CAIPIRINH3A

COMBUSTION OF LIQUID AMMONIA, ASSISTED BY PLASMA DISCHARGES, AS A NOVEL AND CLEAN ENERGY CONVERSION METHOD

Funded by the European Union

Clean Hydrogen Partnership

Green Ammonia Energy
Intensified production, conversion and separation

Ammonia in Shipping: The Facts beyond the Hype

George Skevis
CLEOS

Maritime Energy Transition

Energy Transition/Decarbonization in the shipping industry is **driven by regulation** which translates into **policy** and dictates the **technology mix**

+ Cargo owners are increasingly demanding greener shipping options (key role of shipping as world trade enabler)

+ Financial institutions have increased their focus on green activities and aim to reduce their exposure to non-sustainable businesses (Green Financing, Poseidon Principles)

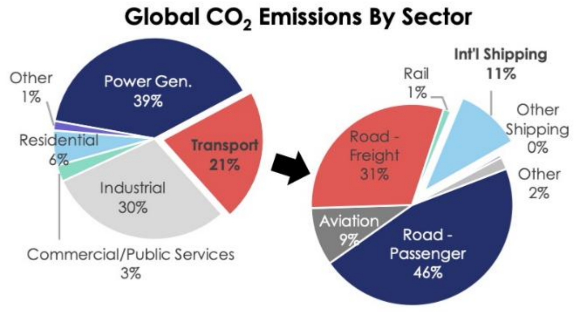
- Complexity of the regulatory landscape (FuelEU Maritime, EU ETS, IMO GFI, CII etc)

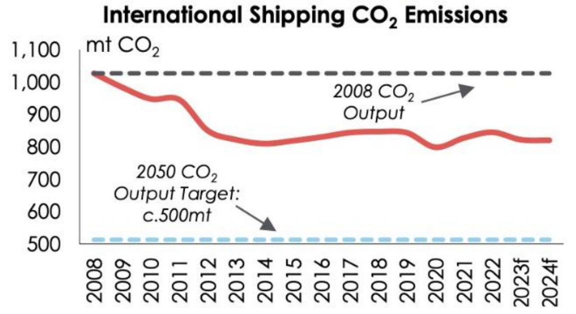
- Complexity of the technological mix, low maturity of solutions (marinization)

- Strict health and safety measures; crew training and perception

- Complexity of the industry (shipowners, operators, charterers, brokers, classification societies etc)

- Lack of on-shore infrastructure





Source : Clarksons Research, IEA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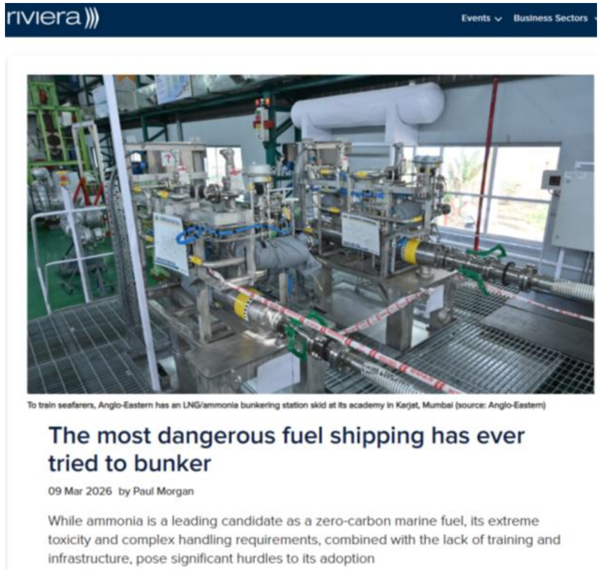
By Julian Atchison on March 15, 2026

Eidesvik signs shipyard contract

Eidesvik Offshore has signed a contract with Norwegian shipyard Halsnøy Dokk for the retrofit of the platform supply vessel *Viking Energy* to run on ammonia fuel. Prefabrication of steel and piping systems will shortly commence, and be completed later in 2026. Major structural modifications, installation and integration of a Wärtsilä 25 ammonia dual-fuel engine, ammonia tank and fuel systems, and further technical upgrades make up the retrofit, after which testing and commissioning will occur. Project Apollo partners indicate that the ship will be available for ammonia-powered operations after delivery later this year, with Equinor to charter the vessel.

Click to learn more about the retrofit of the *Viking Energy*, to be completed this year in Norway. Source: Project Apollo.

Ammonia is a very low quality, highly toxic and unsafe to handle “fuel”


riviera

Events | Business Sectors

To train seafarers, Anglo-Eastern has an LNG/ammonia bunkering station skid at its academy in Karjat, Mumbai (source: Anglo-Eastern)

The most dangerous fuel shipping has ever tried to bunker

09 Mar 2026 by Paul Morgan

While ammonia is a leading candidate as a zero-carbon marine fuel, its extreme toxicity and complex handling requirements, combined with the lack of training and infrastructure, pose significant hurdles to its adoption

so, **Why Ammonia in Shipping?**

- \+ (Can be) Carbon neutral
- \+ Commodity (grey)
- \+ World-wide distribution network
- \+ Security of supply

- \- Poor combustion and emission characteristics (new engine development)
- \- Critical health and safety issues
- \- Cost and availability (green)

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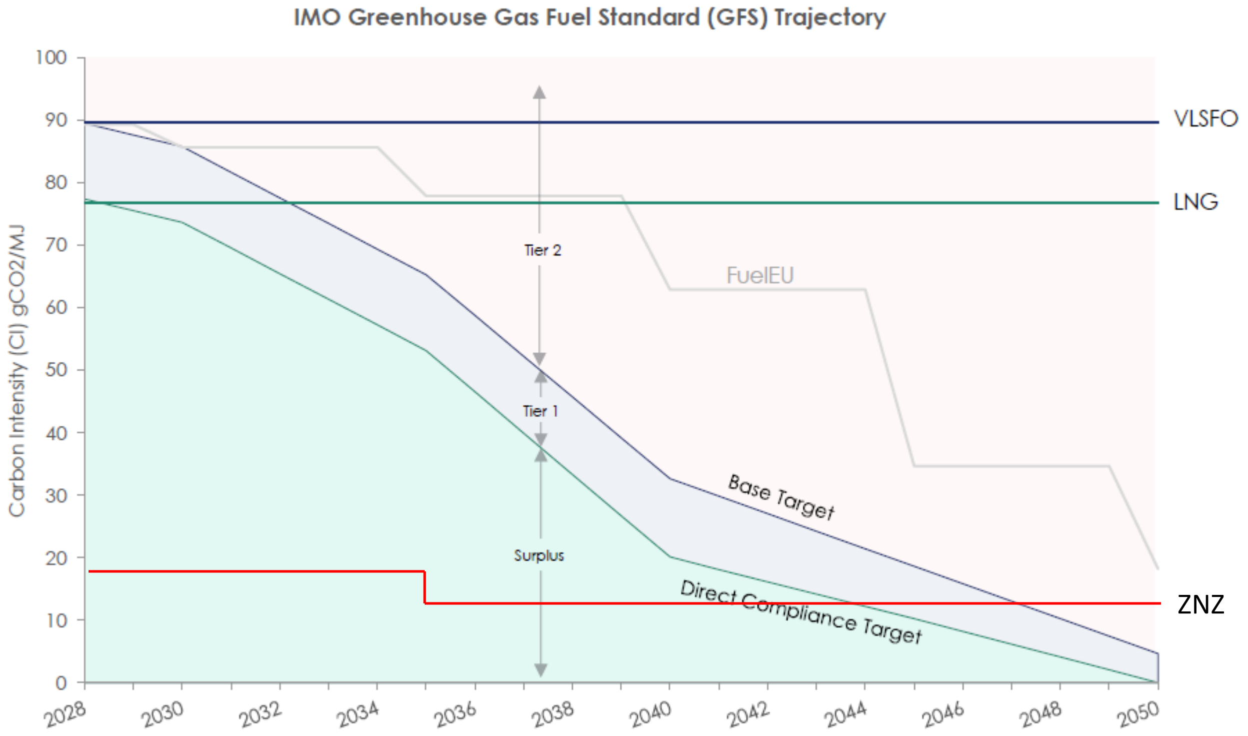
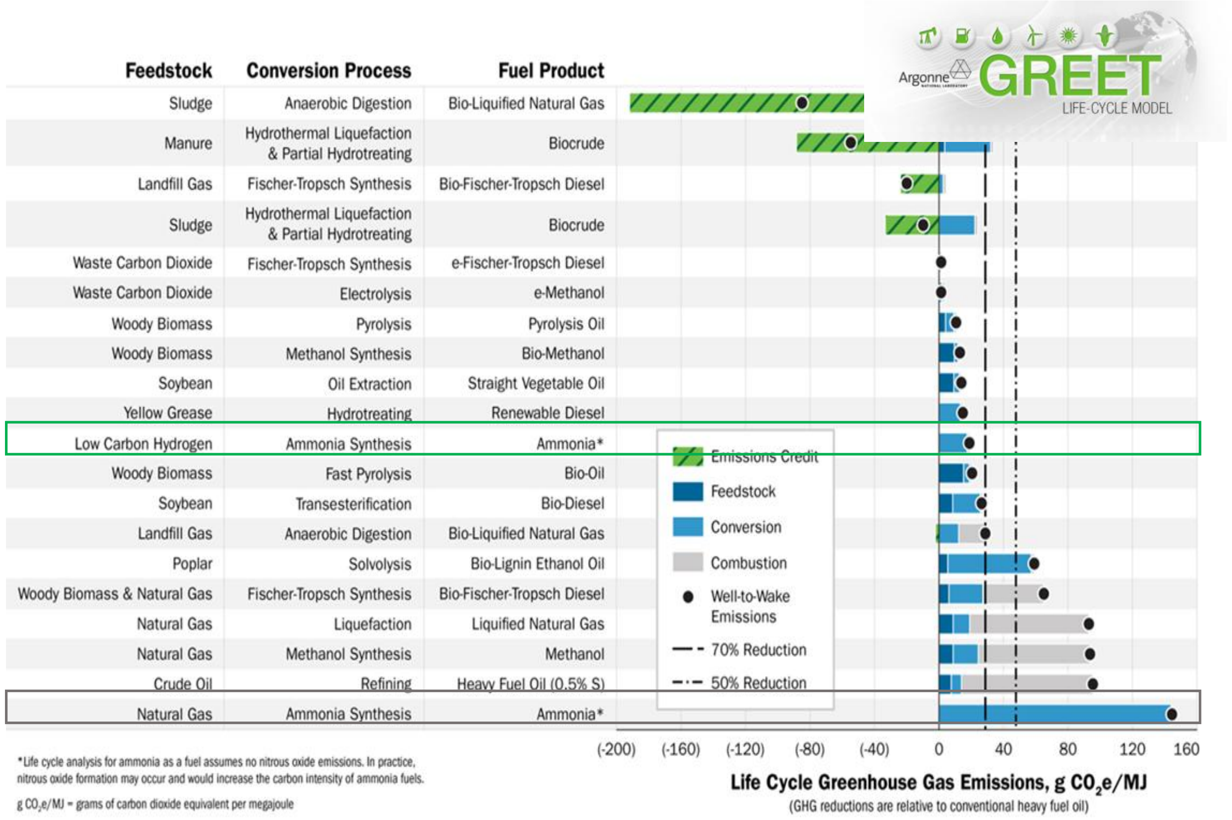
Regulatory Landscape

