Ammonia

Overview

- Background and key characteristics
- Ammonia fuel production value chain
- Feedstocks and energy sources
- Production technologies
- Onshore requirements
- Onboard requirements
- Regulations, standards and guidance
- Environmental impact
- Cost overview
- Barriers and risks
- Summary

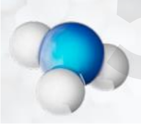
Background and key characteristics

HFO

- Energy density: 42 MJ/kg = 35 MJ/dm^3.
- Flashpoint: 60°C.
- Water solubility: None.
- Most widely-used fuel.

Ammonia (NH_3)

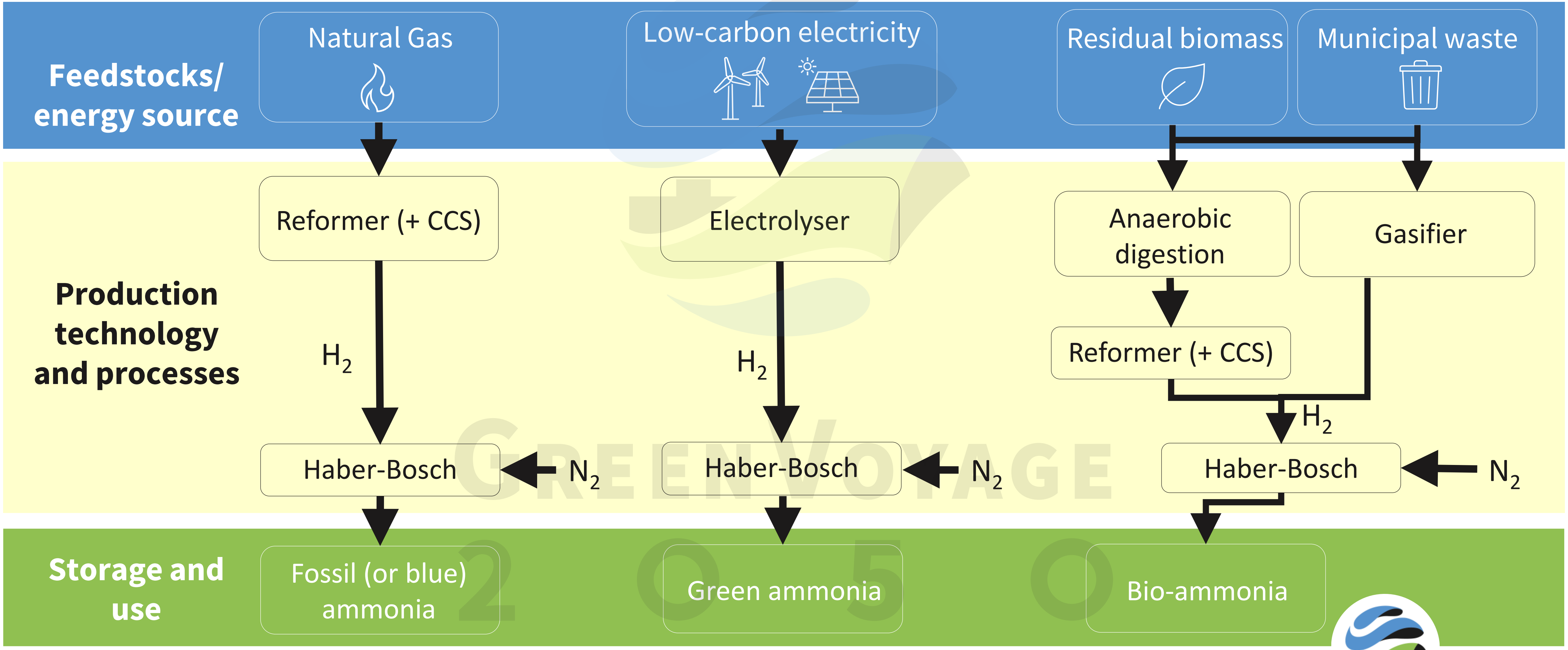
- Energy density: 18.6 MJ/kg = 10.8-12.7 MJ/dm^3 (liquid NH_3)
- Easily liquified by cooling to -33°C or compression to 10 bar
- Low ignition energy, narrow flammability limit (15-28 vol %)
- Water soluble but toxic to aquatic ecosystems
- Commonly used in industry (80% in fertilizers, also refrigerants)
- Well established infrastructure, safe handling and usage procedures



Ammonia availability at ports for transport as a cargo (not as a fuel)

2019 global production = 186 Million Tonnes[1].

