Ammonia as a marine fuel

Prospects for the shipping industry

Documentation of assumptions for Navigate 1.0 (2021)

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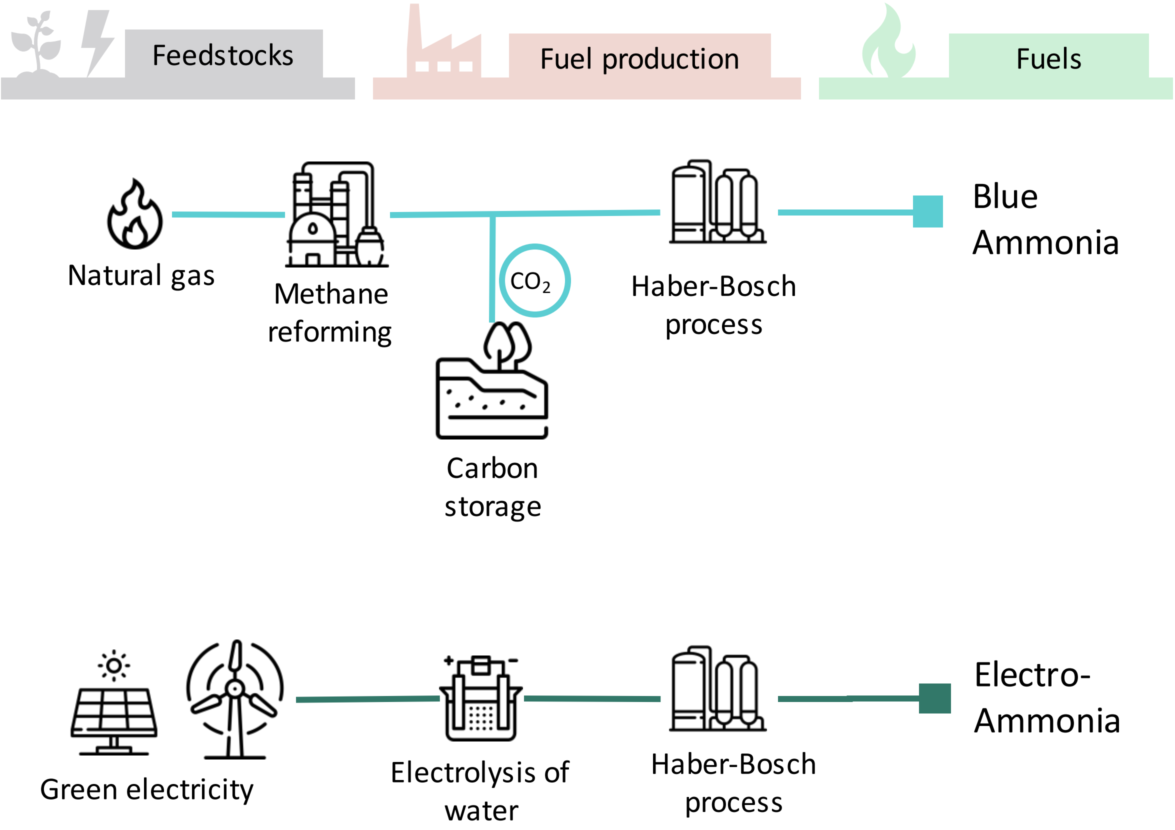
Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

Agenda

Two viable pathways for producing low emission Ammonia



Two low-emissions pathways exist for producing ammonia today

- Low emission ammonia is produced from hydrogen that is generated by either of two processes:
  1. Blue hydrogen: Conventional methane reforming, combined with CO_2 capture and storage
  2. Electro-ammonia: Electrolysis of water, powered by renewable sources
- Grey ammonia has been excluded from the following analysis, because its price and emissions are higher than those of LSFO.