- FuelEU Maritime in place since 2024, IMO GFS faces strong opposition
- Vessels using ZNZ fuels are eligible for financial rewards



Source: IMO, Clarksons Green Transition Estimates



Colour	Synthesis	Carbon Intensity (gCO_2eq/MJ)
Grey	Coal gasification	135-155
Brown	Steam Methane Reforming (SMR)	105-125
Blue	SMR+CCS	25-45
Green	Renewable Electrolysis	5-15

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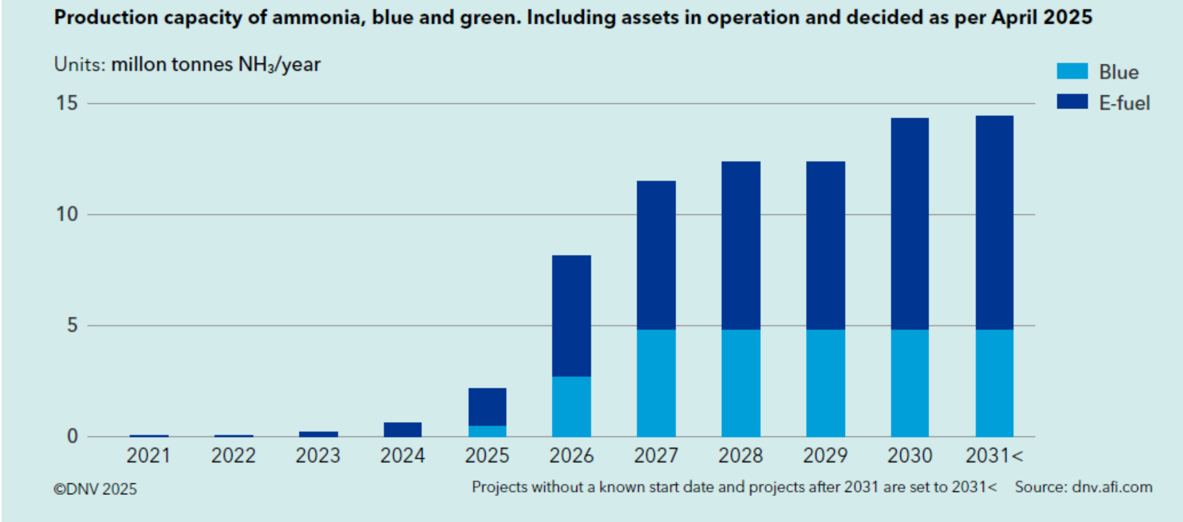
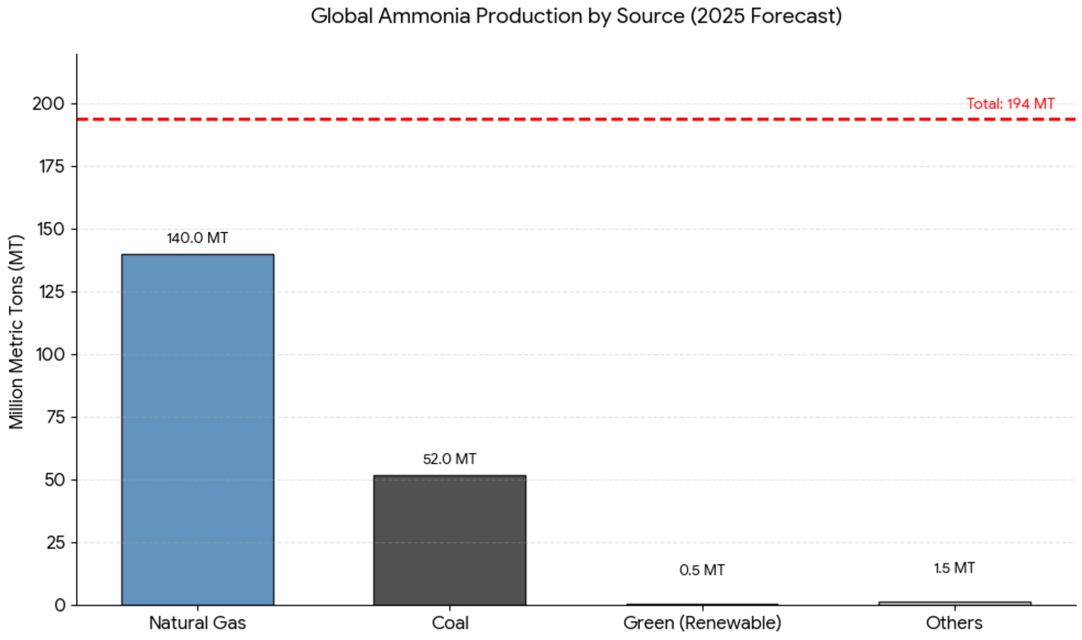
Ammonia Production

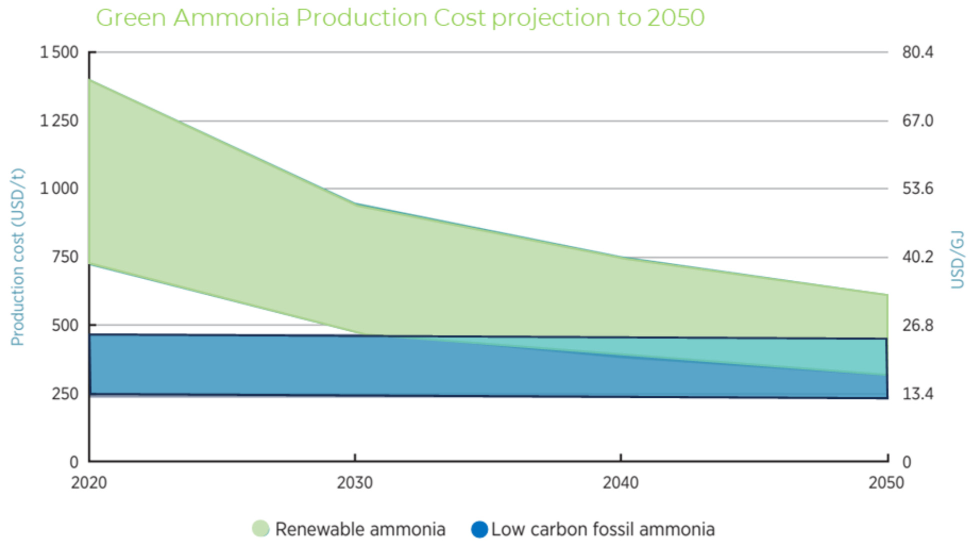
How much do we have

- Global ammonia production in 2025 exceeded 190 Mt
- Green ammonia production only 500 kt in 2025