Ammonia production value chains ($N_2 + 3H_2 \rightarrow 2NH_3$)



Feedstocks and energy sources

Current availability

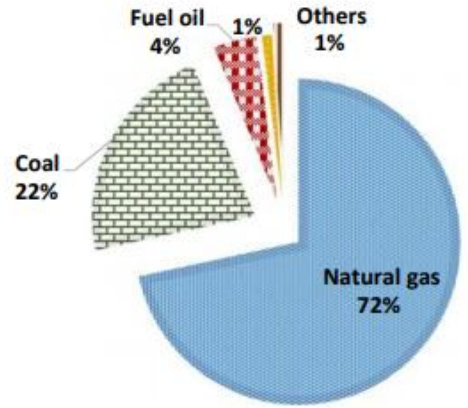
Natural Gas	Low-Carbon Electricity	Air (N_2)	Residual Biomass	Municipal Waste

Widely Available | Availability Constrained | Availability Very Restricted

Key Points

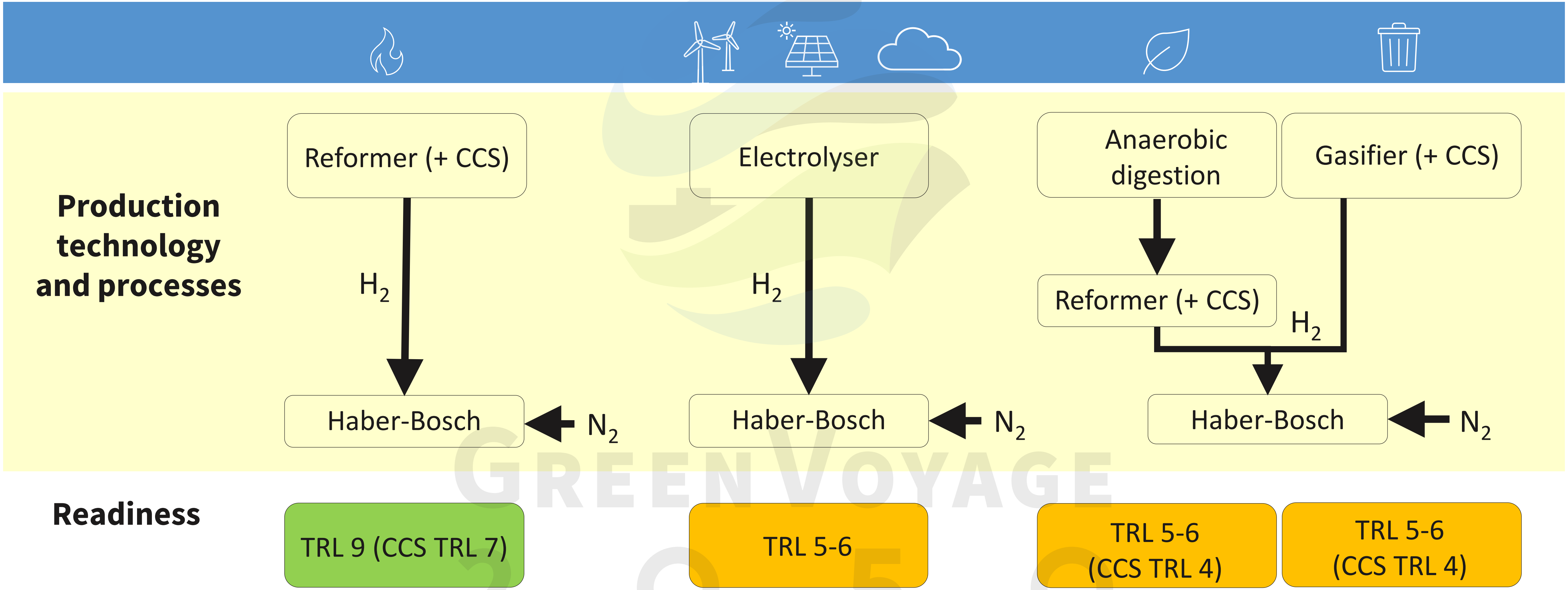
- Nearly all ammonia is currently produced using fossil feedstocks
- The aim is to synthesise ammonia from hydrogen produced from the electrolysis. This currently has a small market share (<1%).
- Choice of low carbon production route is likely to be determined by local availability of energy e.g. cheap natural gas plus CCS, renewable power or sustainable biomass and ammonia transportation economics