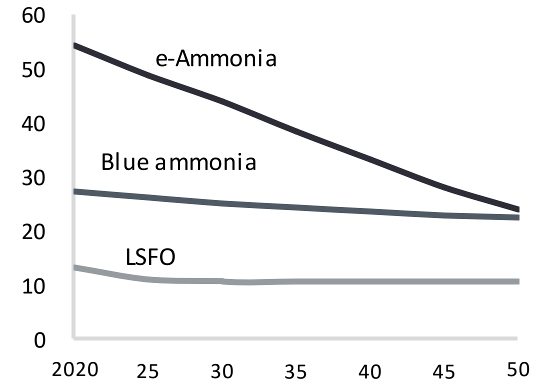
Note: Only key processes are included; Icons from: Bqlnq, freepik, Vitally Gorbachev

Ammonia is a potential low-emission alternative fuel for shipping

Key conclusions

- As a marine fuel, ammonia has potential to significantly decrease emissions, but its implementation is hindered by significant uncertainties:
  - Supply: Infrastructure scale-up needed, for production and distribution
  - Onboard: needed volume and weight, unclear safety requirements, low technology readiness, potential large amounts of pilot fuel (5-15%)
- The choice between electro-ammonia vs. blue ammonia will depend on:
  - the cost and availability of renewable electricity and
  - the carbon taxation level, as producing blue ammonia emits some CO_2
- Impact of safety issues could be severe including toxicity or costs of mitigation measures are potential show-stoppers that need to be addressed upfront.

Cost projections

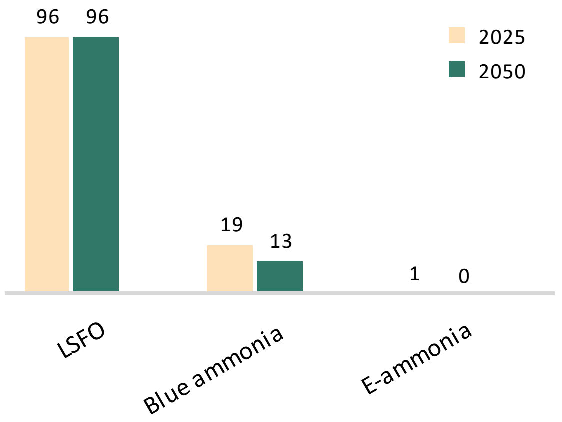


Ammonia requires market-based measures to compete will fossil alternatives

- E-Ammonia's economic feasibility depends on the availability of green electricity. Cost of production is expected to decline steadily.
- Blue ammonia's economic feasibility depends on the proximity to favorable CO_2 storage formations.

Emissions

gCO_2 direct emissions well-to-wake / MJ



Ammonia must overcome barriers to become a fully green fuel option.

- Electro-ammonia alone bears zero emissions, but pilot fuel emissions must be considered in the total.
- Blue ammonia bears upstream methane emissions.
- Blue ammonia production achieves 90%+ CO_2 capture. Efficacy of CO_2 storage is assumed 100%.
- N_2O emissions are assumed 0, as a prerequisite for ammonia to be viable.

Implementation risks

Usage depends on regulatory measures and large-scale production/ infrastructure

- **[Production]** Scaling of infrastructure (RES, CO_2 storage capacity, & NH_3 plants)
- **[Logistics]** Scaling of port infrastructure (storage and bunkering)
- **[Regulatory, onboard]** Safety standards and risk mitigation
- **[Regulatory, onboard]** Minimize ammonia slip and N_2O
- **[Onboard]** Engine and fuel cell development
- **[Onboard]** Ship performance impacted by additional volume/weight

1: Pilot fuel (5%-15%) is needed. Using LSFO, this equals an additional 4-14 gCO_2eq/MJ. Using e.g. a bio-oil will reduce the impact on emissions.