Projected green ammonia production in 2030 barely reaches 10% of total

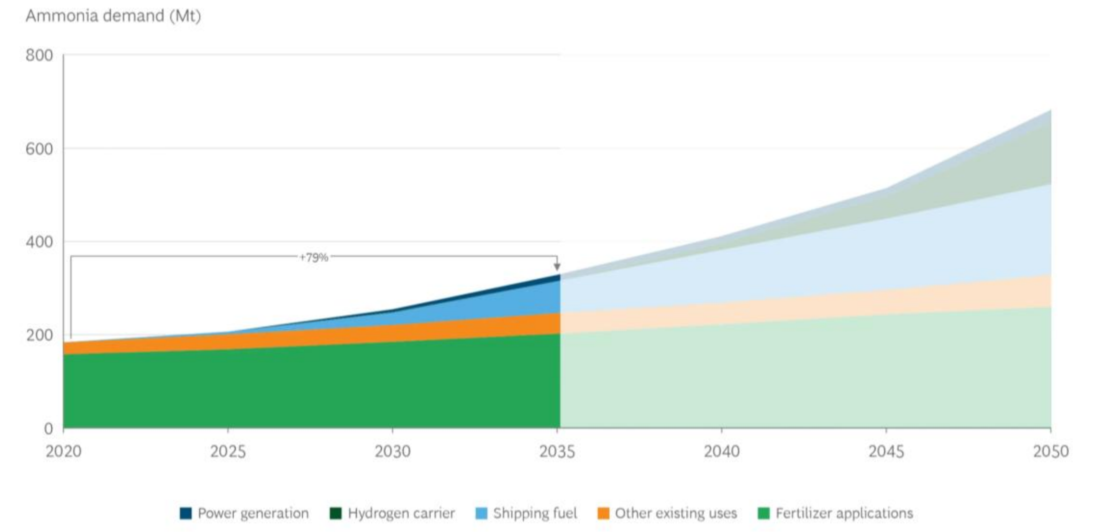


Source: IRENA 2021

Ammonia Consumption

How much do we need

- The global shipping industry consumes approx. 300 MT of HFO
- Assume that (green) ammonia covers 35% of the energy needs by 2050; this translates to 210-220 MT of green ammonia (1.2 times the current total!)



Sources: International Renewable Energy Association; BCG analysis.

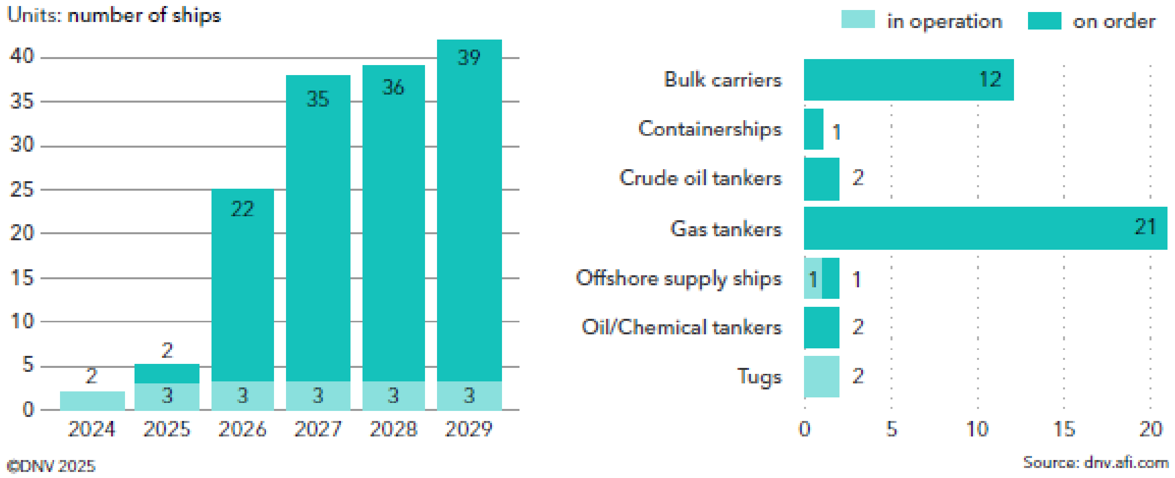
Notes: Estimates are based on the IRENA model of measures required to limit global warming to 1.5°C above preindustrial levels; power generation using ammonia is limited primarily to Japan.

Projected increase in (green) ammonia driven by the shipping sector

- ➢ 37MT of green hydrogen required for the production of 210 MT of ammonia
- ➢ Producing this amount by electrolysis would require almost 2000 TWh of renewable electricity (half EU total electricity production) and 400 million cubic metres of water
- ➢ A 400-fold increase in global green hydrogen capacity!

FIGURE 3-2

Growth of ammonia fuel uptake by number of ships (left) and by ship type (right) as per August 2025

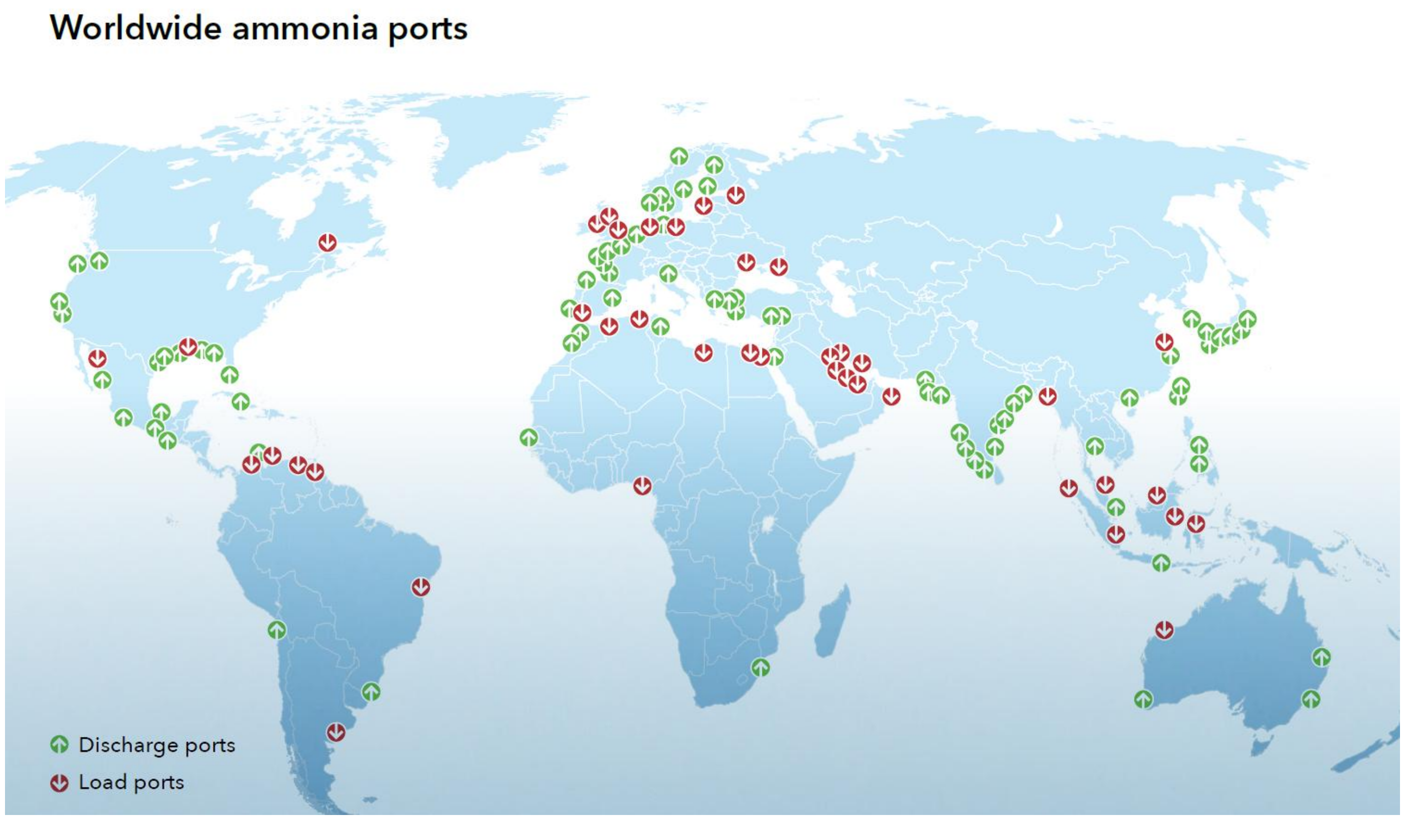


Ammonia Bunkering and Transportation

- Almost 80% of global ammonia is consumed close to production site; the remainder is mainly transported by sea
- Ammonia is typically transported via LPG carriers (similar vapor pressure) of ~ 60-80,000 m^3 capacity
- Three main ship types for NH_3 transportation:
  - **Fully Refrigerated (FR)**: Near atmospheric pressure and -33 °C (*long distance*)
  - **Semi-Refrigerated (Semi-Ref):** Moderate pressure (4-8 bar) and temperatures (-10 °C)
  - **Fully Pressurized:** Ambient temperature and high pressure (18 bar) (*up to 6,000 m^3*)

