2023) and this second phase (updated in May-September 2026). Its purpose is to help readers of the first report understand what is different in this one.

The entire report has been reviewed in this second phase: some wording has been rephrased throughout, and spelling and figure numbering have been aligned for consistency. More specific changes were made in the chapters listed below; sections that are not listed were reviewed but did not undergo major changes. Where a statement is time-sensitive, the year of the underlying data is given in brackets:

Front matter

Abbreviations

- Around 20 new abbreviations added, covering electrolyzer types, production processes, regulatory frameworks and approvals, commercial and modeling terms, units, and shipping terms.

[1] Made by project partners for this report.

Section 1 – Introduction

1.0 Report methodology

- New paragraph explaining the goal of this second phase of MAGPIE 3.4, which is to update the original ammonia supply chain assessment, and what the update covers.

1.3 Ammonia safety

- Description of the effects of large ammonia spills updated to reflect the current state of knowledge.

Section 2 – Supply

2.1 Production process

- Blue ammonia: number of CCS facilities (2025); production capacity and expected future production (2026).
- Green ammonia: green hydrogen production (2024); green ammonia production capacity and expected future production (2026).
- Availability: grey ammonia production capacity (2026); volume transported by ship and expected production (2025); current context for blue and green ammonia availability (2026).
- Green production challenges: electrolyzer CAPEX (2026).
- Price: new graph of grey ammonia price ranges and average price history (2015-2026) to cover more recent data.
- Emissions: 2030 projections of well-to-wake emissions replaced by current ranges (2026), reducing uncertainty.

2.2 Imported or domestic production?

- New graph of the historic price differential between European (TTF) and US (Henry Hub) gas prices (2017-2026) to cover more recent data.

Section 3 – Operations and Infrastructure

3.1 Ammonia value chain

- Transport of ammonia by gas carriers: Fleet dedicated to ammonia transport updated, with the evolution illustrated by the example of Japan (2025).
- Storage – shore: new storage tanks added.
- Marine fuels bunkering: bunkering projects updated, including the Rotterdam bunkering demonstration and additional pilots in Singapore and China.
- Deep dive – bunkering patterns: table of ship ranges by fuel type converted from kilometers to nautical miles, used for shipping distances.
- Ammonia cracking to hydrogen: status of large-scale cracking updated.

3.2 Existing infrastructure

- Existing ammonia terminals and production in Europe: new maps of ammonia terminals (2024) and ammonia production plants (2026).

Section 4 – Demand

4.1 Demand segments

- Deep dive – direct use for power in marine propulsion: detailed figures on ammonia-powered shipping, including vessels in operation, the orderbook and fuel-flexible vessels (2026).

4.3 Challenges to be addressed to stimulate demand

- Regulatory challenges: more explanation of facilitating and incentivizing regulation; update on the IMO interim guidelines, and on ongoing work on IGF Code amendments.
- Marine fuels regulation deep dive: SEEMP added to near-term incentivizing regulation.
- Not just CO_2: methane addressed alongside carbon dioxide and nitrous oxide.

Report structure

- This new section "1.2 Updates" documents the differences between the first phase report and this second phase report.
- The section "Next steps for Task 3.4" from the first edition has been removed, as the work it set out (updating projects and figures, and the Port of Rotterdam scenario analysis) has been carried out in this revision.
- The conclusion has been rewritten to reflect the findings of this second phase, covering the relevance of the ammonia supply chain, the remaining obstacles, the role of ports and the developments that will determine the pace of adoption.

1.2 What is ammonia?

Ammonia is a compound of nitrogen and hydrogen with the formula NH_3. It is a gas at standard ambient pressure and temperature, with a boiling point of -33°C; efficient storage requires it to be under pressure or at low temperature.

It neither contains carbon nor necessarily produces carbon during its manufacture. However, its production is an energy-intensive process, and its environmental impact heavily depends on its method of production.

Around 70% of ammonia is used to manufacture fertilizer and 30% for industrial applications such as plastics, explosives and synthetic fibres[2].

Beyond these applications, ammonia is emerging as a hydrogen carrier and low-emission fuel. It can be converted into useful energy directly through spark ignition or fuel cells, or

[2] IEA, 2021, Ammonia Technology Roadmap, available here

indirectly through dissociation into hydrogen (sometimes referred to as cracking). Its key advantage over hydrogen is its higher energy density and liquefaction temperature, aiding transport and storage. Ammonia is seen as the most technologically advanced method for the carriage of hydrogen by vessel.

Perhaps more than any other factor, ammonia's toxicity has and may continue to hinder its adoption as a fuel and energy carrier. Nevertheless, a depth of industry experience and careful management can mitigate risks.

1.3 Ammonia safety

Ammonia is produced naturally from the breakdown of organic matter in the environment and within the human body. Exposure at these very low levels is not considered a health risk. However, at high concentrations, it is highly toxic. In fact, ammonia is hygroscopic, seeking water from the nearest source, so the high moisture content of eyes, skin and lungs puts them at the greatest risk.

Ammonia has a pungent smell that humans can detect at approximately 3-5 ppm, which can act as an early warning system. Irritation to the eyes, nose, and throat can be expected from 2 hours of exposure to 50 ppm or immediately at 700 ppm. Above 1,500 ppm, humans will experience pulmonary oedema, coughing and laryngospasm. Concentrations of 2,500-4,500 ppm can be fatal in 30 minutes, while 5,000-10,000 ppm is rapidly fatal due to airway obstruction[3].

When ammonia is released, it combines with humidity in the air to form a vapor cloud. This vapor cloud can travel long distances at ground level, posing significant risk to populations in the vicinity of the release. Safety procedures at European ports will help to mitigate the risk. A release on board a vessel poses a greater challenge. Even small concentrations of ammonia in the sea are sufficient to kill marine life.

The acute health and ecological effects of ammonia releases are well documented, and quantitative risk assessment for ammonia handling is established industrial practice. What remains less well characterized is the behavior of large-scale releases in a maritime or port environment, where full-scale spill testing is constrained by the toxicity of the substance itself.

However, ammonia does not burn readily thanks to its narrow flammability range, high ignition temperature, and low laminar burning velocity. The risk of an ammonia fire is lower compared to other fuels.

[3] Public Health England, 2015, Ammonia Toxicological Overview, available here

2. Supply

This section will explain the categorization of ammonia, its availability, emissions, the challenges it faces as a low-emission fuel, and identification of gaps in the supply chain. Our modeling then predicts geographical sources, pricing, and timeline for use.

2.2 Production process

Grey, blue or green ammonia?

Ammonia production involves two main steps: firstly, isolating hydrogen via methane reforming or water electrolysis and secondly, reacting it with nitrogen to produce ammonia. The production pathway determines its classification as grey, blue, or green, although in each case the product is chemically the same. Certification and legislation may categorize ammonia differently in each country, but this grouping does help to explain the production process. A simple process diagram is shown in Figure 2.

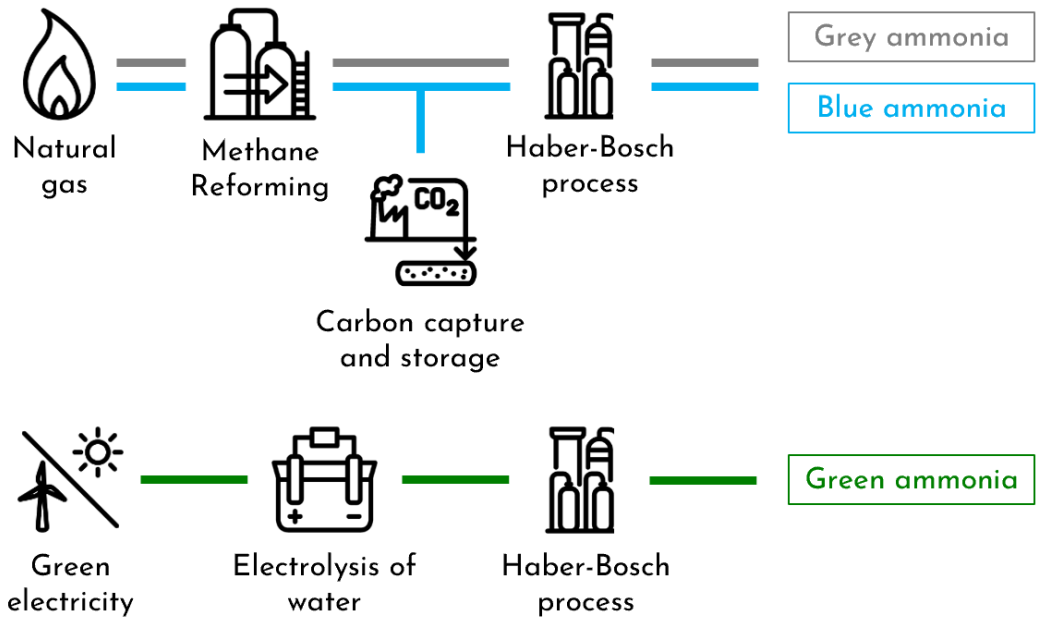


Figure 2: Key processes of grey, blue, and green ammonia production [1]

Grey

Almost all ammonia produced today relies on hydrogen derived from fossil fuels. Around 40% of the total energy input required for ammonia production is used as feedstock. The rest is used as process energy, mainly heat.

Approximately 72% of grey ammonia plants use natural gas (methane reforming), 22% use coal, 5% use heavy fuel oil or naphtha, and the remaining 1% utilize other feedstocks.[4]

This grey ammonia (sometimes referred to as brown) is hugely energy-intensive and generates substantial CO_2 emissions (from fossil-based hydrogen production), around twice as much per tonne as steel production. If the ammonia industry were a country, it would be the 16th largest emitter in the world. Therefore, the decarbonization of today's ammonia industry is critical to achieving greenhouse gas emissions targets.[2]

Blue

Blue ammonia production follows essentially the same pathway as grey ammonia production but includes a step of carbon dioxide capture and storage (CCS), as shown in Figure 2. The hydrogen content is generated by natural gas reforming pathways—most commonly steam methane reforming (SMR) or, increasingly, autothermal reforming (ATR)—combined with CCS. While this route does not make the process entirely CO_2-free, it significantly reduces emissions compared to conventional (grey) production. The overall emissions profile of blue ammonia depends not only on the performance of CCS technologies, which are designed to capture a large share of the CO_2 produced, but also on upstream methane leakage, which is receiving growing scrutiny.

Blue ammonia production is now emerging, with around 1.0 Mt per year of operational capacity as of 2026 and a further 0.5 Mtpa expected later this year (excluding production pathways where captured CO_2 is used for urea production).[5] This development builds on the expansion of CCS, which currently comprises 77 operational facilities globally, with a further 47 under construction.[6] A large share of this capacity is located in regions with abundant fossil fuel resources, particularly the United States, which remains the leading country in CCS activity.

For perspective, global CO_2 emissions in 2024 reached approximately 37.8 billion tonnes, with CCS capturing 64 million tonnes.[7] Although commercial barriers have historically limited wider deployment, progress is now being made to scale up the industry.

Looking ahead, additional blue ammonia capacity of around 6.5 Mtpa is expected by 2030, although timelines and actual output remain uncertain.[5]

Green

Green ammonia, also called electro or e-ammonia, is produced using hydrogen from water electrolysis, where water is split into hydrogen and oxygen using electricity. The Haber-Bosch process then reacts this hydrogen with atmospheric nitrogen to produce ammonia. Provided that the electricity used is renewable, the end product can be 100% emission-free. However, the high temperatures required make this challenging.

[4] IRENA, 2022, Innovation Outlook: Renewable Ammonia, available here
[5] Rystad Energy's Hydrogen Cube, 2026
[6] Global CCS Institute, 2025, Global Status of CCS 2025, available here
[7] IEA, 2025, Global Energy Review, available here

Electrolysis-based hydrogen represents a very small share of global hydrogen production. In 2024, total hydrogen production reached around 100 Mt, of which 0.8 Mt was based on low-emission technologies, with electrolysis accounting for just over 100 kt (around 0.1% of global production).[8] As a result, green ammonia production remains at an early stage of development. However, capacity is beginning to scale up, with around 0.9 Mtpa already operational as of 2026 and a further 0.6 Mtpa expected later this year.[5] Additional capacity, estimated at around 14.4 Mtpa by 2030, is under development and could considerably expand output in the coming years, although it remains subject to uncertainty regarding timelines and final capacities.[5]

Availability

Ammonia is produced, shipped, and consumed globally today. However, the vast majority of this production is still classified as grey ammonia. Low-emission ammonia production, in the form of blue and green ammonia, is expected to scale up in the coming years.

Today, around 218 million tonnes[5] of grey ammonia are produced annually, with around 17-20 million tonnes[9] traded and transported by ship. Production is expected to decline to around 216 Mtpa by 2030 as lower-emission alternatives emerge.[5] This report has ruled out grey ammonia as a hydrogen carrier or low-emission energy source, because its price and emissions are higher than those of low-sulfur fuel oil. Exceptions may be warranted for a transition step, for example, testing new technology ahead of lower-emission supply.

Blue ammonia production is emerging but remains limited in scale. Its deployment depends on the expansion of CCS infrastructure.

Similarly, green ammonia remains at an early stage of development but is progressing, with several projects reaching early commercial scale. Its growth depends on the competitiveness of renewable energy generation, green hydrogen production costs, and supportive policy frameworks. Project development remains inconsistent, with delays and cancellations often linked to regulatory uncertainty, permitting challenges, and difficulties in securing long-term offtake agreements under evolving market conditions. However, a growing number of projects are reaching FID, pointing to a gradual expansion of commercial-scale production in the coming years.

Availability of ammonia versus alternative fuels

It is widely accepted that there will not be a single low-emission fuel of the future. There will be competing fuels for each demand segment, and their commercial availability will impact their adoption.

For example: Biofuels (e.g., biodiesel, bio-methane and bio-methanol) are the most established low-carbon fuel competitors, offering comparable emission reductions to ammonia and being commercially available today. However, demand will exceed supply. Availability is limited as biomass harvesting must be balanced with natural regeneration to

[8] IEA, 2025, Global Hydrogen Review, available here
[9] Ammonia Energy Association, 2025, LEAD, available here

be sustainable. Interestingly, estimates of biofuel availability have been falling over recent years, and regulations have become stricter.