Global Ammonia production by feedstock



IEA 2012

Production technologies



*DAC = Direct air capture / PSC = Point source capture
#Syngas = mixture of $H_2/CO/CO_2/CH_4$

Production technologies

Haber Bosch process:

Source: thyssenkrupp

Onshore requirements

Storage and use | Ammonia

Storage

- Existing storage infrastructure widespread, many ports have existing ammonia storage facilities up to 40,000 tonnes, could form basis of a bunkering infrastructure
- 120 ports worldwide are already equipped with facilities to import or export ammonia
- Modifications would be required to use current fuel storage equipment (due to analogies with LPG).
- Ammonia is corrosive to some materials so care must be taken e.g. for piping
- >0.5% H_2O content significantly improves the safety of storing ammonia by reducing corrosion stress cracking. C-grade ammonia is 99.5% pure and suitable for use as a fuel.

Transportation

- Ammonia currently widely transported globally (via pipeline, ship, trucks and rail).
- Widespread familiarity with loading and unloading ammonia as a bulk product.

Ammonia poses safety issues; these are currently managed but should be scrutinised if its use is to be scaled up

- The safe transportation and use of ammonia in current situations brings an accumulation of safety experience, a mature international set of laws and regulations and a sophisticated support sector providing ammonia users and first responders with safety equipment, training, and education.
- Ammonia distribution is well-established and currently managed with existing standards and procedures, but considering new applications for ammonia such as marine fuel will require careful risk assessment.
- The health risks from ammonia exposure and the environmental risks arising from leaks must be closely scrutinised and all systems must be designed to minimise, and effectively eliminate, these risks.

Safety Issue	Comment
Ammonia is **toxic**; it causes irritation to humans at low concentrations and is life threatening at high concentrations.	Ammonia can be quickly and easily **detected by human smell** due to its strong odour even in low ppm quantities, far below concentrations hazardous to health meaning leaks can be quickly identified.
Ammonia is highly volatile, which enhances the risk of human contact as it will evaporate easily in the case of spills/leakages and if not well contained	Ammonia is **less dense than air** so will quickly dissipate from the scene of a spillage.
Ammonia is **toxic to aquatic life**; it is very soluble in water which must be considered if ammonia is to be distributed by ship and used to power ships	When ammonia is present in water at high enough levels, it is difficult for invertebrates and fish to sufficiently excrete the toxicant, leading to toxic build-up in internal tissues and blood, and potentially death.

Onshore requirements

Storage and use

Ammonia

Bunkering

- Bunkering can be carried out with similar infrastructure to LPG
- Loading and unloading from terminals to ammonia cargo ships is currently handled safely
- A bunkering grid could be established fast and cost efficiently by utilizing the existing storage facilities at ports
- Small gas tanker vessels could be converted to bunker barges. Cost estimates[1]: Ammonia bunker barge CAPEX = $ 15,000,000 / vessel with a capacity of 3,500 tons

[1] National Academies of Sciences, Engineering, and Medicine. 2012. Marine Highway Transport of Toxic Inhalation Hazard Materials. Washington, DC: The National Academies Press.

Onboard requirements

Storage and use — Ammonia

Storage

- On-board, storage under pressure (<17 bar) in **Type C pressurized 2,000 m^3 tanks** is preferred over refrigeration as no liquefication system is required
- Type C tanks are **flexible** installations situated on the deck and can be easily **integrated** in a consolidated design of a commercial ship.
- Larger tanks required for equivalent energy content of fossil fuels. In a type C tank under pressure, ammonia requires ~**3 times** the volume of MGO for the same energy content and the weight penalty for this is 1.8 times greater than using MGO.