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Blue ammonia production costs are projected at 2 - 2,5 times the price of fossil fuel alternatives

Highlights from cost analysis of Blue ammonia pathway

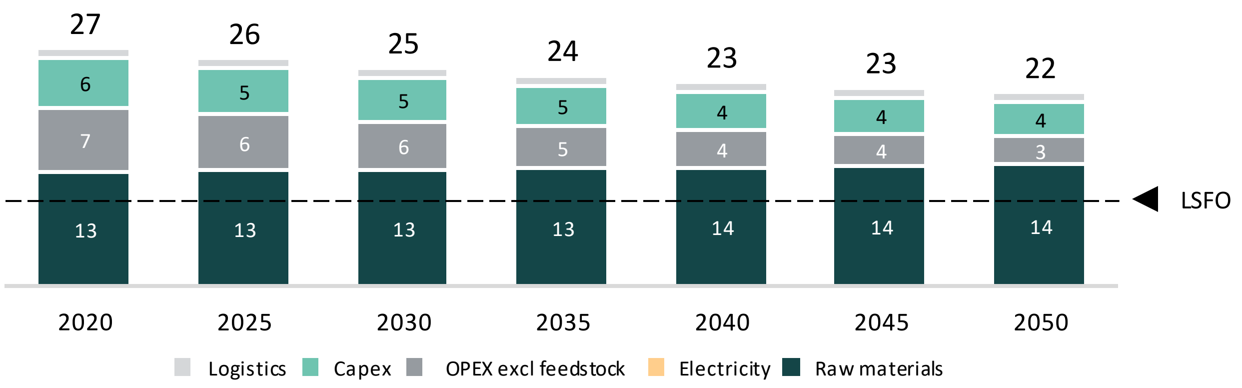
- In all years, the cost of blue ammonia is ca. 2 times higher than the price forecast for LSFO at 10 USD/GJ
- Production cost is projected to decrease by 4% p.a. and reach 20 USD/GJ by 2050.
- The cost of blue ammonia is sensitive to 2 primary factors:
  1. The main cost driver for blue ammonia is the cost of natural gas, which varies between geographies and therefore influences where production is economical.
  2. The cost of CO_2 storage depends on the proximity of ammonia production to geological formations of the proper type and size. Liquefying and transporting CO_2 to distant sites would involve more costs which are not considered in this analysis. Local CCS in the form of EOR requires that both CO_2 slip and CH_4 slip are minimized and regulated; and it also requires the downstream natural gas usage is regulated by low emissions policy.

Blue ammonia will need market-based measures in order to be cost competitive with fossil alternatives

Blue ammonia pathway costs, at port

Weighted global average[1]

USD/GJ **(TRL 9)**



1) Assuming 40 % from lowest cost region, 30 % from 2nd lowest, and 10% from 3-5th.

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Implementation risk, blue Ammonia Supply

Subject	Risks and Challenges	Milestones to Implementation
Feedstock	▪ Sourcing of NG having low fugitive emissions	▪ Establish technical best practice for achieving low methane emissions during NG production and logistics.
Production	▪ Potentially high expense of local CO_2 storage or expense of CO_2 logistics to offshore storage. ▪ Ammonia plants need investment and construction. ▪ Most CO_2 storage does not exist yet; requires >100x ramp-up.	▪ Establish production at locations with proximity to economical permanent CO_2 storage. ▪ Trigger investments for CO_2 storage; already urgent to reach the scale required for 2030 targets. ▪ CO_2 storage must be regulated and demonstrated with effective, nearly permanent containment.
Logistics	▪ Storage facilities at port; adequate amounts for safe storage ▪ Bunkering vessel and bunkering system ▪ Transport lanes and equipment readiness ▪ Standardization of bunkering and safety	▪ Bunkering feasibility needs to be validated. ▪ Bunkering capability and standards must be established at major ports. ▪ Establish green corridors with sufficient critical mass of supply at ports.
Regulatory (Supply)	▪ CO_2 capture rates are maximum 90-95%, so there will always be a small GHG intensity directly from production. ▪ Fugitive emissions from upstream NG supply ▪ Risk of less profitable / stranded assets if electro-ammonia becomes more competitive earlier than expected	▪ Monitoring of (and regulatory standards for) restricting methane emissions. ▪ Demonstration of ammonia production near to NG source, to minimize emissions. ▪ Implement regulatory standards to certify the emissions associated with feedstock. ▪ Establish needed regulatory policy and public awareness to support the establishment of blue ammonia value chain.