E-methanol, produced from renewable sources, is less toxic than ammonia and benefits from existing handling infrastructure. However, its large-scale deployment relies on renewable electricity build-out and the development of electrolyzer technologies. It also requires a sustainable source of CO_2, such as biogenic CO_2 from biomass processing or CO_2 captured via direct air capture. As a result, e-methanol is expected to be more expensive than e-ammonia, which could hinder its adoption (Figure 24).

Liquefied Hydrogen is a nascent technology and faces technological challenges to become commercially available.

Green production challenges

It's often quoted that electrolyzers could run only when there is excess renewable generation. However, this raises two significant challenges for green hydrogen. Firstly, it gives a highly variable and unpredictable production profile which is difficult to manage for offtakers. This is especially relevant during the early years of production when storage capacity is limited. Secondly, running electrolyzers on 100% renewable energy means they may not run for significant lengths of the day due to the variability of wind and solar.

Electrolyzer capital costs remain a significant component of total green hydrogen production costs. Current estimates place average capital expenditure (CAPEX) in the range of $500-1,500/kW for alkaline electrolyzers, $1,000-2,000/kW for Proton Exchange Membrane (PEM) electrolyzers, above $3,000/kW for Solid Oxide Electrolyzer Cells (SOEC), and above $3,500/kW for Anion Exchange Membranes (AEM) electrolyzers.[10] While pilot-scale SOEC installations can reach $5,000-5,800/kW, industrial-scale SOEC and AEM systems are expected to fall below $2,000/kW as they scale up.

Moreover, ammonia synthesis is carried out at elevated temperatures (over 375°C) and pressures (over 100 bar). Reaching these conditions is energy-intensive and thus benefits significantly from constant operations. Some synthesis assets have suggested it could take up to three days to fully restart following a shutdown. Therefore, the need for some dispatchable energy to complement renewables is apparent.

Price

Grey ammonia prices show correlation to the natural gas price. A recent history of traded prices across selected routes is shown in figure 3 below.

[10] World Bank (ESMAP), 2026, Electrolyzers for Hydrogen Production, available here

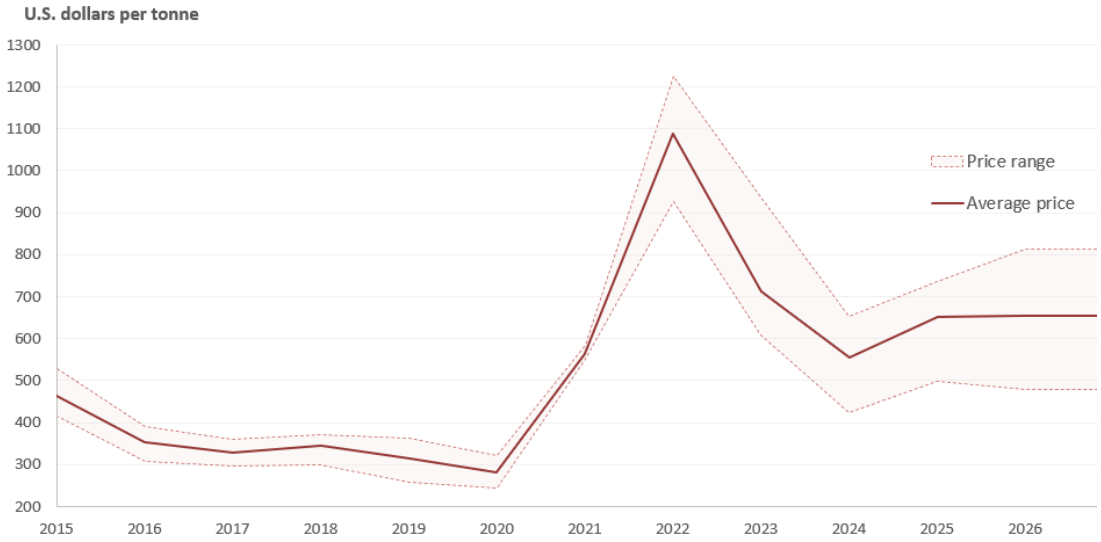


Figure 3: Grey ammonia traded price history [5]

Note: *The prices shown reflect traded ammonia prices across selected shipping routes. A significant share of global ammonia supply is produced and consumed domestically, and these volumes are not captured in route-based traded prices. As a result, the series should be read as indicative of traded-market dynamics rather than a comprehensive global price history.*

The cost of green or blue ammonia is dependent on the cost of hydrogen, evaluated under WP3.3. Our high-level modeling shows ammonia produced using $2/kg of blue or green hydrogen may be in the region of $500 per tonne, while $4/kg hydrogen may produce $900 per tonne. Hydrogen could be significantly more expensive, especially in the near term, raising the cost of low-emission ammonia further.

Emissions

Life cycle greenhouse gas (GHG) emissions vary significantly across fuels, largely driven by production pathways, with ammonia clearly illustrating this variability (Figure 4).

Green ammonia delivers relatively low emissions, typically in the range of 15-32 g CO_2eq/MJ.[11]

Blue ammonia shows a much wider and more uncertain emissions profile, ranging from 18 up to 125 g CO_2eq/MJ.[11] This large spread highlights the sensitivity of its life cycle performance to key parameters, such as CCS efficiency, methane leakage across the natural gas value chain (extraction, processing, and transport), or nitrous oxide emissions during combustion. As a result, blue ammonia's emissions can vary from relatively low to levels comparable to conventional fuels.

Other alternative fuels also show variability: bio-methanol typically ranges from 3 to 30 g CO_2eq/MJ, while bio-methane spans from below zero up to around 40 g CO_2eq/MJ, with organic waste-based pathways capable of achieving very low or even negative emissions.[11]

[11] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2026, Alternative maritime fuel information sheets, available here

Conventional fuels remain at the higher end of the emissions spectrum, with Very Low Sulfur Fuel Oil (VLSFO) representing a highly carbon-intensive baseline.[12] Liquefied Natural Gas (LNG), while often considered a transition fuel, is still associated with significant life cycle emissions, due in part to methane slip.[13]

Alternative fuels can offer reductions, although their benefits remain highly dependent on production pathways and supply chains.

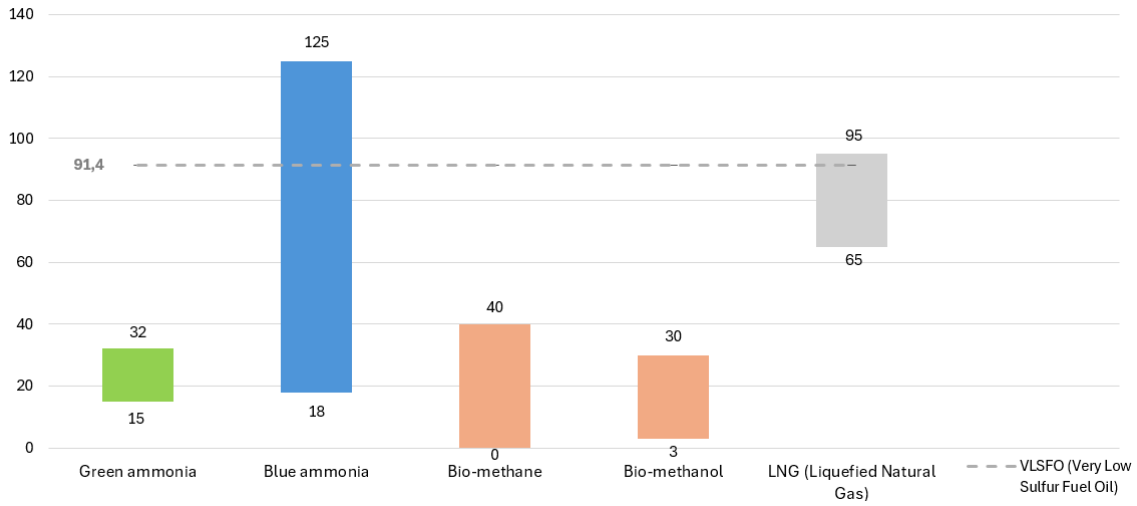


Figure 4: Life cycle GHG emissions by fuel (g CO_2 eq/MJ) [11,12,13]

2.3 Imported or domestic production?

Domestic sources

The conversion of hydrogen into ammonia requires additional energy, so, where hydrogen can be used directly, it generally offers higher energy efficiency. However, ammonia can offer advantages as a hydrogen carrier due to its higher volumetric energy density, and established transport infrastructure, particularly for long-distance transport and maritime applications. As a result, low-emission ammonia is expected to be primarily produced where there is direct demand (e.g., fertilizers or marine fuels), where its use is incentivized (e.g., coal displacement in power generation), or where long-distance transport of hydrogen is required. Low-emission ammonia production within Europe remains limited, constrained by reliance on imported natural gas for blue production and by slow renewable build-out and high hydrogen costs for green production. Nevertheless, there are opportunities where ammonia could be sourced domestically, as developed below.

[12] IFP Energies nouvelles & CMA CGM, 2025, Life cycle assessment of e-/bio-methanol and e-/grey-/blue- ammonia for maritime transport, available here
[13] Sphera, 2026, 3rd Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel, available here

Blue

The production of blue hydrogen requires access to natural gas supply and geologically suitable sites for carbon storage. Europe remains reliant on imported gas, primarily via LNG and pipeline imports, which can affect the competitiveness of domestic blue hydrogen production. However, progressive governmental schemes in countries with domestic resources and access to carbon storage sites, such as Norway and the United Kingdom, position these regions as leading European hubs for early blue hydrogen deployment. In the near term, we expect this hydrogen to be consumed domestically in industrial applications rather than converted into ammonia. However, as policy frameworks evolve and projects ramp up, it is possible that the conversion of hydrogen into ammonia becomes increasingly attractive.

Green

A massive build-out of renewables in Europe is expected to create periods of surplus generation during periods of high availability. This excess capacity could run electrolyzer projects and potentially ammonia production. However, it is challenged by a need for significant storage capacity to maintain a manageable offtake profile, and by capital costs that are too high to justify intermittent operation. Should CAPEX reduce over time, this may become less of an issue.

Production of green hydrogen and subsequently ammonia requires ample land, renewable potential, and governmental support. While reasonable renewable potential exists, the build-out of renewables in Europe is already facing delays. The time required to secure permits for renewable projects often exceeds the construction period for wind, solar, and electrolyzers. The EU is making efforts to accelerate the permit-granting process and the impact of this will be critical. If renewable build-up remains constrained, hydrogen and ammonia production projects seeking PPAs from renewables will have to compete with customers looking to decarbonize their electricity supply. Because of the energy loss during conversion, it can be argued that new renewable electrons are better used to directly decarbonize electricity supply. Ultimately, this will be a decision made by governments while projects are subsidized. For example, in the UK, the Electrolytic Allocation Round 2022 included additional scoring for electricity supplied by new generation assets rather than existing ones—to "avoid negative impacts on wider decarbonization."

Import sources

Potential import sources are mapped in figure 5. The USA remains a major exporter of low-emission hydrogen, transported to Europe as ammonia. Cheap domestic natural gas (see figure 6), a leading share of global carbon capture capacity, and strong policy support under the Inflation Reduction Act—including production tax credits of up to \$3/kg H_2—are the main drivers. Other gas-rich countries, such as Qatar, could follow a similar blue hydrogen export pathway. However, while many projects have been announced, few have yet reached final investment decision or commercial deployment.

Import sources for green ammonia are evaluated in section 2.3 below.

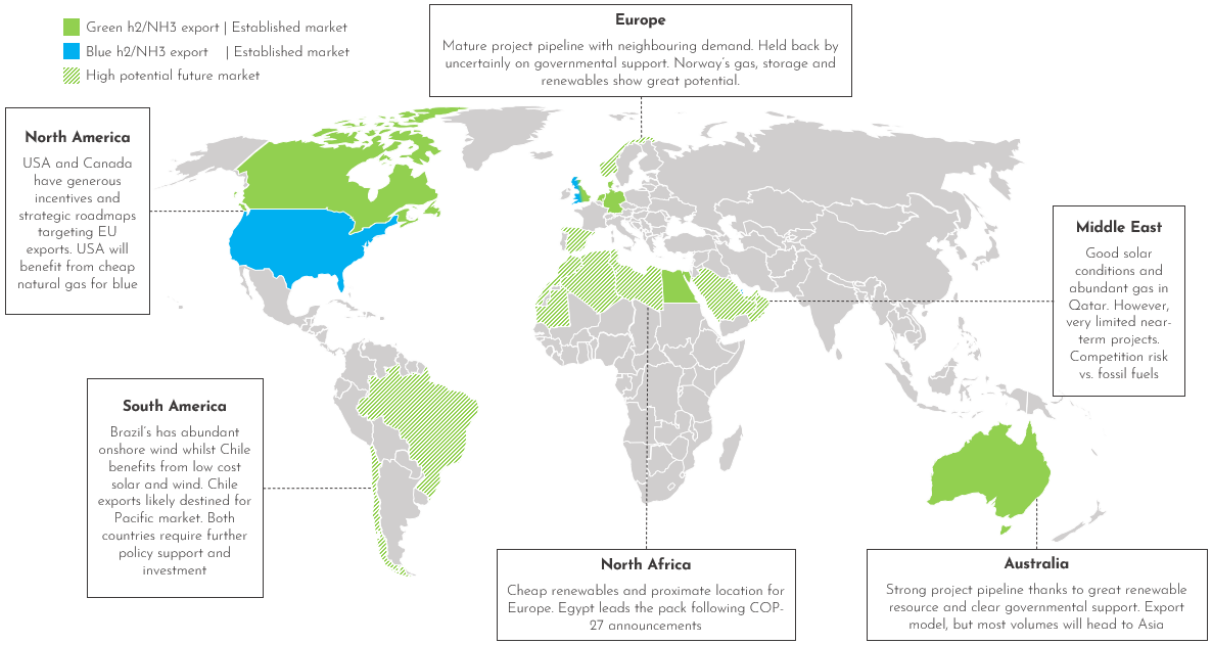


Figure 5: A high-level view of potential ammonia exporters for supply into European ports [1]