Handling

- Transportation of ammonia by ship is covered by IGC Code but this does not allow for the use of ammonia as a fuel
- Double walled pipes must be used inside enclosed spaces

Onboard requirements

Storage and use

Ammonia

Propulsion

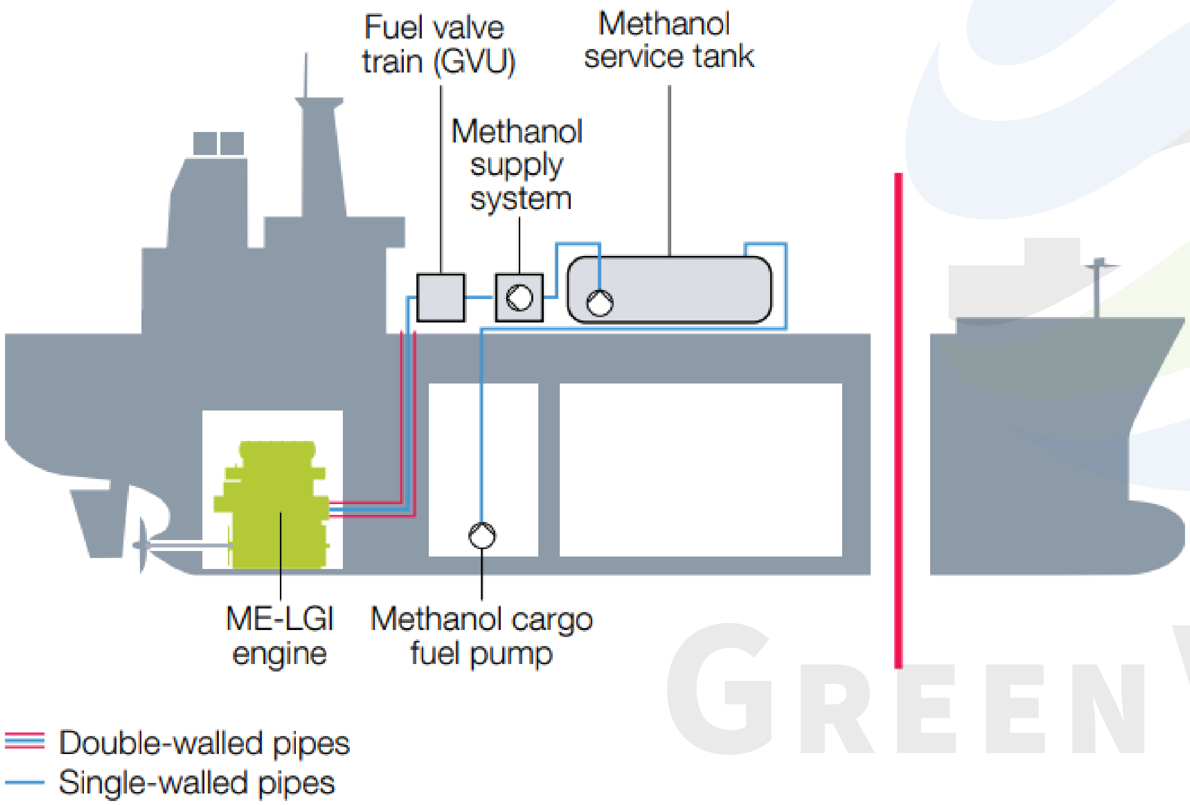
- Ammonia can be used in diesel **combustion engines** with modifications
- **Dual-fuel models** are common; diesel, kerosene, MGO or ~5% cetane is added to NH_3 to start combustion or NH_3 is partially cracked producing a 70:30 NH_3:H_2 blend
- NH_3 or NH_3/H_2 blends can be burnt in a **gas turbine** and may have higher efficiencies
- Fuel cells can either use **NH_3 directly (SOFC)** or H_2 cracked from NH_3 (alkaline or PEM FC)
- PEM fuel cells are **irreparably degraded** by >0.1ppm of NH_3 in the H_2 gas stream which creates challenges for PEM FC applications.
- Direct ammonia fuel cells under development but currently very low power density.
- Hydrogen release from ammonia (cracking) for use in an ICE or fuel cell is **less advanced**