Significant experience in handling ammonia (as a cargo) at sea

Well-established ammonia trading network: enabler of ammonia bunkering



Source: DNV 2020

NH_3 as a Fuel

NH_3 Combustion Characteristics

Overall ammonia is a challenging fuel!

- Narrow flammability limits: Equivalence ratio – φ = **0.63 – 1.4** (compared to diesel: 0.8-6.5)
- High auto-ignition temperature: **930K / 656 °C** (compared to diesel: 253-284°C)
- **Low laminar flame speed: S_L~ 0.07 m/s** (compared to diesel: 0.86 m/s)
- **Adiabatic Flame Temperature = 1800 °C**(compared to diesel: 2300 °C)

For Compression Ignition (CI) Diesel engines low reactivity/autoignition resistant ammonia requires Compression Ratios (CR) of up to 35:1 for pure NH_3 ignition (technically unrealistic: typical marine two-stroke (2-S) engines operate at CR~17-22)

Need for diesel-like pilot fuel & optimized control for satisfactory engine performance

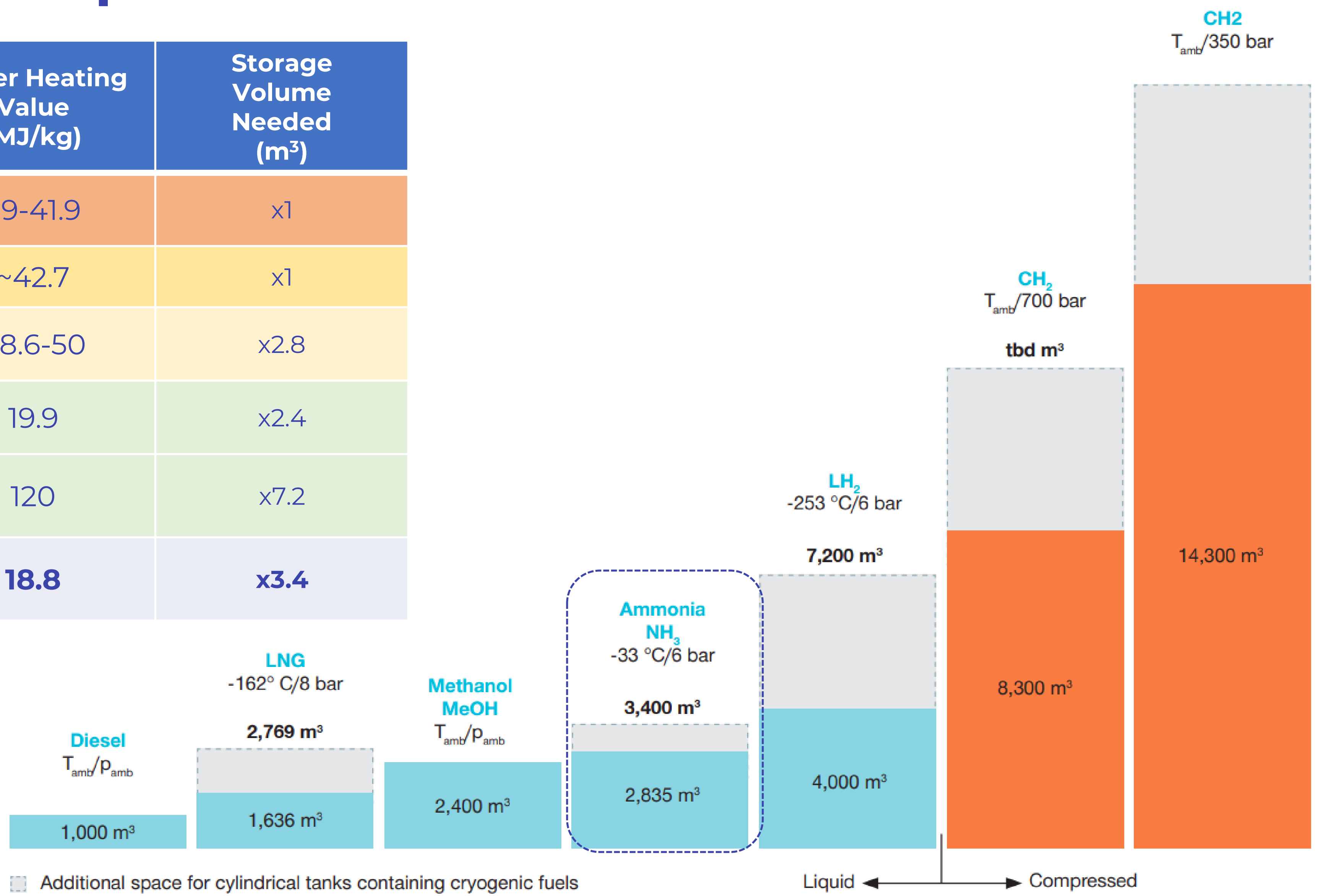
Slower combustion (low laminar flame speed); need for longer residence times in combustion chamber for complete combustion (low-speed 2-S marine engines are a suitable match)

NH_3 Combustion Characteristics

Chemical Formula	CH_3OH	NH_3	LNG	MGO	HFO
LHV (MJ/kg)	20.1	18.8	~45	42.7	40.2
Energy Density (MJ/L)	15.7	12.8	~21	38.4	39.8
Heat of Vaporization (kJ/kg)	1098	1371	~510	~275	2126
Autoignition Temperature (°C)	450	651	~650	250	250
Liquid Density (kg/m³)	798	682	~450	900	991
Cetane Number	-	-	-	~50	38
Octane Number	109	~130	~120	-	-
Boiling point (°C)	12	-33	-162	149-371	350-500
Stoichiometric air/fuel ratio	6.5:1	6.05	~17.2	14.5	14.5
Laminar Flame Speed (m/s)	0.5	0.07	0.36	0.87	0.87
Adiabatic Flame Temperature at 1 bar (°C)	1980	1800	~1920	~2330	~2330

Storage Volume Comparison

Fuel	Volumetric Energy Density (MJ/L)	Lower Heating Value (MJ/kg)	Storage Volume Needed (m^3)
HFO	~36.5	39-41.9	x1
MGO	~36.7	~42.7	x1
LNG	~21	48.6-50	x2.8
MeOH	~16	19.9	x2.4
H_2 (liquid)	~8.5	120	x7.2
NH_3 (liquid)	**~13**	**18.8**	**x3.4**



Source: MAN ES

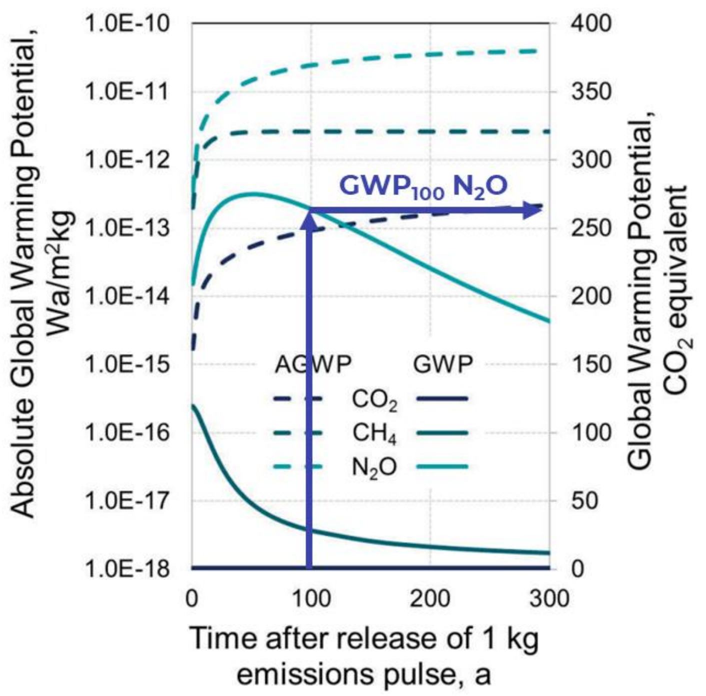
NH_3 Combustion Emissions

- **CO_2 :**Tank-to-Wake abatement (NH_3 is a non-hydrocarbon fuel)
- **N_2O:** A very potent GHG: **$GWP_{100}N_2O$ ~ 273 (**1 kg of N_2O same GH effect as ~273 kg CO_2