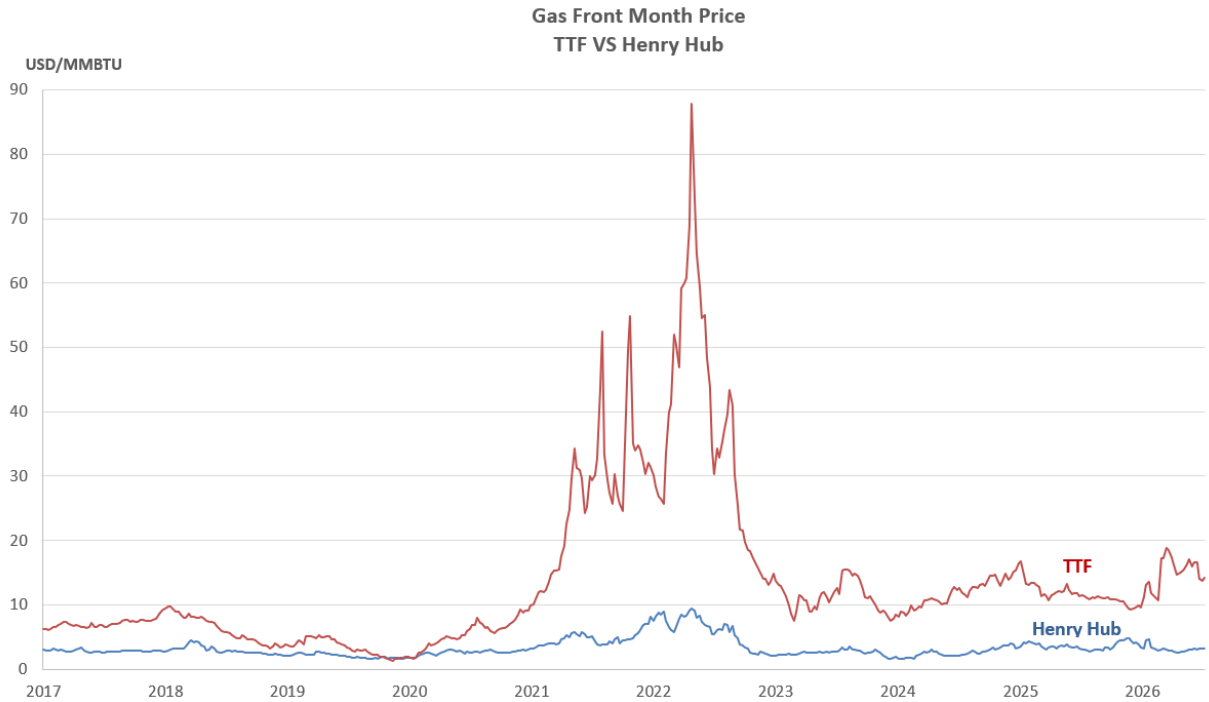


Figure 6: Historic price differential between European (TTF) and US (Henry Hub) gas prices [5]

2.4 Green ammonia supply costs for the Netherlands in the mid-term

The EWI Global PtX Cost Tool is used to calculate and compare the supply costs of green ammonia. The tool determines production and supply costs from 113 origin countries worldwide to a destination country for two different cost scenarios (baseline and optimistic), featuring cost developments until the year 2050. For this report, the EWI Global PtX Cost Tool introduced by Moritz et al., 2023[14] is modified by incorporating the Netherlands as the destination country. The modeling approach is described in more detail in Chapter 5.

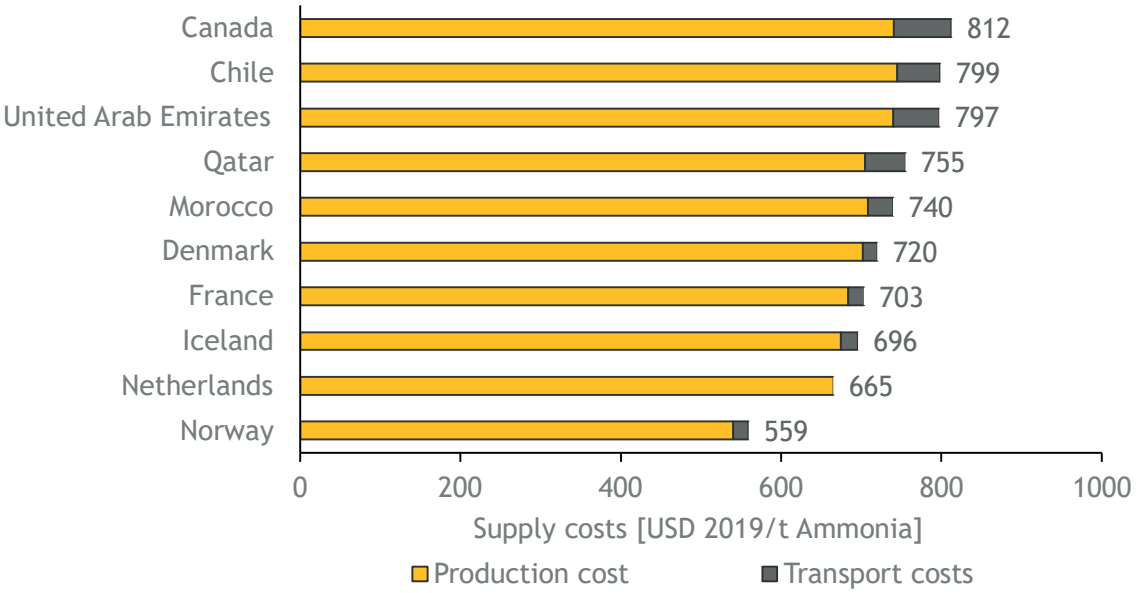


Figure 7: The 10 most economically viable origin countries for green ammonia supply to the Netherlands (data provided by EWI)

Figure 7 shows the green ammonia supply costs to the Netherlands by origin country. The costs are calculated for the baseline cost scenario in 2030. It is assumed that the origin countries supply a quantity of 3 Mt ammonia per year to the Netherlands, corresponding to the country's historical production capacity[15,16]. The graph reveals that production costs account for the largest share of supply costs.

Although ammonia is gaseous under standard conditions, it can be liquefied at -33°C, which requires significantly fewer cooling expenses than methane liquefaction at -162°C or hydrogen liquefaction at -253°C. In its liquid state, ammonia can be transported in large quantities by ship. Compared to the production costs, the transport costs of ammonia account for less than 10% of the supply costs, although their share increases with distance to the Netherlands. From a purely transport perspective, neighboring countries such as France or

[14] Moritz et al., 2023: Moritz, Michael; Schönfisch, Max; Schulte, Simon: Estimating global production and supply costs for green hydrogen and hydrogen-based green energy commodities. In International Journal of Hydrogen Energy 48 (25), pp. 9139–9154. DOI: 10.1016/j.ijhydene.2022.12.046.
[15] OCI, 2021: Investor presentation, available here
[16] Yara, 2020: Yara Company file

Denmark are advantageous for the import of green ammonia due to short transport distances.

However, when considering the dominance of production costs, more distant countries with higher RES potential and lower capital costs can offset their geographical disadvantages. This is the case for Morocco, Qatar, UAE, Chile, or Canada.

Overall, the four most economic sources of green ammonia are European countries close to the Netherlands as well as domestic production. Norway is the most economical supplier of green ammonia, followed by production within the Netherlands itself. The Netherlands benefits from significant and cost-effective onshore wind and offshore RES potential located on the North Sea coast. Therefore, despite being a relatively small country with a high population density, the Netherlands could produce green ammonia domestically at low costs. However, total production potential is limited to about 100 Mt ammonia per year[14].

In the mid-field of the ten most economical suppliers are countries from the MENA-Region: Morocco has abundant low-cost wind and solar energy potentials, while Qatar and the UAE have particularly low-cost solar energy potential. Moreover, ammonia can be imported from Chile and Canada. Both countries have significant and low-cost wind resources.

Figure 8 shows a global overview of the deviation between the supply costs from an origin country to the Netherlands from the domestic production costs in the Netherlands. Countries from which importing green ammonia is more expensive than domestic production are colored red, and countries from which imports are less expensive than domestic production are colored blue. Countries are colored grey if not featured in the data or have a production potential of less than 3 Mt per year.

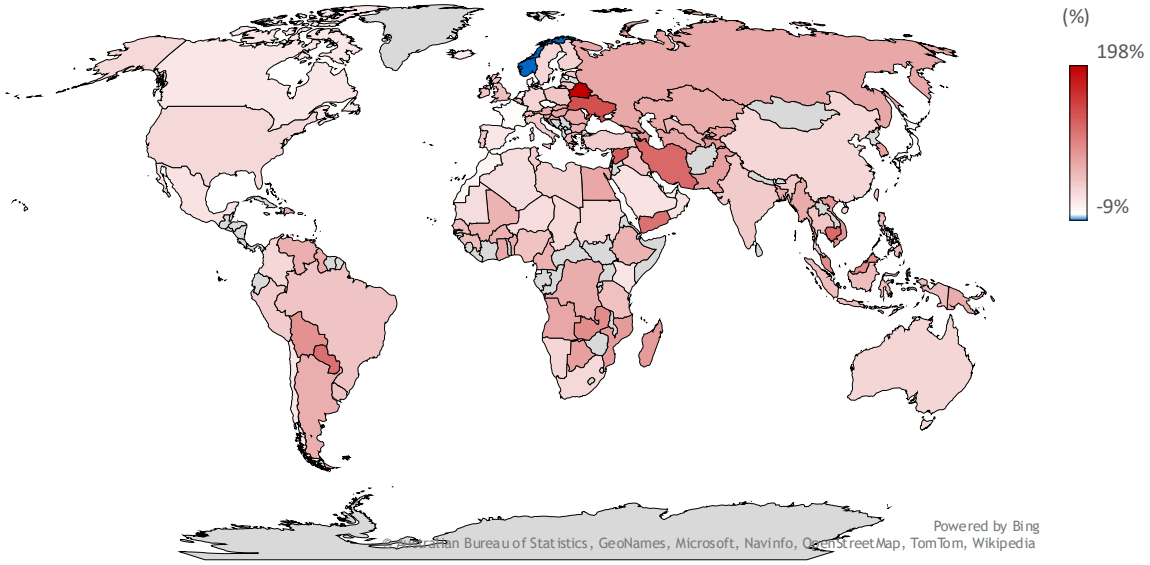


Figure 8: Deviation of supply costs from an origin country to the Netherlands compared to domestic production costs in the Netherlands [17]

Norway is the only country that can supply 3 Mt ammonia per year below the domestic production costs of the Netherlands. Supply costs from Norway are -16% below domestic production costs. Countries that have limited (max. 22%) higher supply costs compared to

[17] Information from Port of Rotterdam.

domestic production in the Netherlands are European countries (Iceland +5%, France +6%, Denmark +8%), MENA countries (Morocco +11%, Qatar +14%, UAE +20%), Chile +20%, and Canada +22%. The cost comparison results show that the supply costs vary greatly depending on the country of origin. This variation is mainly due to differences in production costs, which are influenced by country-specific RES potential and weighted average costs of capital.

The EWI Global PtX Cost Tool calculates supply costs based on RES potential, technology costs, and weighted average costs of capital. The extent to which a single-origin country will supply a particular destination country does not depend on economic conditions alone. Long-term commitments and contracts between origin and departure countries are valued tools to establish trading in renewable energy commodities such as green ammonia. With some of the ten most economical supply countries determined in this analysis, agreements on trade in hydrogen-based energy commodities are already planned or have been signed. These include agreements between the European Union or members and Canada, Chile, UAE, Qatar, Morocco, or Norway. These agreements can secure and reinforce the market ramp-up of green energy commodities on the path toward climate neutrality.

Production costs for conventional ammonia based on grey hydrogen are highly dependent on the price of natural gas and range from 300 to 700 USD/t ammonia in Europe[18,19]. Compared to the grey ammonia production costs of 500 USD/t, the supply costs of green ammonia are 25% to 65% higher, depending on the origin country. Accordingly, a cost gap must be closed for green ammonia to become competitive. Based on Europe's all-time high natural gas prices in 2022, green ammonia could have already been competitive against conventional ammonia. In the medium term, natural gas prices are expected to decrease to historical levels[20], potentially increasing the cost gap between grey and green ammonia again.

In conclusion, imports from Norway and the domestic production of green ammonia might be the most economic options for the Netherlands. However, as the future demand for green ammonia and green hydrogen is still to be determined, there is a crucial question about whether the demand can be covered by these two supply options alone. If not, numerous countries near the Netherlands, from the MENA Region, and from North and South America could provide economically feasible supply options for green ammonia, for a cost premium of less than 20% compared to domestic production costs in the Netherlands.

[18] Bartels, 2008, A feasibility study of implementing an Ammonia Economy
[19] Boulamanti & Moya, 2017, Production costs of the chemical industry in the EU and other countries: Ammonia, methanol and light olefins, available here
[20] EWI, 2022: Institute of Energy Economics at the University of Cologne, Scenarios for the Price Development of Energy Commodities, available here

3. Operations and Infrastructure

While ammonia is produced, transported, stored, and used today, hurdles lie in its path to be used as a low-emission fuel. This section aims to highlight those gaps in the supply chain to ensure they receive the attention and funding they require.