Ammonia propulsion options

Option	Existing fossil engine retrofit conversion	Ammonia-ready combustion engine	Fuel cell (e.g solid oxide/alkaline)
Readiness	TRL 6	TRL 6	TRL 3-4
Capital cost (including required changes to ancillary onboard systems e.g. fuel supply)	Highly project specific	Highly project specific ~5 million Euros [1]	Will be highly project and technology specific
Efficiency (at shaft)	30-40%	Not yet available	Fuel cell specific

[1] https://nh3fuelassociation.org/wp-content/uploads/2018/12/0900-Ammonia_vision-Rene-Sejer-Laursen-MAN.pdf

Ammonia engines



Methanol Fuel System Configuration, MAN

Source: Enerkem, via Methanol Institute Renewable Methanol Report, 2018.

ME-LGI two-stroke dual-fuel engine

- Diagram shown is for methanol but this engine can run on ammonia as well as methanol/LNG/biofuels
- The same systems can be used for NH_3 as for LPG but double walled gas piping is required.

MAN B&W ME-LGI Engine and Fuel Supply System

Regulations, standards and guidance

Body/ Organisation	Documentation	Status/Comment
IMO	IGF Code	• Ammonia is precluded from use as a fuel under current safety regulation and there is no recognized fuel standard common across all the regulated industries • The AEA Fuel Standard Committee has developed a draft product specification to facilitate the acceptance of NH_3 as a fuel. • Lloyds register has approval in principle for a NH_3 fueled 23k TEU containership and an Aframax tanker.
IMO	IGC Code	Different types of ships need different actions to set safety standards for NH_3 fuel: • Liquefied gas carriers e.g. NH_3 carriers, are subject to IGC code which covers NH_3 but does not allow for the use of toxic cargo (NH_3) as a fuel – IMO regulation needs to be amended • Other types of ship are instead subject to the IGF code and the use of ammonia as a fuel is not covered so guidelines must be set based on safety verification. • MAN ES are in the process of obtaining flag state approval to use ammonia as a marine fuel in the IGC Code
US Occupation Safety and Health Administration	NH_3 exposure limits	• 8-hour limit at 25 ppm and 15 minutes limit at 35 ppm. OSHA has defined the level at which persons can be exposed without suffering irreversible health effects as 300 ppm.

Examples of ammonia vessels

- **Viking Energy** is a retrofitted vessel that will run on **ammonia fuel cells** to launch in 2024. It will be built by Eidesvik and Equinor and is expected to sail solely on ammonia for 3,000 hours annually. This is part of the **ShipFC project** funded by the EU with a budget of 230 million NOK (25 million USD). One genset will be converted to a 2 MW **SOFC**. A 100 kW SOFC will first be tested on land and then upscaled with planned installation in the ship in late 2023.
- In August 2020 NYK launched projects for an NH_3 fueled tugboat and an NH_3 gas carrier.
- MAN ES have announced a project for an ammonia-fuelled 23,000 TEU ultra-large container ship and an Afromax tanker.
- ITOCHU has a (Joint Development) pilot project with ammonia as a dual fuel (with LFSO) and a JD for a ship design with ammonia fueled engine.

Viking Energy Source: Equinor

Examples of infrastructure for NH_3 as a marine fuel

ThyssenKrupp: Offshore Ammonia (concept) Source: ThyssenKrupp

Bunkering and infrastructure

- NYK have launched a project to build an NH_3 floating storage regasification barge.
- MAN ES are proposing to manufacture green NH_3 for use as marine fuel.
- Thyssenkrupp is developing the 'WattshiftR concept'. RE from offshore (floating) wind farms can be combined with electrolysis plants (to produce green H_2) fed into green NH_3 plants all situated on North Sea oil rigs. Additional storage of this green NH_3 can then be used to refuel passing marine vessels.
- There are **several pilot-scale** green NH3 production projects under development (20-60 ktpy). One of the most progressed is in the industrial hub of **NEOM** in KSA where a 4 GW green NH_3 plant will be operational by 2025 with the intention of global distribution.