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Electro-ammonia production costs are projected at 2 - 5 times the price of fossil fuel alternatives

Highlights from cost analysis of e-ammonia pathway

- In all years, the cost of e- ammonia is ca. 2 - 5 times higher than the price forecast for LSFO at 10 USD/GJ
- Production cost is projected to decrease by 12% p.a. and reach 23 USD/GJ by 2050.

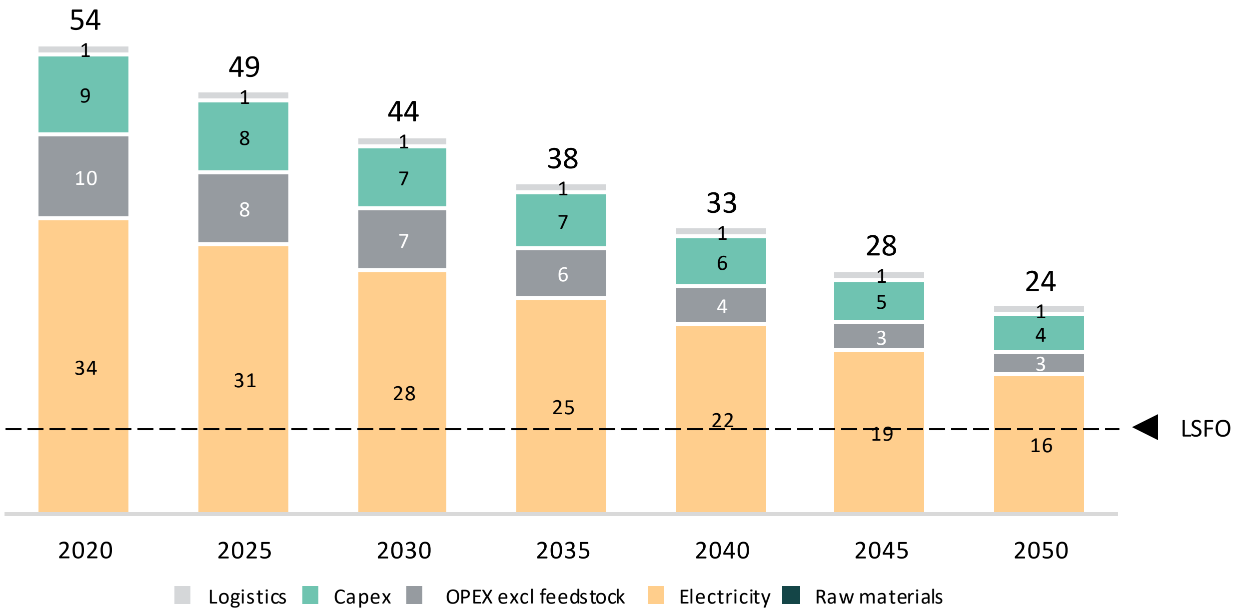
– Renewable electricity cost comprises the largest portion of e-ammonia production cost. The intermittent unavailability of RES necessitates power buffering or equipment turndown. Since the RES cost differs between regions, it largely determines the location where e-ammonia plants are economical.

E-ammonia will need market-based measures in order to be cost competitive with fossil alternatives

E-ammonia pathway costs, at port

Weighted global average[1]

USD/GJ **(TRL 9)**



1) Assuming 40 % from lowest cost region, 30 % from 2nd lowest, and 10% from 3-5th.