3.2 Ammonia value chain

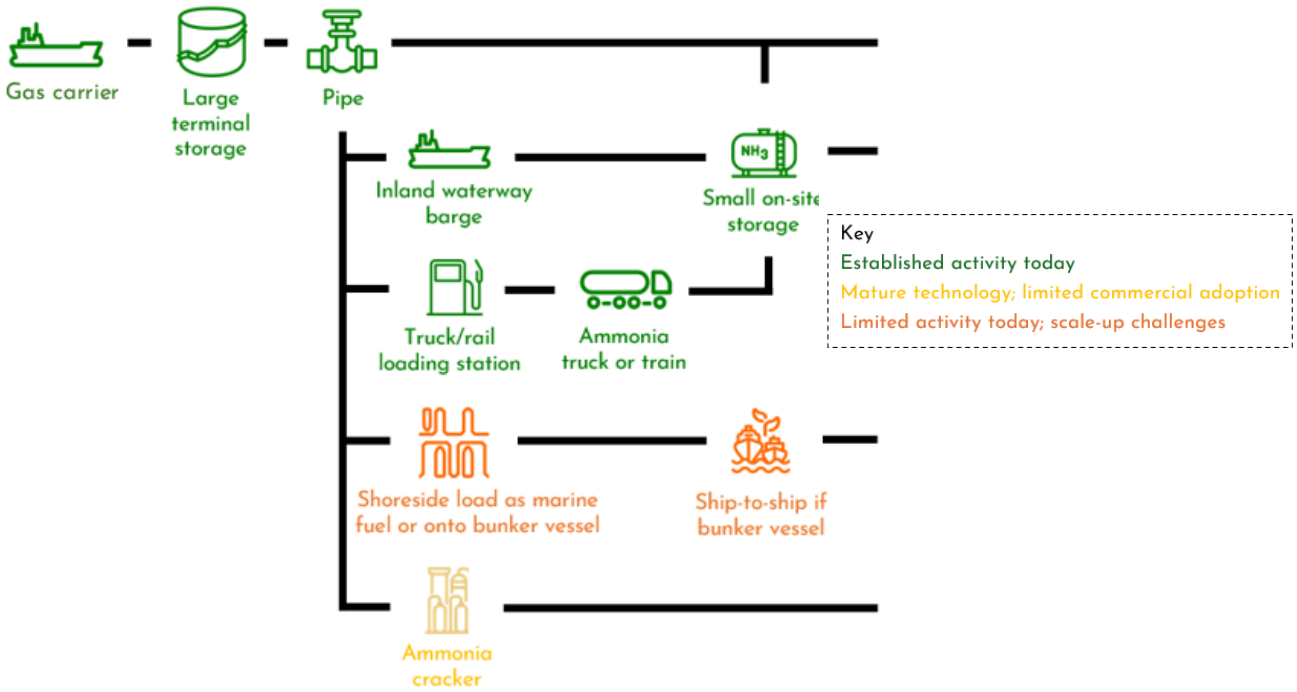


Figure 9: Status of operations and infrastructure within the ammonia value chain [1]

Transport of ammonia by gas carriers

Around 17-20 million tonnes of ammonia are transported by sea every year, representing roughly 8% of global production.[9] This volume relies on a relatively small, dedicated fleet of approximately 80 ammonia carriers, mostly composed of midsize vessels of around 37,000 m^3. Smaller vessels, below 30,000 m^3, account for a limited share of transported volumes, while larger carriers, typically around 60,000 m^3, also represent a smaller share but are mainly used for long-distance transport. Looking ahead, the fleet is expected to evolve toward larger vessel classes. Around 60 new ammonia carriers have been announced, with a significant portion consisting of very large gas carriers above 80,000 m^3.

While ammonia shipping is a well-established activity, scaling up to meet future demand will require substantial fleet expansion and technological adaptation. The development of larger vessels will likely require a switch from prismatic to membrane tank designs to manage the structural constraints as the ship rolls.

For perspective, Japan has drafted a roadmap that plans to grow the country's demand for ammonia as a fuel to 3 million tonnes a year by 2030 and to 30 million tonnes by 2050.[9] Currently, about 1.1 million tonnes of ammonia are used in Japan per year, mainly for the fertilizer industry.[21] 235,000 tonnes are imported, with the rest produced domestically. Using a mid-sized carrier of 45,000 m3, their current import demand requires just around eight deliveries a year. If Japan imported all 3 million tonnes proposed for fuel, it would take around 100 deliveries. To achieve a 20% ammonia blend with coal across all the major utilities, coal power plants would require 20 million tonnes, or around 650 deliveries.

Storage

Ammonia is an efficient hydrogen carrier, with a higher volumetric hydrogen density than compressed or liquefied hydrogen and can be stored using relatively inexpensive infrastructure. To store ammonia, it is either liquefied under pressure (10 bar at 25°C) or refrigerated (boiling point -33°C). Large storage tanks, both onshore and onboard ships, typically rely on refrigeration as it is more cost-effective and safer, while smaller-scale transport by truck or rail generally uses pressurized tanks.

Shore

Ammonia storage capacity at the production plant is designed to ensure continuous operation of the synthesis unit and to avoid curtailment. This requires maintaining sufficient inventory to accommodate shipping constraints, including vessel frequency, loading times, receiving terminal capacity, and weather-related delays. In particular, maintaining enough stored ammonia to fully load transport vessels is a key requirement.

The total production plant storage quantity is then split into an economical and safe number of tanks considering economies of scale and tank size limitations subject to seismic and plot restraints. Ammonia import terminals' storage capacity is generally sized to accommodate the offloading of a transport ship's inventory.

Shore-based ammonia storage tanks are already deployed at industrial scale, typically with capacities up to around 40,000-60,000 MT. For comparison, much larger tanks exist in the oil industry, with the largest floating roof tank reaching 156,000 MT of crude oil (Ras Badran, Egypt). Recent developments indicate an upward trend in ammonia storage capacities. Tanks in the 50,000 MT range have been implemented at sites such as Antwerp, Belgium (BASF), and Mesaieed, Qatar (QAFCO, Figure 11). Even larger units of around 70,000 MT have been constructed more recently, for example, in Texas City (Gulf Coast Ammonia) and Saudi Arabia (NEOM GH2). By contrast, pressurized storage systems, such as bullet tanks, Horton spheres, and pressure vessels, are typically sized up to 2,000 MT.

A high-integrity ammonia storage tank should be double-walled (Figure 10). The primary container uses low-temperature carbon manganese steel. Insulation is typically applied in the annular space between the walls, while the outside container must be protected from ice, which could cause heaving. The tank should sit on an elevated, piled concrete base to protect against frost heave and be surrounded by a dike in case of release. A minimum of two pressure relief valves and vacuum relief valves allows for safer maintenance. A vaporizer

[21] IHI Corporation, 2025, Integrated Report, available here

and emergency shut-off valve in the supply line respectively protect against low-low and high-high pressure scenarios. There should be a separate standalone access tower. Only proven compressors should be used for refrigeration, with emergency power access. Three independent level and pressure indicators, multiple earthing bosses, a flare, wind direction indicator, and emergency lighting are among the other requirements. Careful attention in design should be paid to possible extreme weather events and seismic activity. A full hydrostatic test of the tank (for at least one week) should be taken alongside acoustic emission tests before use. The acoustic emission test should also be carried out after the first fill of ammonia and on a regular basis. This is not an exhaustive list and is only provided for an appreciation of the variety of safety considerations applicable.

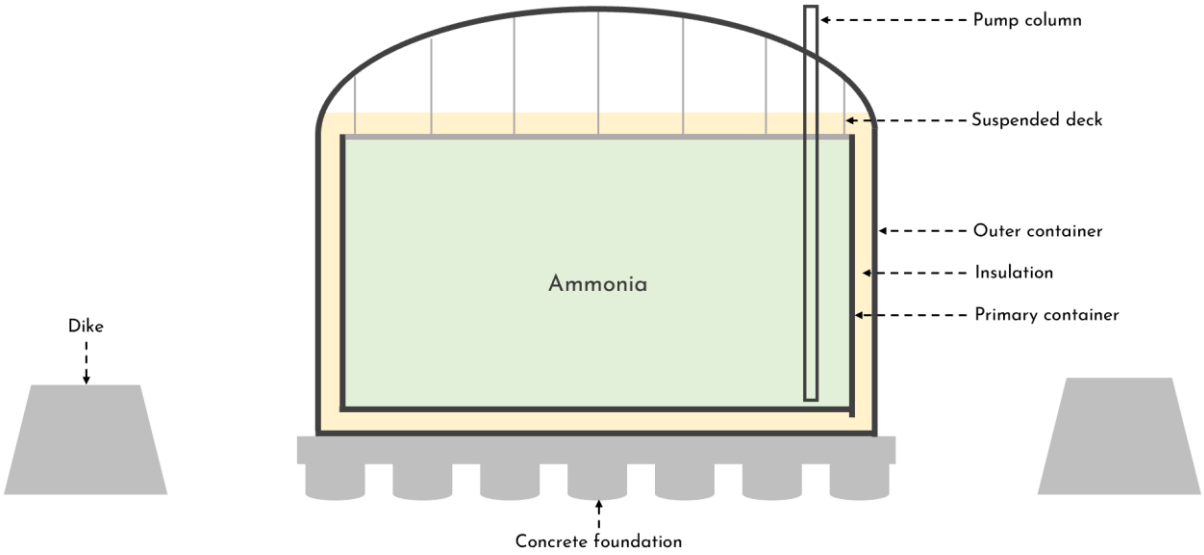


Figure 10: Simplified drawing of an ammonia storage tank [1]



Figure 11: QAFCO's two 50,000 tonnes refrigerated ammonia storage tanks [22]

[22] QAFCO website, available here

The volume of storage required to meet the estimated demand scenario in the Port of Rotterdam (Figure 12, referencing Figure 22) is significant. This is a gap in the current supply chain and is expensive to complete. Therefore, parties may wish to consider the economies of scale savings possible through shared storage.

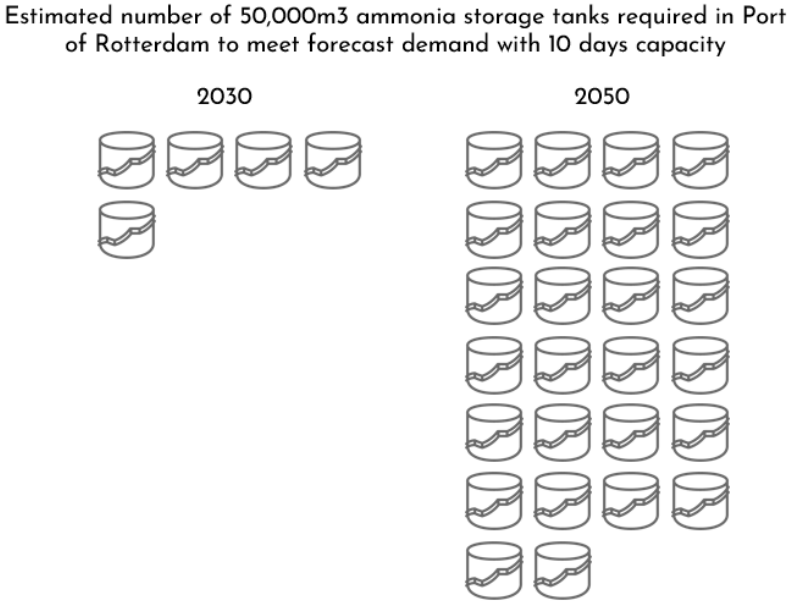


Figure 12: Visualization of potential ammonia storage capacity in Port of Rotterdam (data provided by the Port of Rotterdam) [1]

Floating

Some ports may look to floating storage rather than shore infrastructure to increase the distance to population. Existing or new gas carriers could be utilized. Large gas carriers have storage capacities broadly comparable to industrial-scale ammonia storage tanks.

However, personnel on board have limited evacuation opportunities compared to land, and any leak at sea may have an immediate impact on marine ecosystems.

Dedicated floating ammonia storage remains at the design stage. Some concepts for floating storage with regasification capability, which transfer ammonia to shore as a gas via pipeline, have received Approval in Principle (AiP) from classification societies. For example:

- The ammonia floating storage and regasification barge (A-FSRB) developed by NYK Line, Nihon Shipyard and IHI (AiP in December 2022 from ClassNK).[23]

- The ammonia floating storage and regasification unit (FSRU) developed by HD Hyundai Heavy Industries (HHI) and Korea Shipbuilding & Offshore Engineering (KSOE) (AiP in April 2023 from Lloyd's Register). [24]

[23] NYK Line, 2023, Parties Obtain World's First AiP for Ammonia Floating Storage and Regasification Barge, available here
[24] Lloyd's Register, 2023, Approval in Principle for HD HHI and KSOE ammonia FSRU, available here

Small on-site storage

Smaller customer sites may choose to utilize bullet tank storage rather than the larger shore tanks mentioned above. This may be quicker, cheaper, and flexible for small volumes. These tanks are already commonly used for LNG. Ammonia could be stored for longer durations in bullet tanks than LNG because of the higher liquefaction temperature limiting the boil-off gas.

Inland distribution

Depending on volumes, distances, and available infrastructure, different modes of distribution can be used: pipeline; inland waterway barge; and truck and rail.

Pipeline

Ammonia transport by pipeline has been established for decades. In the United States, a major network connecting multiple Midwestern states delivers around 1.5 million tonnes of ammonia per year.[25] The longest ammonia pipeline ever built is the 2,420 km Tolyatti – Odesa pipeline between Russia and Ukraine. However, it has not been operational in recent years. In Europe, infrastructure remains limited to short-distance systems, with the largest pipeline of 74 km in Italy.

Ammonia in pipelines is transported under pressure in liquid form and provides an efficient and cost-effective route either directly to end users, or to transfer points for complementary modes of distribution such as inland waterway barges and truck/rail loading stations (see Figure 9).

Looking ahead, ensuring robust safety standards is critical given the expected scale-up of ammonia transportation by pipeline. Historical experience highlights that incidents have arisen from a range of causes, including external corrosion, malicious acts, overpressure, maintenance-related issues, metal fatigue cracking, and seam failure exacerbated by freeze-thaw cycles.[26] These cases illustrate that risks span both technical system failures and human or external factors.

Pipeline routing from storage to end users therefore requires careful planning, particularly in port environments characterized by a high density of people and complex industrial operations. For example, the Port of Rotterdam already hosts a highly dense network of industrial assets and pipeline infrastructure, requiring any new pipelines to be integrated within tightly constrained environments.

[25] Ammonia Energy Association, 2025, Ammonia pipelines: existing networks, future deployments, and safety considerations, available here

[26] Fertilizers Europe, 2013, Guidance for inspection of and leak detection in liquid ammonia pipelines, available here

Inland waterway barge

Notable amounts of ammonia traverse waterways via barge in the USA today, primarily along the Mississippi River. Europe's inland waterways also see ammonia transportation by barge. Future growth in low-emission ammonia demand would require scaling up both the barge fleet and the supporting port infrastructure (such as barge-compatible loading and unloading facilities).

Truck and rail

In Europe, as in the USA, ammonia is already transported by truck and rail, which are well-established and widely used for regional distribution. However, these modes are generally less cost-effective than pipelines or barges for handling large volumes.

Marine fuels bunkering

Ammonia bunkering has recently moved beyond the demonstration phase. Several pilot operations have been successfully carried out in ports such as Singapore (2024), Rotterdam (2025), and Dalian (China, 2025).[27] The first commercial-scale bunkering operations were completed in Ulsan, South Korea, in 2026, marking a key milestone toward industrial deployment.
This report has fed into an ammonia bunkering demonstration in the Port of Rotterdam under Work Package 5, Demo 4. Demo 4 was completed and learnings disseminated through an Ammonia Bunkering Demonstration Report (D5.1, May 2026)[28].

Ammonia is frequently transferred between terminal and ship cargo tanks across European ports today. Bunkering of ammonia could be a largely similar operation but delivered into a fuel tank rather than storage tanks. However, risks associated with ammonia will necessitate additional safety provisions.