- **NO_x :** controversial effects of NH_3; two competing trends:

  Thermal NO_x formation is favoured by high combustion temperatures; NH_3 low adiabatic flame temperature leads to lower overall in-cylinder temperature that reduce **NO_x**

  NO_x due to fuel-bound nitrogen: NH_3 contains N-atom, reacting with O_2



Source: German Weisser, WinGD, CIMAC 2019

- **NH_3 slip:** fugitive NH_3 emissions (similar pathways to methane slip in LNG-fueled engines)
- **SO_x :** elimination (only from pilot diesel fuel)
- **PM:** elimination (only from pilot diesel fuel)

NH_3-fueled Ships

NH_3 Marine Engines
Overview

First commercial dual-fuel ammonia 2-S & 4-S engines have appeared on the market. First on-board (commercial) installations

Key projects

(1) World first ammonia-fueled vessel for commercial use (August 2024): Tug-boat *Sakigake* retrofitted with a 4-S dual fuel engine (IHI)

(2) Wärtsilä AmmoniaPac expected to be installed in *Viking Energy* platform-support vessel (PSV) late 2026

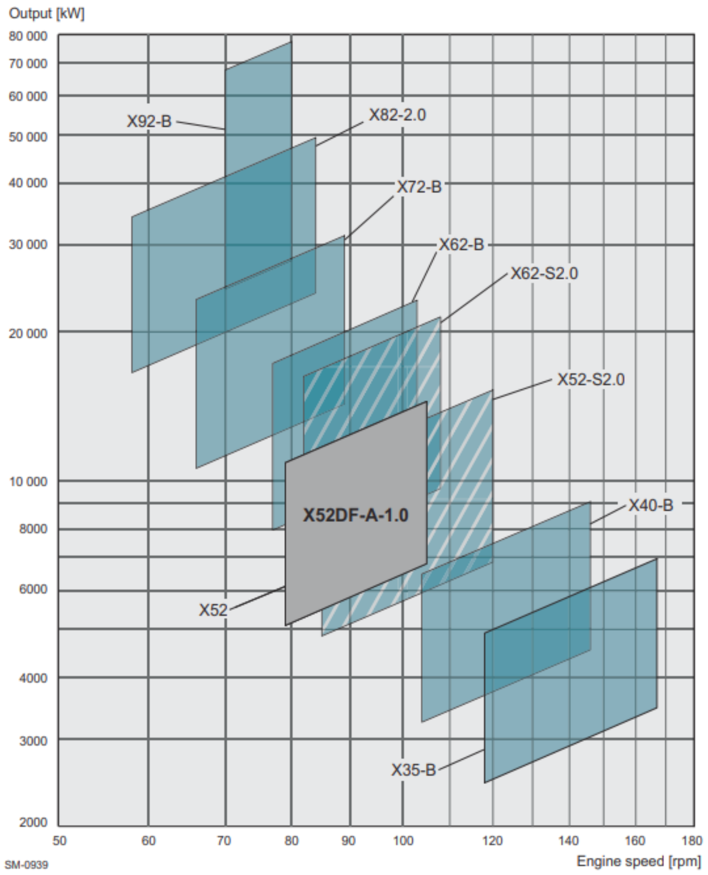
(3) The first Everllence ME-LGIA commercial engine is scheduled for delivery in Q1 2026

(4) WinGD has delivered and installed the world's first ammonia-fueled two-stroke engine (the X52-DF-A) on a 46,000m³ LPG/ammonia carrier for EXMAR. Commercial service expected to commence late 2026.

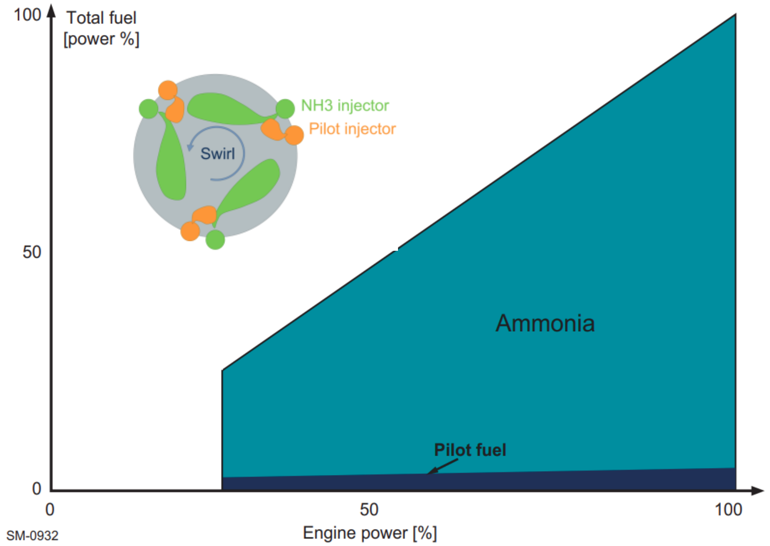
NH_3 2-Stroke Marine Engines

WinGD X-DF-A

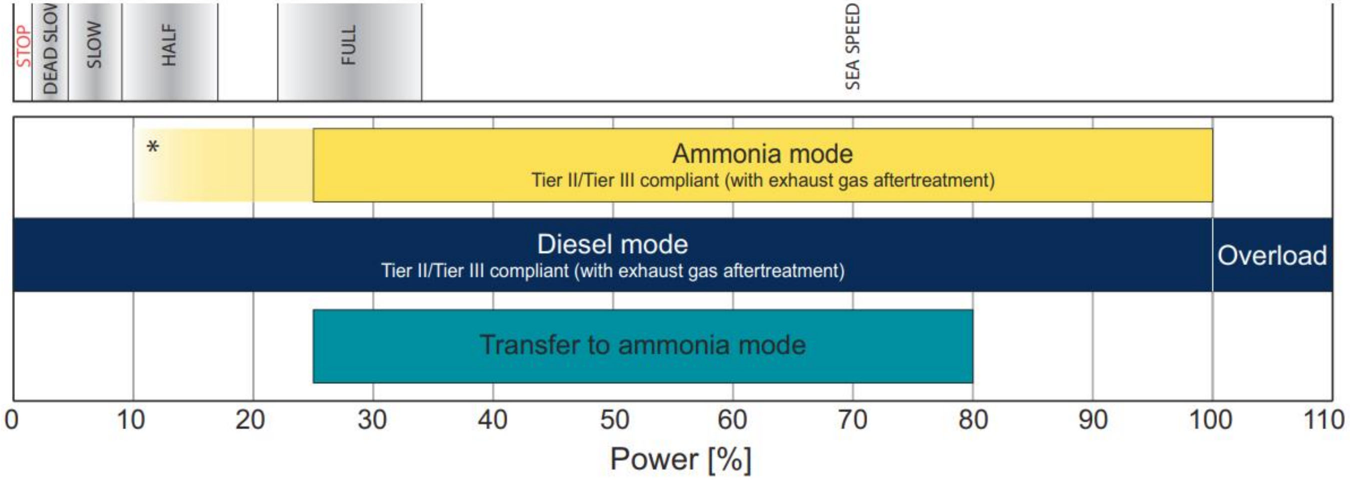
WinGD Winterthur Gas & Diesel



Engine operates in a **high pressure dual-fuel mode:** Fuel injected directly into compressed air and ignited by pilot. Stable combustion, low ammonia slip, challenges in handling high pressure.