Implementation risk, e-Ammonia Supply

Subject	Risks and Challenges	Milestones to Implementation
Feedstock	▪ Global RES capacities may not be at the scale required by shipping and the demand from other sectors. Batteries and required materials may be scarce relative to buffering needs. ▪ Electrolysis manufacturing may not meet the required levels, in order to supply of hydrogen from electrolysis using RES	▪ Scale-up of RES capacity to meet global demand and be available for shipping. Land use policies, labor, and supply chain in place to reach scale. ▪ Growth of battery materials supply chain, or establishment of other solutions to address variable electricity supply. ▪ High-paced growth of Electrolysis sector: manufacturing and supply chain.
Production	▪ Production site location with proximity to feedstock ▪ Economical production requires large-scale capacity plants dedicated to shipping.	▪ New commercial ammonia plants operating on low-cost RES and with adequate proximity to relevant ports. ▪ Scale-up of electro-ammonia infrastructure globally.
Logistics	▪ Storage facilities at port; adequate amounts for safe storage ▪ Bunkering vessel and bunkering system ▪ Transport lanes and equipment readiness ▪ Standardization of bunkering and safety	▪ Bunkering feasibility needs to be validated. ▪ Bunkering capability and standards must be established at major ports. ▪ Establish green corridors with sufficient critical mass of supply at ports.
Regulatory	▪ No significant barriers considering direct emissions from supply of electro-ammonia.	

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High uncertainty regarding onboard implementation due to needed volume, unclear safety requirements, and low TRLs

Subject	Considerations	Potential risk mitigations
Energy density and volume	• Requires 3.6 times the volume and 2.2 times the weight compared to VLSFO for the same energy content • Required independent tank plus insulation further increases volume and weight	• Depending on vessel type, size and operational profile: optimize speed and range requirements, bunker more frequently, or accept cargo capacity loss
Fuel Supply & Storage	• Depending on required volume and ship type, ammonia is stored either fully pressurized at ambient temperature or semi- to fully refrigerated in either Type-C, prismatic, or membrane tank types. • Corrosive in presence of moisture; is an alkaline reducing agent; and reacts with acids, halogens, and oxidizing agents	• Careful material selection (iron, steel, and specific non-ferrous alloys) for tanks, pipes, and structural components where ammonia is used; similar to existing multi-purpose LPG carriers
Safety	• Toxicity (at low concentrations) can poison onboard personnel (considered hazardous) • Very low odor threshold (5ppm) could raise concerns by people onboard or in surrounding areas if detected • Bunkering requires liquid/vapor transfer with different vessel containment systems that increases risk of release • Ammonia spill could cause environmental damage or risk human and marine life • Crew awareness and upskilling needed to properly handle ammonia • Certain regions may deny bunkering ammonia due to safety concerns or not allow concurrent bunkering and cargo operations	• Odour can be detectable before concentrations with health risk • Deluge and detox systems, independent ventilation, emergency extraction, vent mast location • Bunkering technology & safe interface design with return flow of ammonia vapour/liquefaction • Shared experience from fertilizer, chemical and industrial cooling industries (training programs, maintenance, inspection, and ventilation procedures) • Development of recent LNG and methanol fuelled vessels to be used as a procedural reference • Crew training and safety managements systems standards

Sources: ABS "Sustainability whitepaper: ammonia as marine fuel"
MAN Energy Solutions "MAN B&W two-stroke engine operating on ammonia"

High uncertainty regarding onboard implementation due to needed volume, unclear safety requirements, and low TRLs

Subject	Considerations	Potential risk mitigations
Emissions	• Tank-to-wake CO_2 emissions reduced >85% compared to HFO Tier II (depending on pilot fuel %) • SOx and particulate emissions reduced 90-100% compared to HFO Tier II • Potential ammonia slip or N_2O emissions reducing total GHG emission benefit as N_2O has a global warming potential more than 300 times CO_2	• Consider as part of the engine combustion optimization process • Develop after-treatment technologies to minimize emissions (SCR most likely needed for NOx and N_2O)
Regulation	• IGC Code does not permit ammonia cargo use as fuel due to its toxicity • IGF Code requires alternative design approved by Flag	• Prescriptive rules for ammonia as a marine fuel to be developed • Classification societies have released guidelines for ammonia-fueled vessels
Energy Converters	• Marine engines do not currently exist and are currently under development • Poor combustion characteristics; need for large amounts of pilot fuel (5-15% for 2-strokes and up to 30% for 4-strokes) • Fuel cell technology not commercially available and competitive	• 2-stroke and 4-stroke engine development ongoing with target for first commercially available engines around 2025 • Use of biofuels as pilot fuel to further reduce emissions • Fuel cell technology development and demonstration projects

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