Of conventional fuel bunkering, LNG is the closest comparison. Likely routes to supply marine vessels include:

- In port, by shoreside terminal using fixed infrastructure
- In port, by barge or trucks
- In secure anchorage, by bunker barge or gas carriers capable of doing ship-to-ship transfers of ammonia

Shoreside loading may be restricted in some locations due to the risk to the local population from a possible release of ammonia. Concurrent bunkering with cargo operations is challenging due to the risk for shoreside operators. Losing the opportunity for simultaneous operations will have a commercial impact on vessel owners.

Ammonia bunkering by bunker barge at anchorage may decrease the risk to local populations by adding distance. However, operations at sea will be exposed to marine

[27] Ammonia Energy Association, 2025, Ammonia bunkering: moving from demonstration to operations, available here
[28] MAGPIE Project, 2026, Ammonia Bunkering Demonstration Report, available here

conditions. If the secure anchorage is at some distance from the port, the potential for floating storage could be considered.

Larger transfer quantities can introduce greater risk and hence additional safety restrictions.

Ammonia has poor combustion characteristics which necessitate the use of a pilot fuel, such as diesel. The quantity required is 5-15% for two-stroke engines and up to 30% for four-stroke engines.[29] Ships will have to ensure access to both ammonia and a pilot fuel.

Deep dive: bunkering patterns

Ammonia's utilization as a marine fuel is challenged by its energy density—approximately three times the tank volume is required compared to fuel oil for the same range. However, many ships currently have ranges considerably longer than their actual trip length to allow them to take advantage of differences in fuel prices between ports. It is estimated that the top 20 bunker ports in the world provide over 90% of all bunkers to shipping. Bunkering is highly concentrated at the moment, but could this change with ammonia?

The bunker capacity of large ocean-going ships is typically designed to allow uninterrupted sailing at design speed for 30-40 days. However, since most vessels operate at speeds below their design speed, their effective range is often even greater in practice. As a result, most containerships only bunker once per round trip in the cheapest port. This is also common for large bulk carriers and tankers operating on fixed routes between two regions. In contrast, short-sea ships trading along the European coast often take on bunkers opportunistically along their route when more favorable prices are available.

With alternative fuels, it is expected that this behavior will change, especially for fuels with much lower densities such as ammonia, hydrogen, and electricity from batteries. Owners will have to weigh up the reduction of cargo capacity to accommodate larger fuel tanks, or a reduction in range.

Depending on respective operations, new ranges could emerge. Some may remain large enough to allow bunkering optimization, but others may have to bunker by necessity after each trip or en route.

Table 1 illustrates how vessel range varies across different marine fuels, assuming a constant onboard fuel storage volume.[30] The results are expressed in nautical miles (NM) and relative to fuel oil, which serves as the reference (100%).

[29] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2023, Managing Emissions from Ammonia-Fueled Vessels, available here

[30] TUDelft, 2023, Andrew Snaathost, Alternative marine energy carrier impact on ship powering and the environment, available here

Fuel	Relative range (% of fuel oil)	Bulk carriers (NM)	Tankers (NM)	Container ships (NM)
Fuel Oil	100%	20,606	16,293	14,532
Methanol	42%	8,751	6,918	6,171
LNG (Liquefied Natural Gas)	40%	8,325	6,582	5,870
Ammonia	28%	5,772	4,564	4,071
Hydrogen	12%	2,402	1,899	1,694
Batteries	1%	247	195	174

Table 1: Average vessel range by fuel type, under constant storage volume [30]

We hypothesize that, should ammonia or alternative low-emission / lower energy density fuels be adopted, the current dominance of major bunker ports may be reduced. However, this will also depend on factors such as existing ammonia infrastructure in the port or safety considerations.

Ammonia cracker

After storing the product in the port, there are three potential routes for handling NH_3. Onwards transport as NH_3, direct use in the port as bunkering fuel, or cracking NH_3 to H_2 for use in the port or onwards transportation. This paragraph focuses on the cracking process. The NH_3 cracking process essentially comprises four steps illustrated by a simple schematic in Figure 13 and described below.

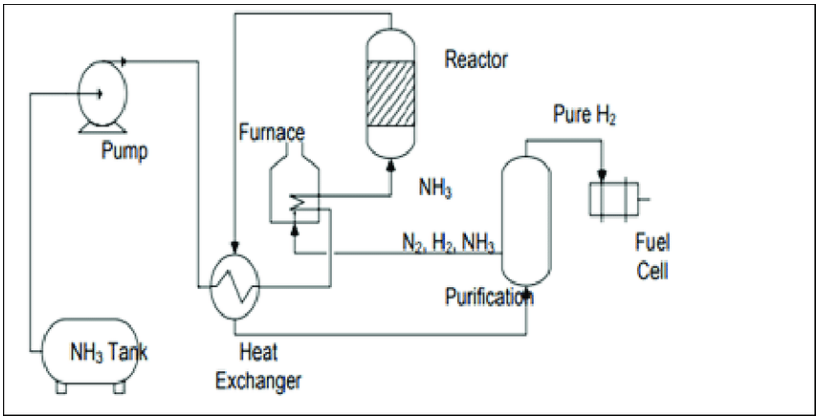


Figure 13: Simplified flow diagram of NH_3 cracking [31]

[31] Journal of Physics: Conference Series 2018, *Ammonia as Hydrogen Storage Media, Sustainable Method to Hydrogen Evolution*, A. Dia, S. Allami, H. Jwad.

Ammonia evaporation and preheat

Liquid ammonia feedstock (99.5 wt% pure) from storage is pumped to the ammonia evaporation and preheat section. Ammonia needs to be vaporized before being fed to the cracking furnace. Ammonia is preheated using energy contained in the cracked gas product.

Ammonia cracking

Ammonia cracking is a catalytic endothermic process, i.e., one where energy needs to be supplied, to break the N-H bond but also to ensure that the feed is at reaction temperature. Pre-heated vaporized ammonia is routed to the cracking furnace (with catalyst-containing tubes) where fuel is fired to provide the required additional energy. In order to have no CO_2 emissions from the process, one cannot use external sources of fuel. Therefore, the possible choices are NH_3 feed, cracked product gas, PSA tail gas, and purified H_2 product. There is no make-up of catalyst to the process. The catalyst is loaded at the start of the process (start of run or SOR) and needs to be replaced at the end of life (end of run or EOR). The EOR is typically marked by the maximum process operating temperature acceptable by the process equipment at which the required process yields can be obtained.

Heat recovery from cracked gas

Cracked gas from the furnace consists of N_2, H_2, and unconverted NH_3. This hot gas stream needs to be cooled before being purified. Heat is extracted from this stream into the process feed stream.

The cracked gas stream may be washed to recover unconverted NH_3 by routing the water-NH_3 containing stream to a distillation column. Ammonia is recycled to the cracker feed to improve the overall process conversion.

Purification of cracked gas

Cooled cracked gas is routed to a PSA (Pressure Swing Adsorption) unit to separate H_2 with the desired product purity. The tail gas (containing the rest of the components as well as some (approx. 10-15%) H_2 in the feed to the PSA) is routed to the cracker as fuel gas. Product H_2 gas may be compressed to the process operating pressure.

Cracking at large scale is still in development. Whereas each individual step in the process is technically proven, large-scale crackers for ammonia have not yet been widely deployed. It is anticipated that quick scale-up will be realized if the market demand increases. Several projects are under development or being commissioned in key European import hubs, including operational or planned crackers in Antwerp, Rotterdam and Brunsbüttel. The resulting hydrogen can be fed into the local, regional or national pipeline networks.

Advantages:

As NH_3 is a common chemical, a lot of the infrastructure is already in place. Although ammonia cracking has not yet been widely deployed at large scale, it can be implemented

relatively quickly. Crackers can ramp up and down with demand and balance the pipeline systems. Manufacturing in remote locations and transport to and from the ports is actively being developed at the moment.

Disadvantages:

NH_3 is a toxic chemical with large environmental impact in case of incidents. Large capital layout is required to design and build the installation, but per kg of H_2 produced over the design life of the plant these costs represent only a fraction of the total H_2 price.

Recommendations:

Regulation and specifications for handling and storing NH_3 need to be up to date to enable safe processes.

3.3 Existing infrastructure

Existing ammonia terminals and production in Europe

Ammonia's toxicity may influence port developments unevenly, driven by local, regional, and country-level perceptions and regulatory approaches. Ports with existing ammonia infrastructure may be faster to adopt ammonia as a low-emission fuel compared to those where it would represent a new fuel.

To this effect, Europe is already home to a broad network of ammonia terminals, with over 40 facilities (Figure 14). Among the busiest ports in Europe, by cargo tonnage, a majority have access to ammonia terminals located within or in close proximity to the port, highlighting a strong overlap between major shipping hubs and existing ammonia handling capabilities. Notable ammonia absentees include the ports of Amsterdam, Algeciras, and Marseille.

It is also worth noting that ammonia infrastructure is not restricted to sparsely populated areas, as multiple terminals are located in or near major industrial and urban regions.

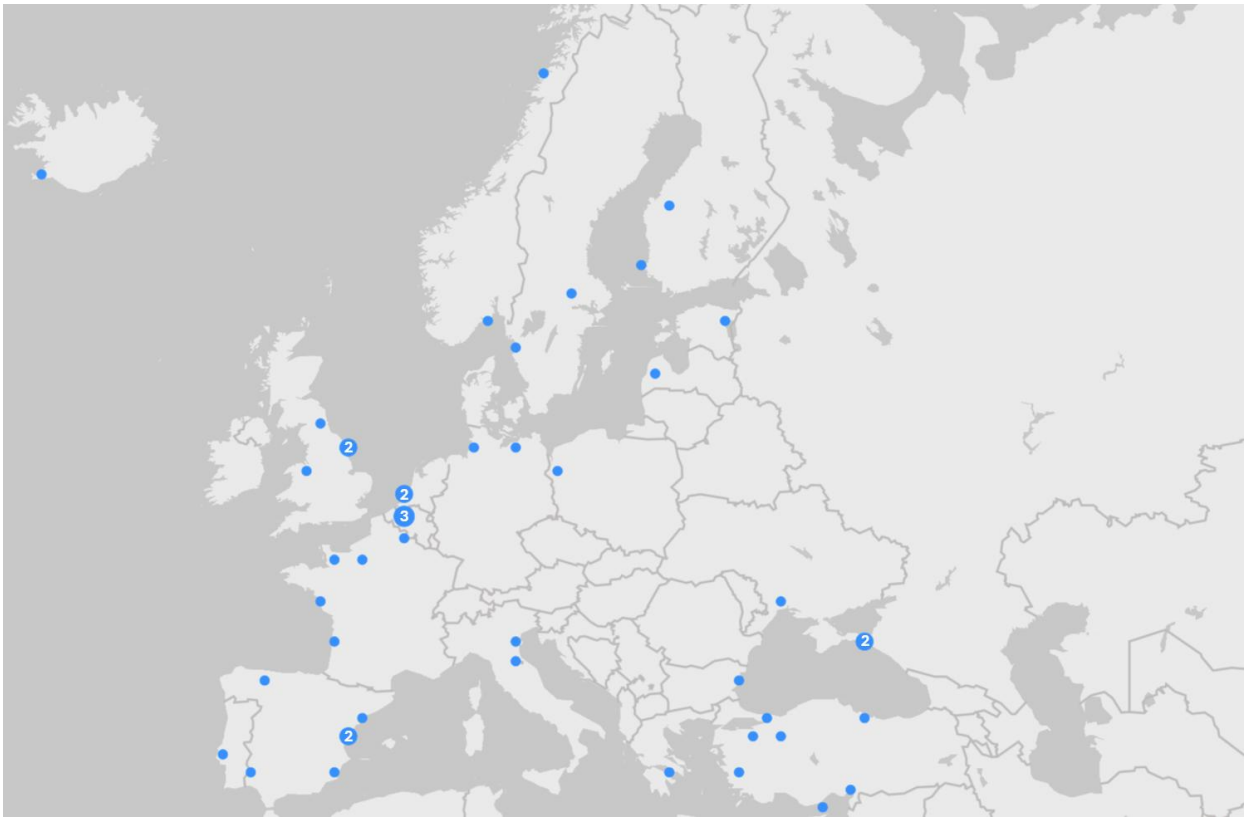


Figure 14: European ammonia storage terminals (based on World Ammonia Map, 2024, IMO) [32]

Note: *Numbers indicate multiple distinct ammonia terminals located in the same area. These terminals are not necessarily co-located and may be separated by significant distances but are not individually distinguishable with this map scale.*

This logic can also apply to the ports and regions where ammonia production plants are already established (figure 15).

[32] World Ammonia Map, 2024, IMO Future Fuels, available here



Figure 15: European operational ammonia production plants [5]

Note: *The map illustrates the geographical distribution of ammonia production sites across Europe, without reflecting differences in production capacity or the number of units at each location. Most operational plants represented correspond to conventional (grey) ammonia production.*

Potential to convert LNG shore infrastructure

It is technically possible to convert LNG terminals for ammonia use, but this is neither simple nor costless. While conversion may offer cost savings compared with new-build terminals, it can, in some cases, be more expensive than expanding existing ammonia infrastructure where feasible.

Designing LNG terminals with future conversion in mind ("ammonia-ready" design) could maximize equipment reuse and reduce overall costs. This would typically involve stronger tank foundations, integration of ammonia-specific safety requirements into process control systems, and the use of compatible materials for components such as seals and gaskets. Without such design considerations, operators may face both operational constraints and the need for significant retrofits. This could include limitations on storage capacity, as well as the replacement of control systems and material-sensitive components such as seals or piping elements.

Each part of the import terminal must be assessed on a case-by-case basis. For example, boil-off gas systems may require limited modification, whereas pumps are likely to require replacement due to ammonia's different physical and chemical properties compared with

LNG. Ammonia has a higher volumetric energy density than LNG (around 1.5×), which affects flow characteristics and equipment sizing, in addition to its toxicity and material compatibility requirements.

In addition, LNG terminals would need to undergo re-permitting to handle ammonia, which poses different environmental and safety risks. This may be challenging, as existing LNG sites were not originally selected with consideration of ammonia-related hazards.

Another consideration is the energy requirement of ammonia terminals. While additional energy is already needed for core operations such as pumping, the inclusion of ammonia cracking significantly increases heat demand. If this energy is not sourced from low-emission pathways, it could offset part of the decarbonization benefits.