Ammonia mode	5% MGO/MDO pilot fuel 95% ammonia
Diesel mode	100% MGO/MDO/HFO



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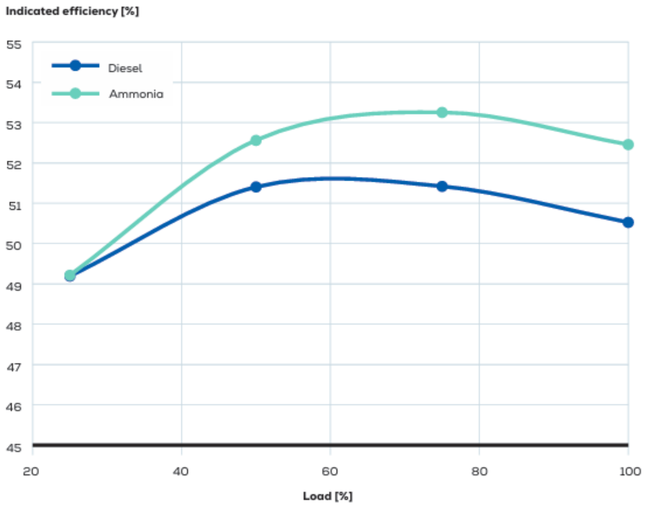
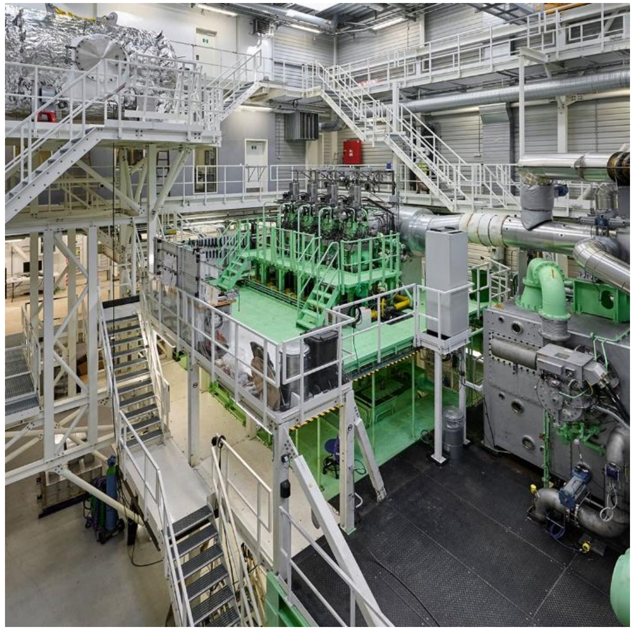
NH_3 2-S Marine Engines

Everllence (MAN) B&W ME-LGIA



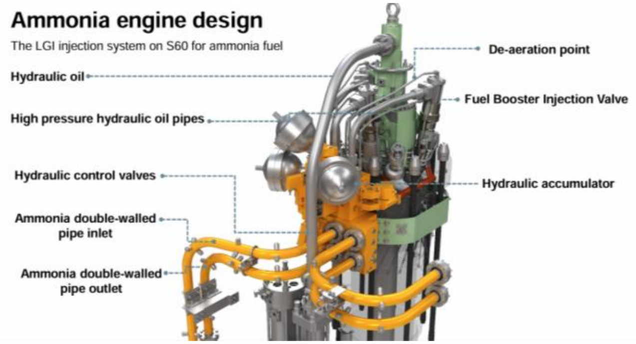
Engine operates in the same **high pressure dual-fuel mode principle** as the WinGD X-DF-A engine. Higher reported thermal efficiencies in ammonia (vs diesel) mode.



Key differences with X-DF-A

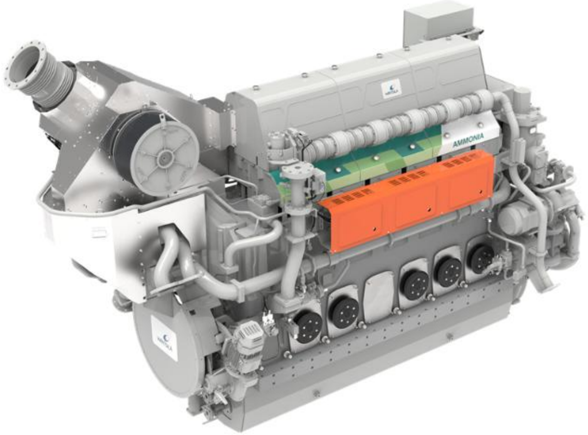
(1) A FBIV-A using a unit injector, combining a booster pump and injection valve on the cylinder head. The X-DF-A engine decouples the Actuation Control Unit (ACU) from the injection valve

(2) ME-LGIA uses fugitive NH_3 as a reducing agent in SCR; X-DF-A primarily uses iCER (intelligent Control by Exhaust Recycling) to optimize combustion



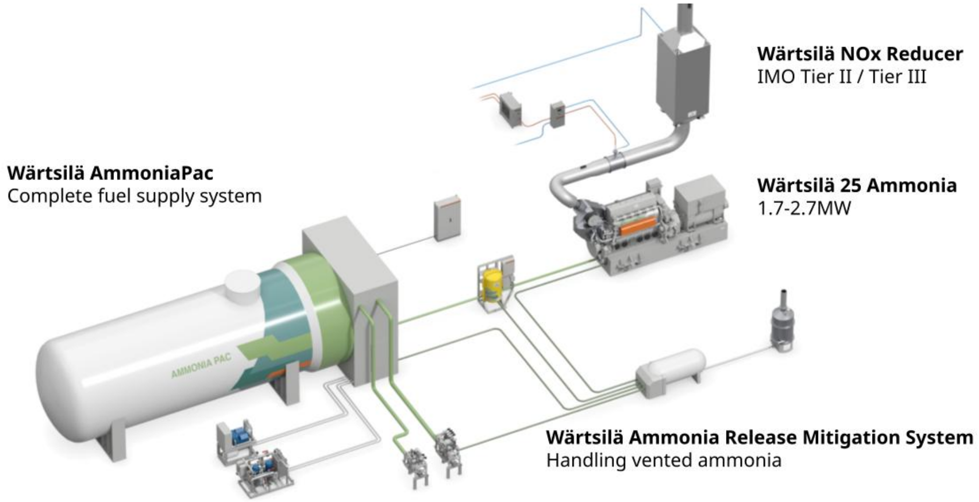
NH_3 4-S Marine Engines

- Wärtsilä has introduced (2023) the marine sector's **first commercially available** 4-stroke engine-based solution for ammonia fuel
- The design is based on Wärtsilä 25DF engine platform; released in 2022 as diesel-LNG dual-fuel engine package
- Integrated in the so-called Wärtsilä AmmoniaPac including Wärtsilä NOR (SCR) for NOx and Wärtsilä WARMS (catalytic system) for ammonia slip



Technical details

(1) Output power: 1.7-3.4 kW
(2) Thermal efficiency: up to 42.5%
(3) Diesel pilot fuel 5% at 100% load up to 9% at 25% load
(4) Ammonia slip can exceed limits without after-treatment



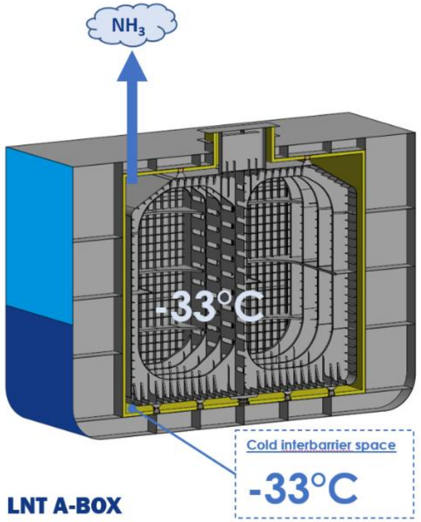
Ammonia On-board Safety, Handling & Emissions

Storage: Ammonia can be stored at moderate conditions compared to LNG and LH2 (reduced energy requirement and complexity)

Guidelines and procedures established for *ammonia as a cargo (aqueous ammonia < 28% concentration*) – not as a *bunker fuel (anhydrous ammonia >99% purity).* IMO recognized ammonia as a fuel in December 2024)

Ammonia causes stress corrosion cracking. Tanks must use low-strength steel or specialized alloys; materials with more than 5% nickel (common in LNG tanks) avoided.