Environmental impacts

	Blue ammonia	Green ammonia	Bio-ammonia
Emission reduction drivers	• CH_4 production and transport emissions • CCS efficiency	• Electricity carbon intensity • Renewable sources vs. grid	• Nature of feedstock (e.g. farmed/waste)
Well-to-wake GHG emission savings Vs. HFO	**~14%[1]**	**~77%[1]**	**Highly feedstock dependent**

Key Points

- Neither combustion of ammonia nor its use in a fuel cell produces CO_2, so WtW emissions from NH_3 alone will depend on the production pathway for the NH_3 fuel being used. Fuel cells have no emissions except N_2
- However, if an ICE is used, concurrent combustion of the pilot fuel will lead to GHG emissions. The magnitude of these will depend on what pilot fuel is being used (e.g. diesel, MGO or H_2), how it was produced and to what % it is blended.
- Considering non-CO_2 impacts, ICE/gas turbines should be combined with SCR devices (to stop NO_X emissions) and metal halides (to stop NH_3 slip) in the exhaust and then would have no soot, NOx, particulate or NH_3 emissions.

[1] E4tech analysis based on IEA (2019): Excludes downstream transport and distribution and refueling. MGO pilot fuel used (17% on energy basis).

Fuel cost overview

Production route	Blue ammonia	Green ammonia
Key drivers (Expected trend: positive/negative/either)	• Natural gas price • CCS CapEx	• Green electricity cost • Electrolyser CapEx • Electrolyser utilisation
Current cost (per GJ fuel)	**16 – 27 USD***	**23 – 27 USD**
Current cost vs. HFO market price (per GJ fuel)[1]	Additional 10-15 USD[1]	Additional 17-15 USD[1]
Potential for cost reduction vs current cost	High for CCS	High for electrolysers and renewable energy

Current unabated fossil ammonia market price vs HFO market price

-50 to -200 USD

*high cost uncertainty associated with CCS technology

[1] Source: E4tech analysis

Barriers and risks

Category	Barrier / Risk	Comment
Commercial	High ammonia **production costs**, especially green but also blue	High - Excessive fuel cost is strong barrier to widespread adoption. However, significant cost reductions are expected across production pathways and policy action may make economics more favourable.
	Cost of engine **replacement/conversion**.	Medium - Increasing development of ammonia engines/replacements
	Low **volumetric energy density** leads to large tank volume requirements (in fixed shape containers)	Medium - Loss of cargo/passenger space has varying degree of concern depending on the intended application of the vessel
	Currently **no bunkering infrastructure**	Medium/low – in short-term this is a large barrier to commercial operation but ammonia bunkering could develop quickly utilising current ammonia infrastructure at ports

Barriers and risks

Category	Barrier / Risk	Comment
Policy	Lack of **regulations** for bunkering and storage onboard and offboard	High – Ammonia as fuel is not included in the IGF Code, bunkering procedures, storage and fuel cell standards need identifying.
Sustainability	Variable **sustainability impacts** of biomass and waste feedstocks	Medium – Important to have agreed sustainability criteria for fuel value chains
	Dominance of **fossil fuels** in hydrogen production for ammonia	High – Ammonia is almost entirely supplied from natural gas and coal today, which would not meet reduction targets
Technical	**Industrialization and scale up** of electrolyser and fuel cell components	Medium - Lifetime of stacks and reformer units need to be proven
	Challenge of low ignition temperature range for combustion engines	Medium – Ammonia internal combustion engines are a very active area of development
	Minimization of NO_x and N_2O emissions	Medium – needs to be managed with development of internal combustion engines to reach NOx regulations and minimize the negative effect that nitrous oxide emissions would have on emission savings

Ammonia summary

Key points

- Ammonia is currently widely handled as cargo substance with recognised regulations and guidelines, but as yet limited deployment as marine fuel
- Onshore infrastructure and equipment for storage and transportation of ammonia is well understood but would need scaling up and extended to new locations
- Bunkering infrastructure for ships and its regulation does not currently exist
- Safety is a barrier and hazards need to be mitigated appropriately
- Production routes use generally well understood processes.
- Decarbonisation success will depend on electrolysis from renewable electricity (green H_2) and CCS (blue H_2)
- Ammonia internal combustion engines are in development by the major maritime engine manufacturers but are not yet commercially available
- Fuel cell technology and cracking of ammonia to produce hydrogen needs further research and development