Overall, converting LNG infrastructure entails costs and risks for terminal owners, particularly given uncertainty around future ammonia demand. However, ammonia is often considered one of the more feasible pathways for repurposing LNG infrastructure in a decarbonizing energy system, with several pilot and early-stage projects currently being explored.

By contrast:

(a) Conversion of LNG infrastructure to liquid hydrogen is generally considered impractical, as it would require near-complete replacement of tanks, piping, and process systems due to the much lower storage temperature (liquid temperature of -253° C for hydrogen versus -162° C for natural gas).
(b) Methanol, by comparison, is a mature fuel and may be able to utilize parts of LNG infrastructure, including storage tanks, with relatively limited expenditure. However, changes to piping, valves, and safety systems would still be required, and it remains a carbon-based vector.
(c) Liquid organic hydrogen carriers (LOHCs) may offer similar infrastructure compatibility advantages but face separate challenges related to scaling up dehydrogenation processes.

Potential to convert ships to use ammonia as a marine fuel

Ammonia-fueled vessel design requires holistic design changes compared to vessels running on conventional fuel oil. This includes storage tanks, bunkering stations, fuel preparation and supply systems, ventilation, and engine design. In contrast, LNG-fueled vessels already incorporate many of these gas fuel handling systems and would require a less fundamental redesign. However, significant adaptations are required to address the specific risks of ammonia, particularly its toxicity. While features such as double-walled piping are already standard in LNG systems and remain relevant, their design and associated safety measures must be adapted to ammonia's properties, including enhanced leak detection, ventilation, and containment requirements.

The storage tank system will likely form the majority of the cost and be the key design consideration considering ammonia's lower energy density. Ammonia requires approximately three times the tank volume to deliver the same energy output as fuel oil. This will generally come at the expense of either range or cargo capacity. This isn't just a sticking point for ammonia. Other green fuels see similar challenges—see table 1.

The optimization of ammonia storage on board may depend on the vessel type. Tankers may utilize ISO Type-C tanks on deck, limiting the reduction in cargo volume, while vessels without free deck space, e.g., container ships, would benefit from the greater space-volume efficiency of membrane or prismatic tanks built into the hull. Final configurations will depend on safety requirements and space optimization.

The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping analyzed that the optimal ammonia tank location for a 15,000 TEU container vessel is below the accommodation, where the fuel oil tank would typically be located.[33] Due to the larger volume required, maintaining an equivalent range to a fuel oil vessel would reduce cargo capacity by approximately 4%. In this configuration, the fuel oil tank would be moved between cargo holds, as illustrated in figure 16 below.

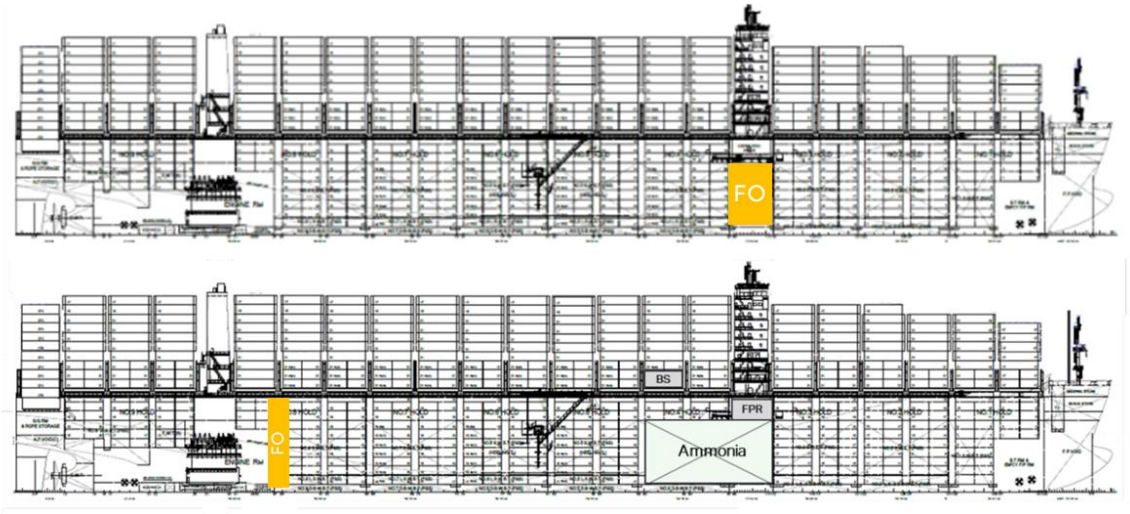


Figure 16: Designs for a 15,000 TEU container vessel [33]

Top is fuel oil only. Bottom is dual-fuel ammonia and fuel oil

However, this is only possible for a new-build. A ship converting from fuel oil to ammonia would install the ammonia tanks across three cargo bays to achieve the same range, resulting in a 7% reduction in cargo capacity. This is shown in figure 17 below.



Figure 17: Designs of the 15,000 TEU container vessel converted to run on ammonia [33]

[33] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022, Preparing Container Vessels for Conversion to Green Fuels, available here

By comparison, LNG-fueled vessels are structurally better positioned for ammonia conversion. The fuel tank is typically located under the accommodation, reducing the need for major structural modifications during conversion.

Conversions not only reduce the cargo capacity but are also more costly than newbuilds. For container vessels, analysis suggests that it is economically preferable to construct the vessel as dual-fuel from the beginning if owners anticipate switching from fuel oil to ammonia within 8 years of operation. If the switch occurs after eight years, it is more economical to make no preparations at the new-build stage, as partial readiness provides limited value due to the extent of modifications required. For LNG, a similar timing logic applies, but greater preparation can be incorporated at the new-build stage since gas systems are required in any case.

While these findings are specific to container vessels, they illustrate a broader challenge: vessel owners require a certain level of confidence in the future competitiveness and availability of alternative fuels to justify early investment. Acceleration of ammonia's adoption requires mechanisms that help transfer part of this uncertainty and risk away from shipowners, for example, through policy support or targeted incentives.

4. Demand

This section considers the demand sectors, timeline for adoption, forecast volumes and the gaps in the supply chain that need to be addressed. We deep dive on the Port of Rotterdam demand.

4.2 Demand segments

For this report, we have categorized the demand for ammonia into five segments: fertilizer, industrial demand, power generation, marine fuels and as a hydrogen carrier, as visualized in figure 18 below.

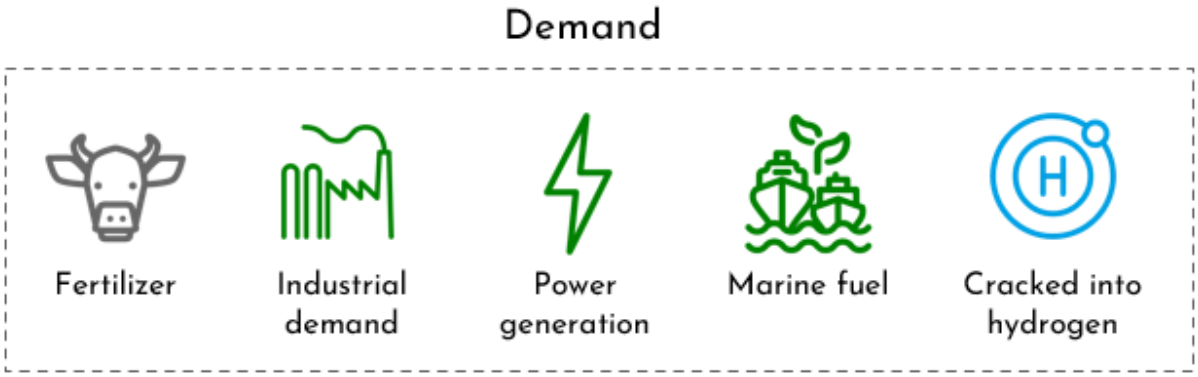


Figure 18: Ammonia demand segments [1]

Deep dive: direct use for power in marine propulsion

Despite its toxicity, ammonia is considered by many as an effective hydrogen carrier and emerging fuel for seagoing vessels, due to its potential as a cost-effective, carbon-free, and relatively energy-dense fuel. However, adopting ammonia as a marine fuel does not by itself resolve a key challenge, namely how its stored energy can be efficiently converted into mechanical or electrical power on board ships. In response to this challenge, engine manufacturers are primarily focusing on diesel-ammonia dual-fuel internal combustion engines (ICEs), which currently represent the most mature technological pathway. In parallel, proponents of fuel cells are advocating the development of ammonia fuel cells (FCs), which are expected to play a more significant role in the longer term.

Ammonia-powered shipping is still at an early stage of deployment but is progressing rapidly. As of 2026, eight vessels are in operation worldwide, including three bulk carriers, two tugboats, one LPG carrier, and two platform supply vessels (PSVs). Of the two ammonia-capable PSVs, one is currently in service while the other is undergoing repairs. Most of these ships operate on dual-fuel ICE configurations, combining ammonia with conventional fuels such as Very Low Sulfur Intermediate Fuel Oil (VLS IFO), Very Low Sulfur Marine Diesel Oil (VLS MDO), or Very Low Sulfur Marine Gas Oil (VLS MGO). At the same time, the orderbook is expanding, with 47 ammonia-capable ships currently on order. Although ammonia represents only a small share of the alternative-fuel fleet (around 0.7% of gross tonnage on order), this reflects growing industry interest. In addition, a significant number

of vessels are being built with future fuel flexibility: 376 ammonia-ready ships are already in service, and a further 361 are on order, indicating strong momentum toward ammonia and other low-emission fuels.[34]

Figure 19 illustrates the expected technology pathway, with ammonia dual-fueled engines (ICEs) moving from first demonstration to commercial application in the mid-2020s, with fuel cell systems following at a later stage. Although this timeline is based on earlier projections, developments to date confirm it, with the first ammonia dual-fuel vessels now in operation and a growing orderbook. Ammonia fuel cells remain at an earlier stage of development, in line with the figure.

Broader scale-up is expected in the 2030s as technologies mature, safety frameworks are consolidated, and supply chains develop.

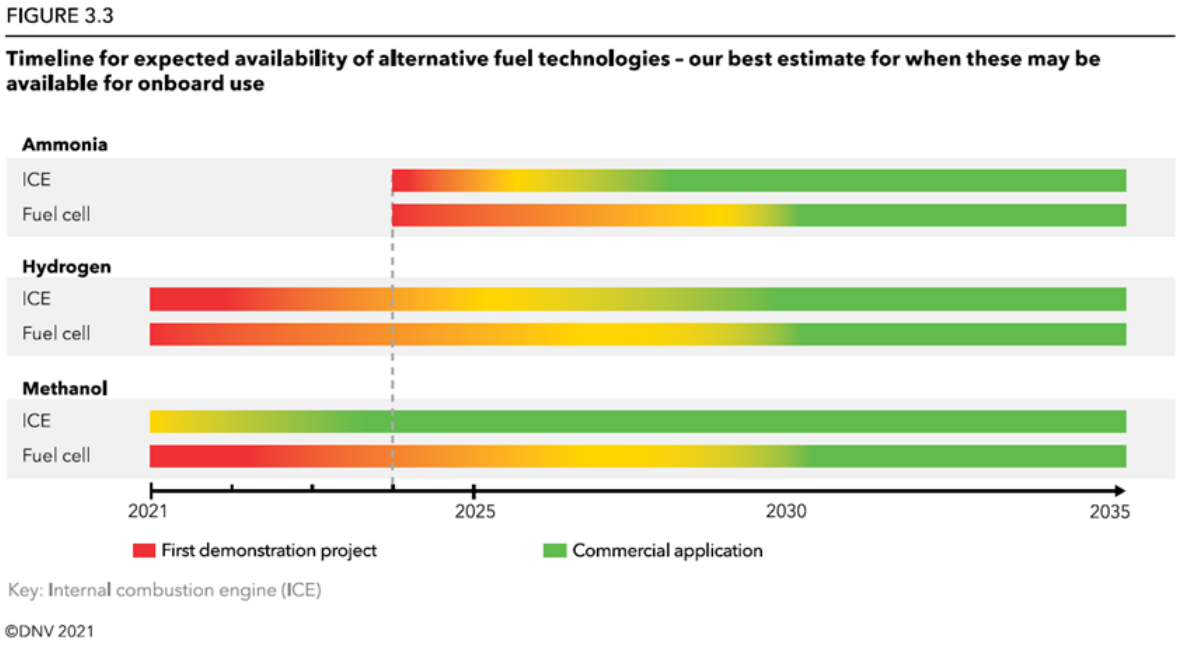


Figure 19: Timeline for ammonia, hydrogen and methanol combustion engines and fuel cells [35]

From a technical perspective, ammonia-fueled ICEs typically require selective catalytic reduction (SCR) systems to comply with NO_x emission limits (see Figure 20). In conventional ships, SCR systems typically use urea, which decomposes into ammonia in the exhaust gas, as it is safer to store and handle than ammonia itself. In the case of ammonia-fueled vessels, however, ammonia is already available on board as fuel and can therefore be used directly as the reagent in the SCR system, avoiding the need for dedicated urea storage and handling systems.