Type C (Pressurized)



Prismatic (Refrigerated)

Handling: Low viscosity and high toxicity fuel; special care is needed for Fuel Supply System (FSS) optimization

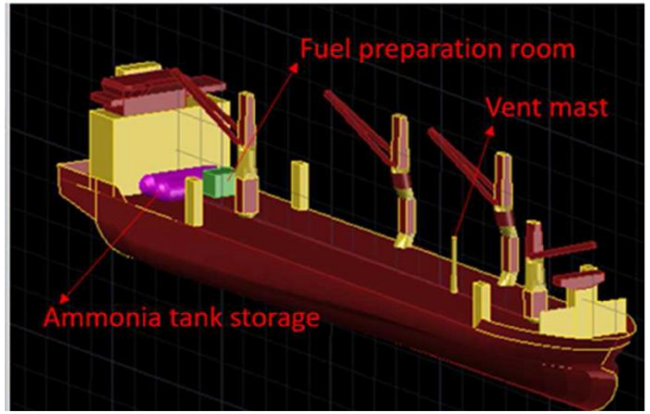
Double wall piping, specialized materials, ammonia detection systems

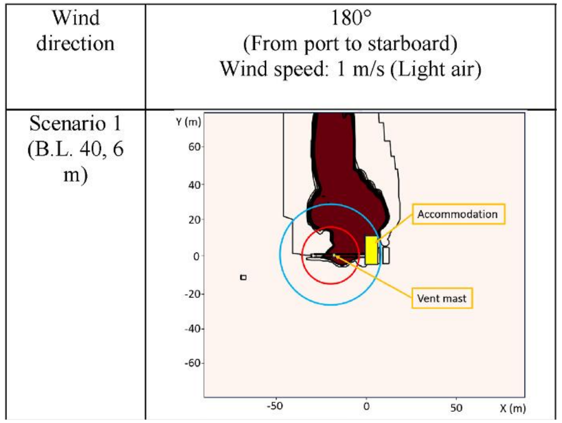
Ammonia On-board Safety, Handling & Emissions

1. **Gas vent mast:** Tank & line safety valve, catch & detox system
2. **Ventilation of double wall pipe system:** NH_3 fuel liquid and gas piping in engine room, piping from bunker station to engine room
3. **NH_3 slip from various consumers:** Main engine (ME), generator engine (GE), aux boiler, GCU, reliquefaction plant, compressor
4. **Ventilation of enclosed space:** Machinery/fuel handling system in that space or from surrounding space
5. **Instrument:** Gas detector, calorific meter, calibration gas
6. **Bunker station:** Hose connection/disconnection, quick coupler, emergency release system

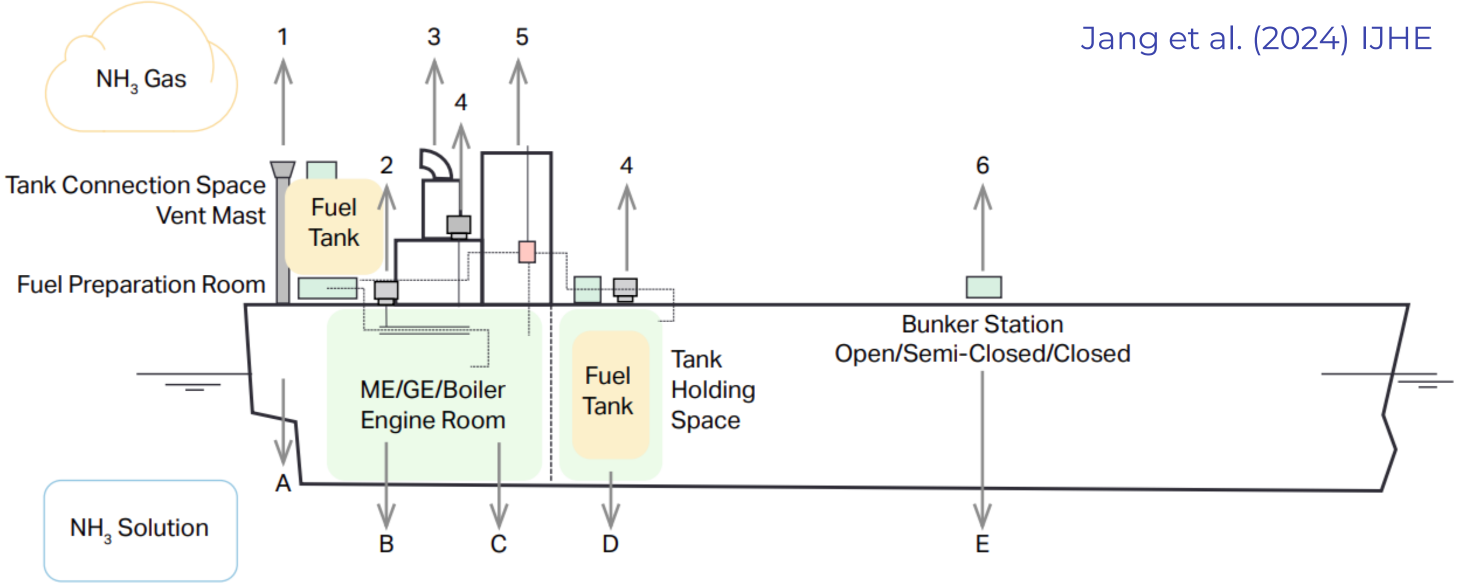
A. **Deck water spray system:** Leakages from piping system and storage tank on exposed deck
B. **NH_3 catcher and detox system:** Main engine, generator engine, aux boiler, GCU, if equipped, compressor
C. **Heat exchange fluid:** Heat exchanger (tube/plate)
D. **Enclosed space bilge system:** Leakages from independent tank, piping, stub piece, valve, plug etc. If equipped, local water sprinkler for NH_3
E. **Water curtain / spill tank system:** Leakages from bunker hose, quick coupler, emergency release system

Ammonia release dispersion studies to optimize ship design (crew safety)





Jang et al. (2024) IJHE

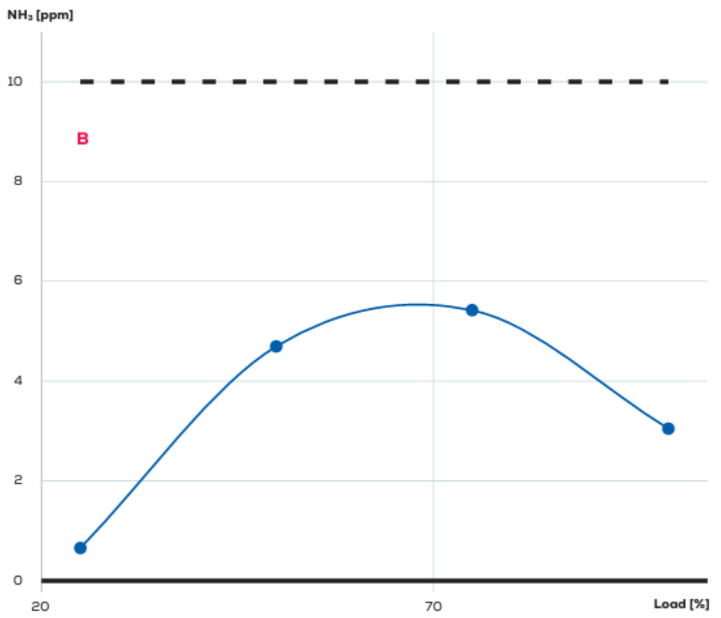


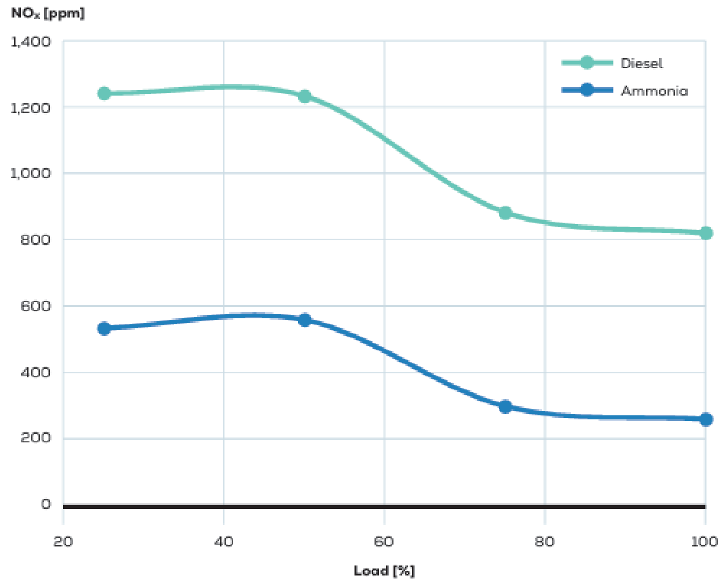
Source: MMMCZCS

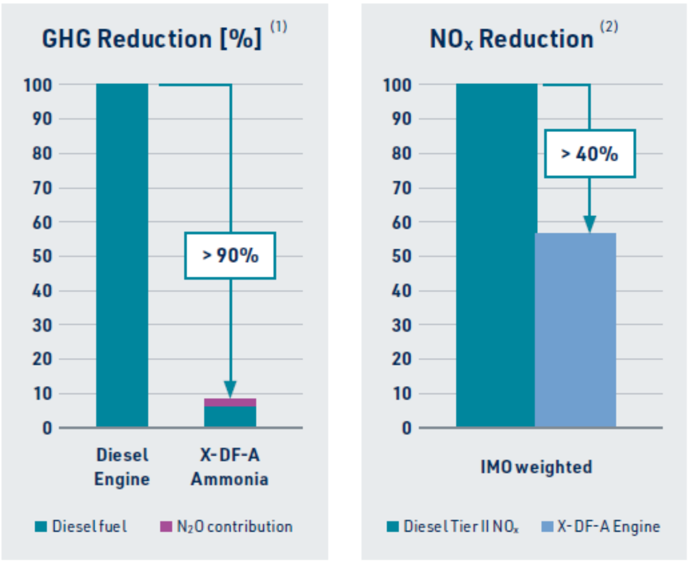
Emission Control Strategy (I)