Beyond conventional dual-fuel ICE configurations, further innovations are being explored, including hybrid systems combining ICEs with fuel cells (e.g., the AmmoniaDrive project),

[34] Clarksons Research, 2026
[35] DNV, 2021, Maritime Energy Transition Outlook, available here

although these concepts remain at an early research stage and are not yet close to commercial deployment.[36]

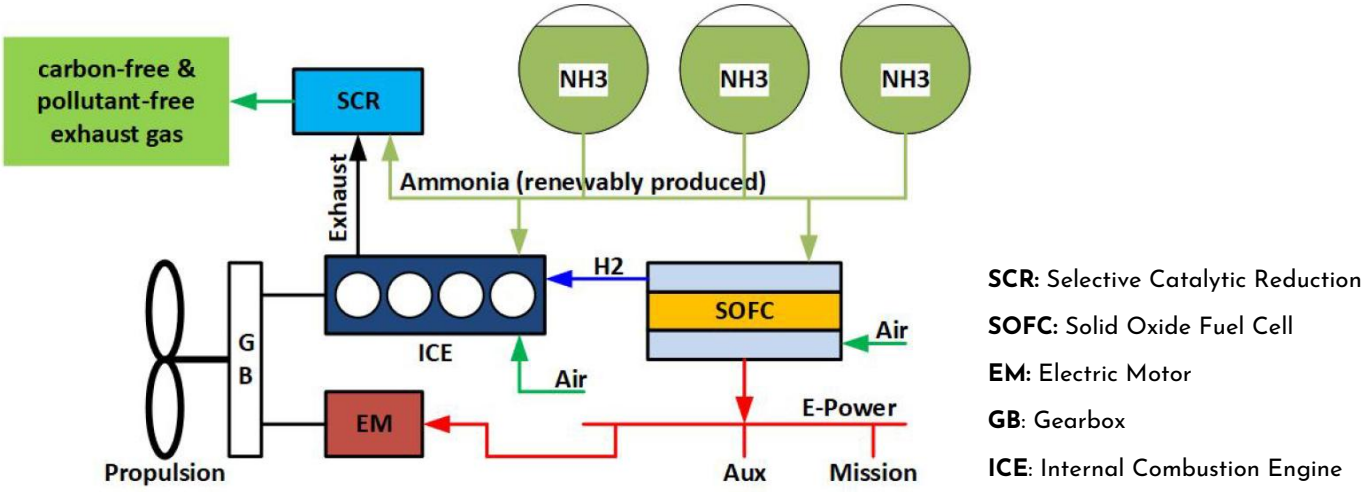


Figure 20: AmmoniaDrive's study of internal combustion engine combined with fuel cell [36]

Deep dive: business case for ammonia-powered port-based workboats

Ammonia is being explored as a potential fuel for dredgers and workboats as part of efforts to reduce greenhouse gas emissions in the maritime sector. We forecast the earliest potential introduction of ammonia-powered dredgers and workboats in the Port of Rotterdam to be 2028, due to the current technology readiness level of ammonia power sources (marine engines and ammonia fuel cells).

The demand for ammonia from port-based workboats may then increase rapidly. An optimistic forecast is 250 tonnes in 2028, 400 tonnes in 2029 and 500 tonnes in 2030. This is based on our estimation of the potential scope for 20 MW+ dredgers and workboats up to 2030 within and in the vicinity of the Port of Rotterdam, with a 50% substitution rate of ammonia in internal combustion engines.

However, this demand forecast assumes enough incentivization to make low-emission ammonia affordable commercially. This could be applied at the state level, or even locally. Within the Port of Rotterdam, an incentive is already in place to use greener fuels on board workboats. Every fuel has a 'Milieu Kosten Indicator' (MKI, which translates to English as Environmental Cost Indicator) which is lower when the environmental impact of a fuel is lower (CO_2, NOx, Particulate Matter). When contractors tender for projects within the Port of Rotterdam, they get a notional discount on their bid. This discount is calculated by multiplying the total MKI score of their bid (based on fuel type and quantity) by an amount of money per MKI point for the chosen fuel solution. This yields a 'Milieu Kwaliteits Waarde' (MKW, which translates to English as Environmental Quality Value). As of 2023, an MKW value of 2 euro per MKI point was commonly applied. This does not yet result in an economically viable business case in combination with the ammonia fuel costs (figure 7) plus the cost of bunkering. To enable an economical transition to this new technology, we estimate

[36] TUDelft, 2022, AmmoniaDrive, available here

that a minimum MKW value of 10 euro per MKI point may be required (assuming no other separate incentivization).

Providing support to port authorities to fund increased MKW valuation is one option to spur adoption amongst port-based workboats, provided that technology matures and the regulatory framework evolves to enable the use of ammonia as a marine fuel.

4.3 Demand forecast

Global demand

Forecasting ammonia demand in emerging applications remains highly uncertain due to unresolved questions around cost, safety, and technological maturity. Existing projections vary widely, with estimates for marine fuel demand ranging from negligible levels to as much as 900 million tonnes.

Nonetheless, a perspective on scale is important. Therefore, we have included a view from the International Renewable Energy Agency, which combines several demand estimates and uses the median for each application. These projections are conveniently not dissimilar to our categorization. This is shown in figure 21 below.

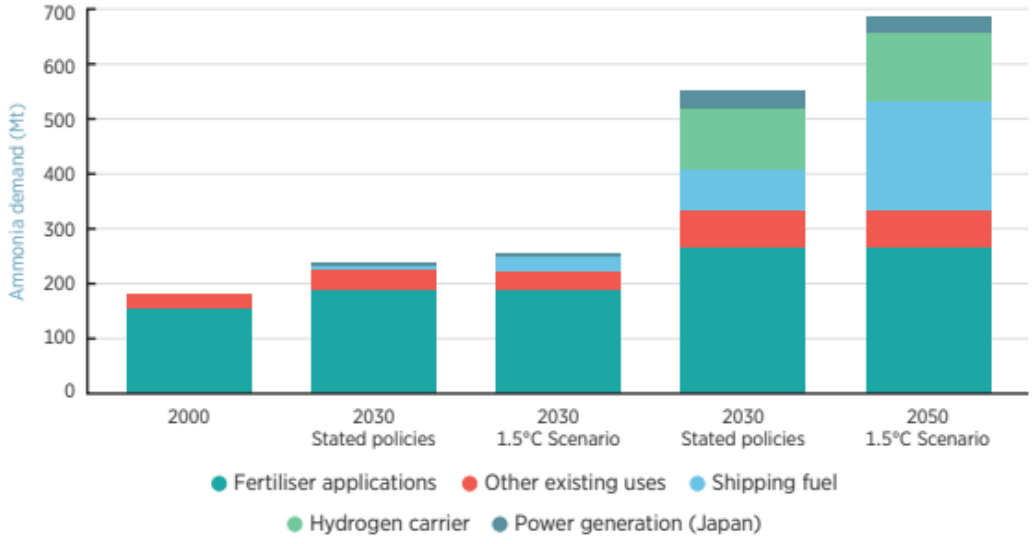


Figure 21: An ammonia demand forecast by segment from IRENA [4]

Port of Rotterdam demand deep dive

Figure 22 shows a forecast value chain for the Port of Rotterdam in 2030, drawing out imports, a high-level value chain and demand segments.

In 2030, 9.5 million tonnes of ammonia (1.5 million tonnes of hydrogen equivalent) is forecast to be imported by vessel. The biggest driver is power generation consuming almost half. The remainder will go into marine fuels, industry and be cracked into hydrogen.

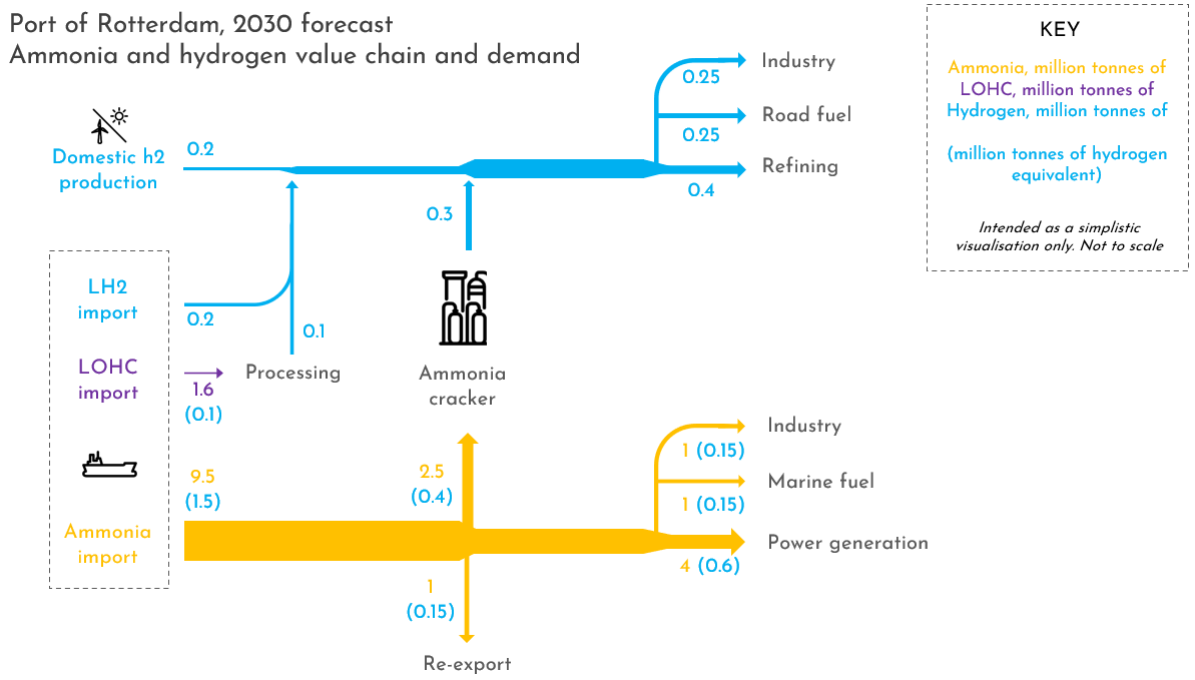


Figure 22: Forecast ammonia and hydrogen imports, demand and value chain for the Port of Rotterdam in 2030 (provided by the Port of Rotterdam)

By 2050, the ammonia value chain in the Port of Rotterdam is forecast to grow significantly to 47 million tonnes imported. Marine fuel becomes the biggest consumer. This is shown in figure 23 below.

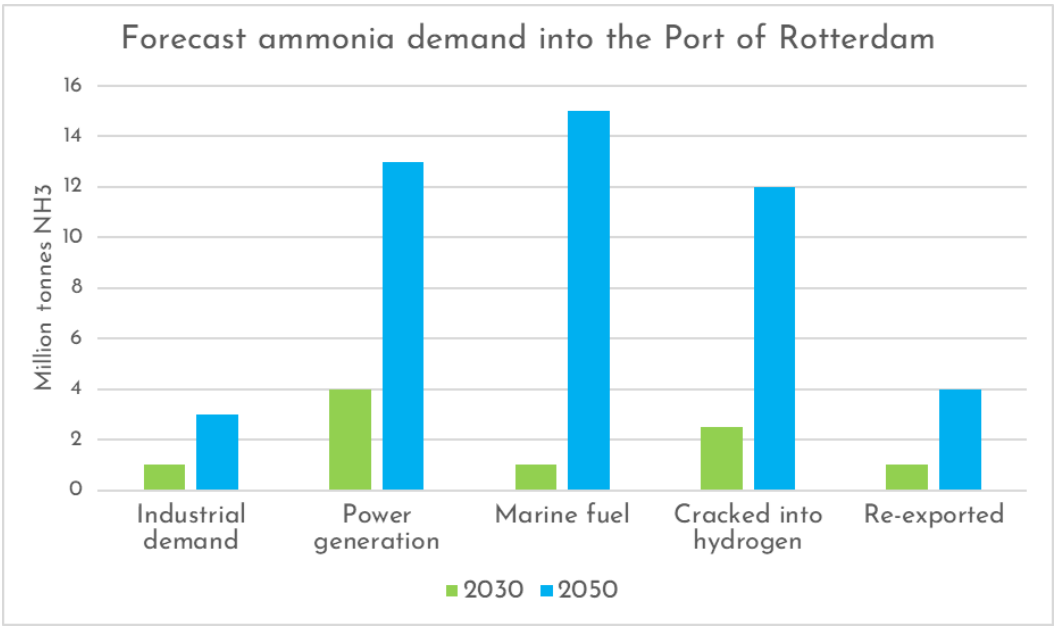


Figure 23: Forecast ammonia demand into the Port of Rotterdam by segment in 2030 and 2050 (provided by the Port of Rotterdam)

4.4 Challenges to be addressed to stimulate demand

Commercial challenges

Price

Ammonia currently remains more expensive than conventional fossil fuels. However, it is increasingly viewed as a competitive option relative to other low-emission marine fuels. Significant policy incentives will be required to stimulate demand.

Figure 24 shows the potential impact of carbon pricing on the production costs of ammonia, alternative low-emission fuels, and traditional fossil fuels.

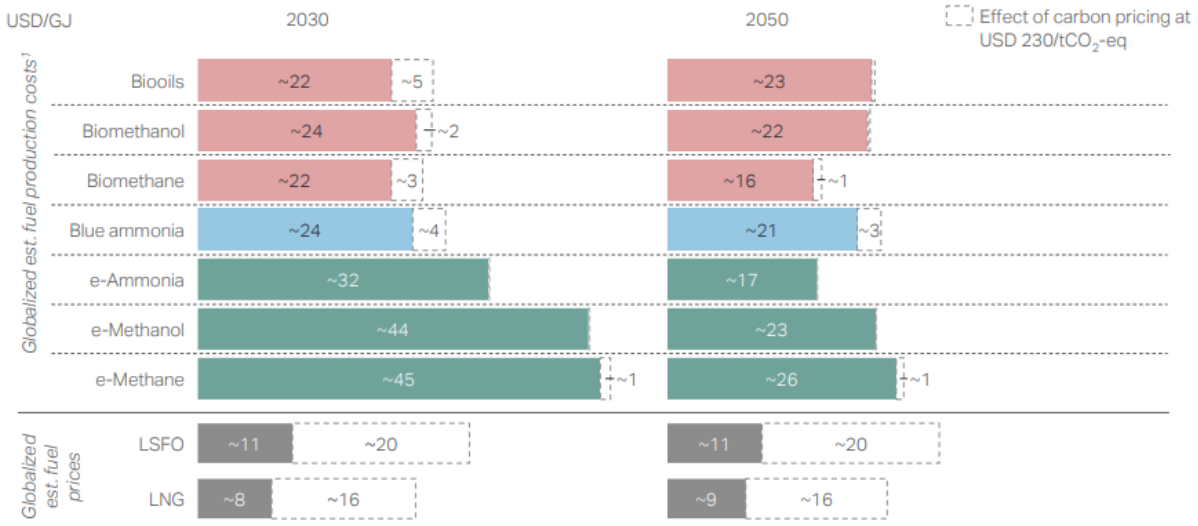


Figure 24: Effect of carbon pricing on various fuels [37]

Committed volumes for marine fuels

Ammonia-capable engines are deployed primarily as dual-fuel systems, combining ammonia with a pilot fuel. This configuration provides operational flexibility, allowing vessels to fall back on conventional fuels if ammonia is unavailable. It also allows shipowners to optimize fuel selection based on price, which may reduce their willingness to commit to long-term take-or-pay contracts.

Conversely, suppliers typically rely on such contracts to underpin investment decisions and secure debt financing. While some projects are already moving forward, often supported by strategic or public funding, establishing a fully scalable value chain for alternative marine fuels will likely require that some party absorbs demand risk. Governments are often better positioned to mitigate these risks in support of decarbonization objectives.