The Maersk McKinney Møller Center for Zero Carbon Shipping (MMMCZCS) has proposed thresholds for NH_3-related emissions: **10-30 ppm for NH_3** and **0.06 g/kWh for N_2O. Tier II & III regulations apply for NO_x.**

Makers claimed performance







[1] Calculated over E3 cycle, IMO weights applied.
[2] Results are referred to Tier II values (measurements before SCR)

Everllence 7S60ME-LGIA

WinGD Winterthur Gas & Diesel X-DF-A

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Emission Control Strategy (II)

Considering a worst-case scenario: NH_3 slip and N_2O levels are above acceptable limits/not mitigated by engine design optimization; need for additional aftertreatment

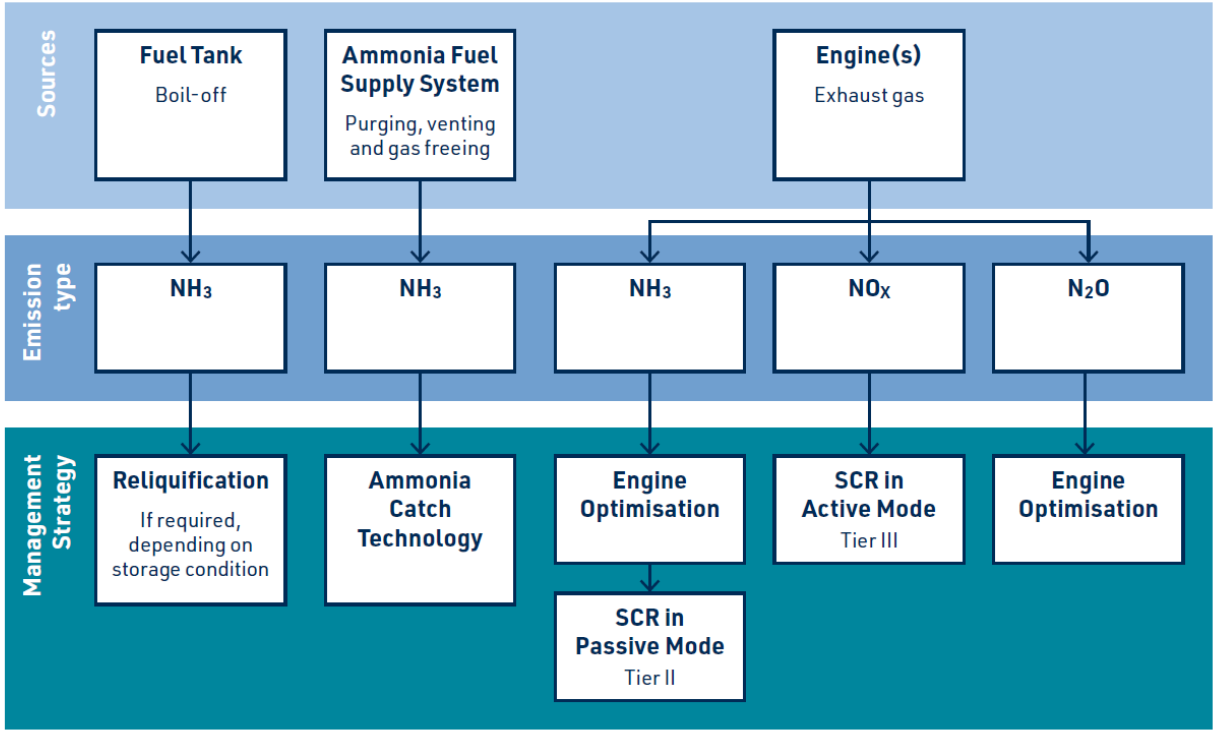
Proposed strategy considers NH_3 slip from both Fuel Supply System and engine

Proposed strategy:

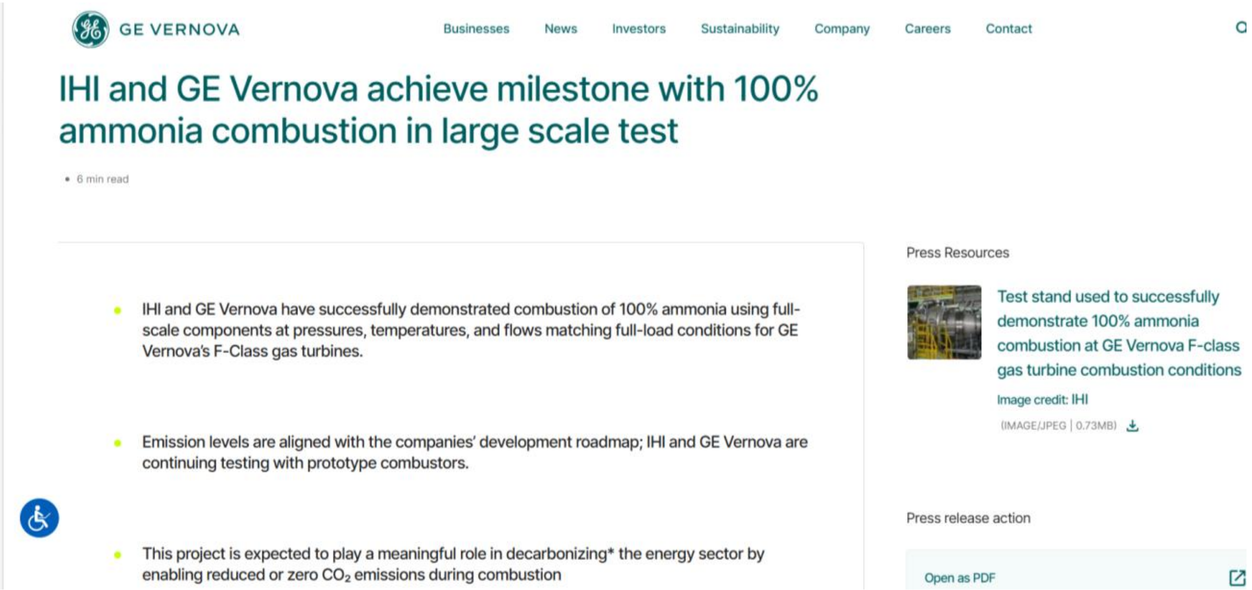
Pre-combustion (in FSS) NH_3 slip: NH_3 Boil-off Gas (BOG) management system comprising of: (i) Gas Combustion Unit (GCU)/ Boiler, (ii) Water catcher/ Chemical absorber, and (iii) Reliquefaction Plant

N_2O can be treated using a catalyst, even in a NO_x Selective Catalytic Reduction (SCR) system

Post-combustion NH_3 slip: Fugitive NH_3 in the exhaust gas can be used as a reducing agent in de-NO_x/N_2O SCR; if NH_3 is excessive for the SCR then additional Ammonia Slip Catalyst (ASC) downstream the SCR



New Technologies …


GE VERNOVA

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IHI and GE Vernova achieve milestone with 100% ammonia combustion in large scale test

• 6 min read

- IHI and GE Vernova have successfully demonstrated combustion of 100% ammonia using full-scale components at pressures, temperatures, and flows matching full-load conditions for GE Vernova's F-Class gas turbines.
- Emission levels are aligned with the companies' development roadmap; IHI and GE Vernova are continuing testing with prototype combustors.
- This project is expected to play a meaningful role in decarbonizing* the energy sector by enabling reduced or zero CO_2 emissions during combustion

Press Resources

Test stand used to successfully demonstrate 100% ammonia combustion at GE Vernova F-class gas turbine combustion conditions

Image credit: IHI

(IMAGE/JPEG | 0.73MB)

Press release action

Open as PDF

… watch this space!

09:55	"Leveraging ammonia-cracking solutions to decarbonize the maritime industry: the APOLO project", ***Markos Charsoulas***, H2Site | APOLO
10:20	"JM Davy Technologies sustainable solutions in the ammonia sector" ***Marie Genelot***, Johnson Matthey Davy Technologies | AMBHER & APOLO
10:45	**Coffee & posters**
11:15	"Low-emission Ammonia Production and Utilization in Europe", ***Kevin Rouwenhorst***, Ammonia Energy Association
11:40	"Life cycle perspectives on Ammonia based technologies representing AMBHER", ***Matilde Festi***, RINA | AMBHER
12:05	"Hydrogen Membranes for the Green Ammonia Economy" ***Camel Makhloufi***, ZEFIRA | MEASURED

Thank you!