The potential impact of fuel price exposure has already been observed in LNG bunkering. While LNG can offer lower life cycle greenhouse gas emissions than conventional fuels under

[37] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022, Maritime Decarbonization Strategy, available here

certain conditions, price dynamics have proven decisive. Following a decline during the period of elevated gas prices in 2021 – 2022, LNG bunkering activity in Europe has remained highly sensitive to market conditions. Although demand has since recovered in some locations, uptake continues to be uneven, suggesting limited long-term offtake commitments.

This experience highlights the financial risks faced by suppliers in the absence of demand certainty and may reduce their willingness to invest in new fuel supply infrastructure without additional guarantees or policy support.

Regulatory challenges

New regulation is a prerequisite for the adoption of ammonia as a low-emission fuel and will have to both incentivize and facilitate its uptake. This section outlines the critical gaps that exist today and offers several considerations for regulatory design, based on discussions with stakeholders across the value chain.

'Facilitating' regulation is needed to govern how ammonia is used, including its safe handling, storage, combustion, and associated personnel training. Given its toxicity and specific handling requirements, it is necessary to establish appropriate technical and operational measures, including specifications for fuel tanks, ventilation, and leak detection, as well as crew training and operational procedures. The International Maritime Organization (IMO) has approved interim guidelines for the safety of ships using ammonia as fuel (MSC.1/Circ.1687, 2024), while further work on IGF Code amendments is ongoing.[38] Ensuring robust and harmonized frameworks is essential to support safe operations, build industry confidence, and enable the large-scale deployment of ammonia.

In parallel, 'incentivizing' regulation is needed to encourage industry, power generators, and ship owners to switch from cheaper fossil fuels to low-emission alternatives. This can take the form of financial support mechanisms—such as subsidies or reward schemes for low-emission fuels—or market-based measures.

Marine fuels regulation deep dive

Global regulation of shipping falls under the remit of the IMO. The regulations below (Figure 25) need to be updated or drafted to facilitate and incentivize ammonia as a low-emission fuel.

[38] IMO, 2024, Interim Guidelines for the Safety of Ships Using Ammonia As Fuel (issued 2025), available here

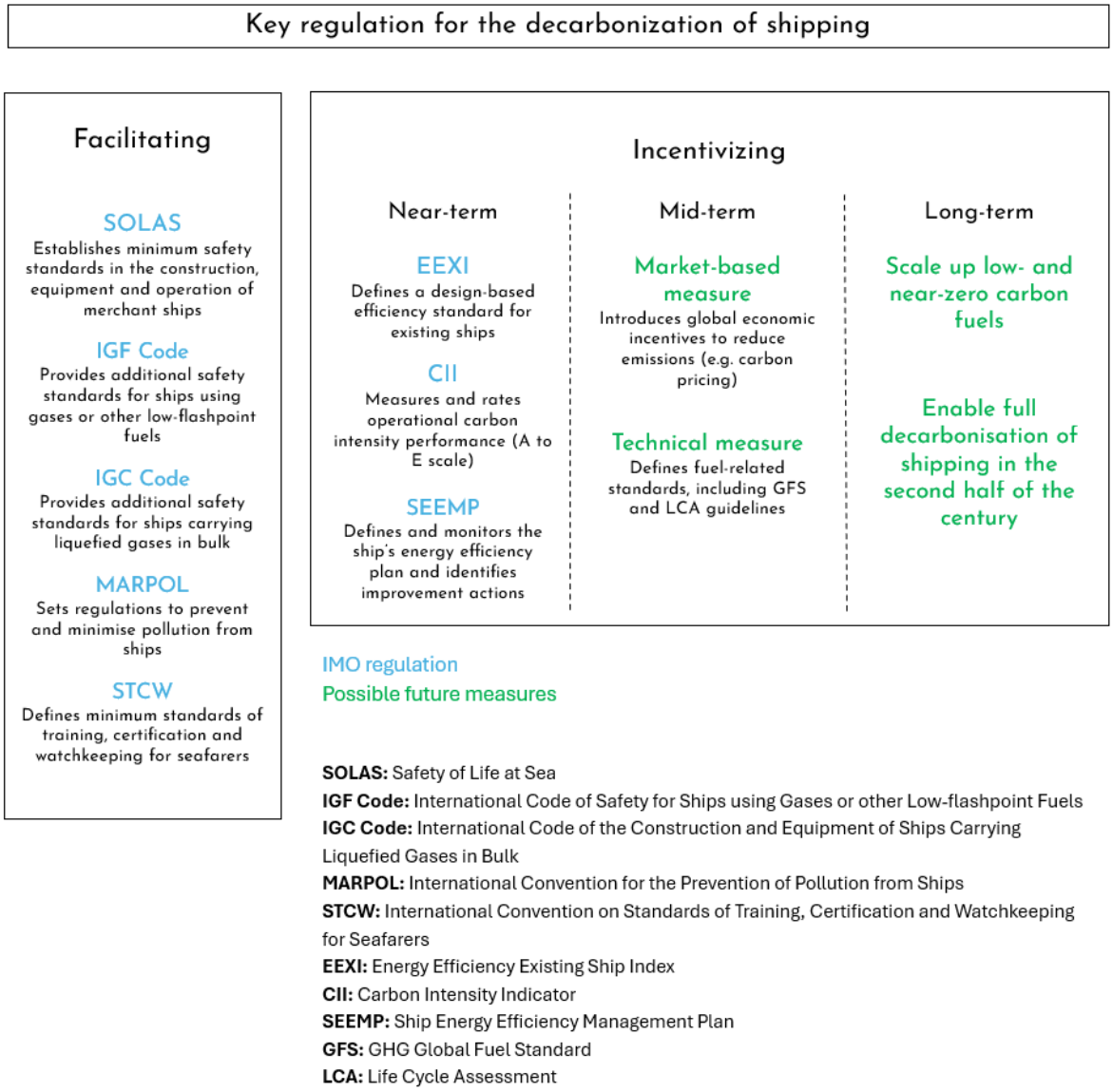


Figure 25: Key regulation for the global decarbonization of shipping [1]

Regulation drafting considerations:

1. **Global versus regional**

In a global industry such as shipping, regulation is most effective when applied at a global level. A ship owner adopting ammonia to reduce its emissions under one region's regulation shouldn't be disadvantaged against its competitors in another region with less strict regulation.

Ammonia is well suited for long-distance "deep-sea" routes. Given that such vessels operate across multiple regulatory jurisdictions, regional approaches may be less effective in driving its adoption.

Although the IMO has strengthened its decarbonization strategy, it is still considered insufficient to align with the Paris 1.5°C trajectory. As a result, the European Union has implemented regulatory measures to accelerate emission reductions, including market-based mechanisms and life cycle-based standards. While these measures are expected to support the transition, they also raise the risk of creating a fragmented regulatory landscape. In particular, this could create a "two-tier" global fleet, where new vessels adopt low-emission fuels in regulated regions such as Europe while continuing to rely on conventional fuels elsewhere. This would disadvantage the economies of EU countries.

2. Well-to-wake emissions for shipping

Historically, IMO regulations have focused primarily on tank-to-wake (operational) greenhouse gas emissions from shipping. While this approach remains central to existing frameworks, it does not capture emissions generated upstream in fuel production and transport. Regulatory approaches are now evolving. For instance, the EU has adopted a life cycle-based framework under FuelEU Maritime, which evaluates fuels on a well-to-wake basis. [39]

Life cycle assessment (LCA) is the most comprehensive method for evaluating the environmental impacts of fuels across their entire life cycle, although approaches can vary and are often complex. Considering emissions across the full life cycle is essential to avoid incomplete or misleading comparisons between fuels. In this context, well-to-wake is commonly used as a standardized and simplified approach to capture and compare total life cycle emissions.

3. Not just CO_2

Nitrous oxide (N_2O) has around 300 times the warming potential of CO_2, while methane (CH_4) is approximately 80 times more potent. To avoid replacing CO_2 emissions with gases that have a greater impact on global warming, all greenhouse gas emissions should be targeted within regulation. Accordingly, N_2O and methane are typically accounted for in CO_2-equivalent (CO_2e) terms, so their greater warming impact is not underestimated.

4. Danger of prescriptive measures

Prescriptive regulation sets both the objective to be achieved and the specific way to achieve it. In other words, it tells actors not only what to do, but also how to do it. While this can provide clarity and certainty, it also carries risks—particularly in rapidly evolving sectors where technologies and practices are still emerging. By embedding current methods into regulation, prescriptive approaches can assume that today's solutions will remain optimal in the future, potentially constraining innovation. As a result, such measures may slow down the development and uptake of more effective solutions that could deliver better environmental outcomes over time.

[39] European Parliament and Council of the EU, 2023, Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport (FuelEU Maritime), available here

5. Benefit of "multipliers"

Goal-based regulation, for example, requiring a reduction in GHG emissions of x%, allows industry players to identify and adopt the most cost-effective measures in a 'free market' context, avoiding overly prescriptive approaches.

However, such approaches do not necessarily drive the industry toward long-term solutions. For instance, shippers may find that operational measures improving efficiency, such as speed reduction, are more cost-effective in the short term than switching to low-emission fuels such as green ammonia. A concrete example can be seen under the IMO's Carbon Intensity Indicator (CII), where operators can improve their rating through measures like slower steaming, without necessarily adopting alternative fuels.

To accelerate the uptake of these fuels, regulators may consider strengthening targeted incentives to make them more competitive relative to other compliance options. This could include financial mechanisms, such as subsidies or reward schemes for the use of low-emission fuels (as currently being discussed at the IMO), or the use of energy multipliers that artificially increase the credited emissions reductions of certain fuels.

Such measures would maintain flexibility in compliance pathways while better aligning with the long-term objective of transitioning to low-emission shipping.

6. Green corridors and first movers

Establishing a whole new industry, globally, all at once is a mammoth task. Incentivizing first movers and specific locations can help accelerate development. In this regard, the ammonia value chain may be influenced by the speed at which individual European ports adopt it as a low-emission fuel.

Provided that there is sufficient policy support in the region, first movers may be ports with significant proximate potential customers. For example, Wilhelmshaven has been a focal point for ammonia imports to access significant demand in Germany, with projects focused on ammonia cracking and hydrogen integration. Similarly, major ports such as Rotterdam (Netherlands), Brunsbüttel (Germany), and Antwerp (Belgium) are positioning themselves as strategic hubs for ammonia imports, supported by their proximity to large industrial demand centers and existing infrastructure.

5. Modelling the Ammonia Supply Chain

This chapter describes the modeling approach behind the green ammonia supply costs presented in Section 2.3. The analysis is based on the EWI Global PtX Cost Tool, which encompasses supply, production, storage, conversion, and transport considerations. The results in Section 2.3 are calculated for the baseline cost scenario in 2030 and a supply volume of 3 Mt ammonia per year.

5.2 PtX cost model

In this report, the Netherlands is set as the destination country, and the analysis draws on projected cost developments until the year 2050.

Supply costs are the sum of production costs and transport costs. The levelized production cost estimation in the EWI Global PtX Cost Tool is the result of an optimization model. The model minimizes the production cost of hydrogen (or a derivative) by adjusting plant capacity and operation of a system consisting of a renewable energy source (either wind onshore, wind offshore, or PV), an electrolyzer, a hydrogen storage tank, and a hydrogen conversion plant (i.e., the Haber-Bosch process for ammonia). The renewable energy source is dedicated to the production of hydrogen (derivatives). There are different classes for each renewable energy source in each country, which differ according to the average capacity factors and production potential. The classes represent the differences in sites within a country. Cost drivers for the levelized production costs are country-specific renewable energy capacity factor profiles and weighted average costs of capital. The levelized transport costs are calculated from each origin country to the destination country based on pipeline or maritime transport. For each route, the tool estimates the most economic transport option. The routes run from capital to capital. In the case of maritime transport, the routes run from the capital to the relevant port in the origin country, to the relevant port in the destination country, and then to the capital in the destination country. By this approach, transport costs within the origin and destination country are generalized.

A more comprehensive model description of the tool can be found in D.3.4 -"Gaps and developments hydrogen supply chain for future demand", and D.3.10 -" Long-term assessment energy supply and demand model", and with greater detail in Moritz et al., 2023[14].

6. Conclusion

This report has determined that ammonia already benefits from a well-established global supply chain, being produced and traded around the world today. The challenge is not to create a new supply chain, but to determine how the existing one can evolve to meet emerging demand for low-emission ammonia. The major gaps and required developments are thus: producing low-emission ammonia at scale; growing and adapting the existing chain to serve new demand segments (power generation, marine fuel, as a hydrogen carrier, etc.); and establishing the regulation that makes low-emission supply commercially viable.

On supply, the picture has improved since the first phase of this work (D.3.6, in 2023). Blue and green ammonia have both moved from announcement to early operation, and the two pathways are now expanding towards early commercial scale. Volumes nonetheless remain small next to grey production: build-out depends on CCS availability for blue ammonia, and on the competitiveness of renewable energy generation, green hydrogen production costs, and supportive policy frameworks for green ammonia. The larger near-term emissions gain lies in using low-emission ammonia to displace the grey production already in operation, alongside its use in the new demand segments. On sourcing, the supply costs modeled for the Netherlands are lowest for Norway and for domestic production in the Netherlands, followed by other European origins, which favors domestic production and regional import arrangements over long-distance supply in the near term.

On operations and infrastructure, every component of the chain—gas carriers, terminals, storage, bunkering and cracking—already exists, but each has to grow substantially and be adapted from handling ammonia as a cargo to supplying it as a fuel. The first ammonia-powered vessels are already in service and bunkering has been demonstrated, so what remains is a question of scale rather than feasibility. Much of this converges in ports, and those with ammonia terminals and storage already in place can add bunkering capability with less new infrastructure and permitting difficulties than ports starting from nothing. Port-based workboats are a practical way to begin, since a port authority can create that first demand itself. Demand is now tangible rather than prospective, with an orderbook building behind those first vessels and forecasts pointing to substantial import volumes for the Port of Rotterdam by 2050.

The obstacles are consistent across the chain: cost, commercial uncertainty, and safety. Regulation is the main enabler of progress, and it has moved substantially since the first phase of this report, with interim IMO guidelines for ships using ammonia as fuel now approved. Incentives strong enough to close the cost gap are still missing, and to be effective they will need to apply globally. What will set the pace from here is the strength of those incentives; the investment decisions that convert announced green projects into operating capacity; and the consolidation of safety standards and crew training. Progress in each case depends on how far governments and port authorities carry the first-mover cost burden.