Ammonia as a fuel for two-stroke powered vessels

MAN Energy Solutions
Future in the making

Test results after 12 months of testing

Presentation @ NTIK Hamburg e.V. – 08.10.2024

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1 Outlook of ammonia as marine fuel

2 Ammonia engine development update

3 Market introduction strategy

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Ammonia as marine fuel?

Motivation

~ 80-90 % of global freight
is transported by sea

~ 33.000

Two-stroke powered large merchant marine vessels in the world

~ 24.000

MAN B&W two-stroke engines

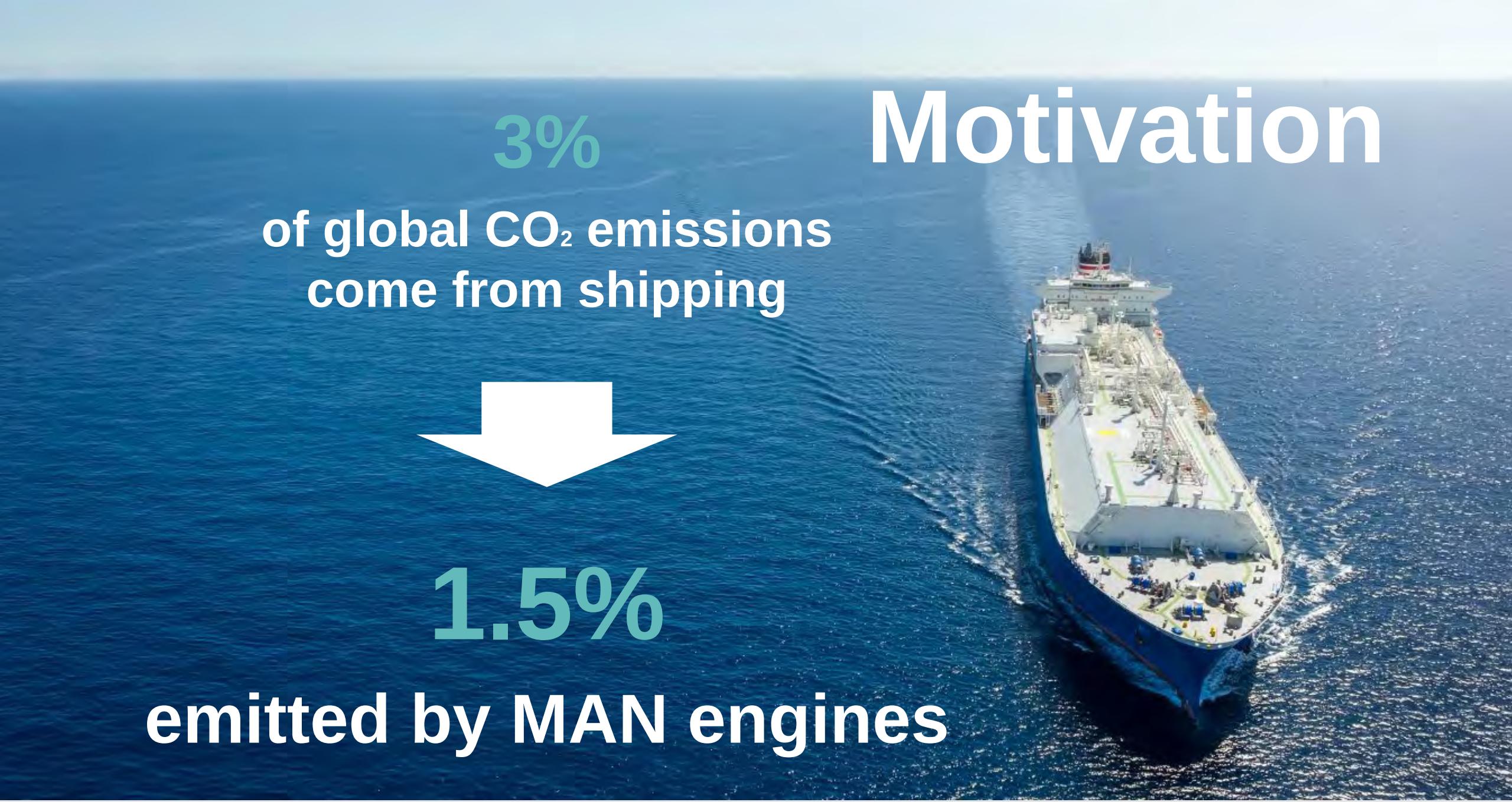
Motivation

3%

of global CO_2 emissions come from shipping

1.5%

emitted by MAN engines



Moving big things to zero

MAN Energy Solutions

with green engines on climate-friendly fuels

MAN 2 stroke Dual Fuel figures - Status quo

1440 x

2s DF engines

32,5 GW

Total DF power

64 %

2s DF in 2024 (kW)

500 x

2DF vessels in service

27 %

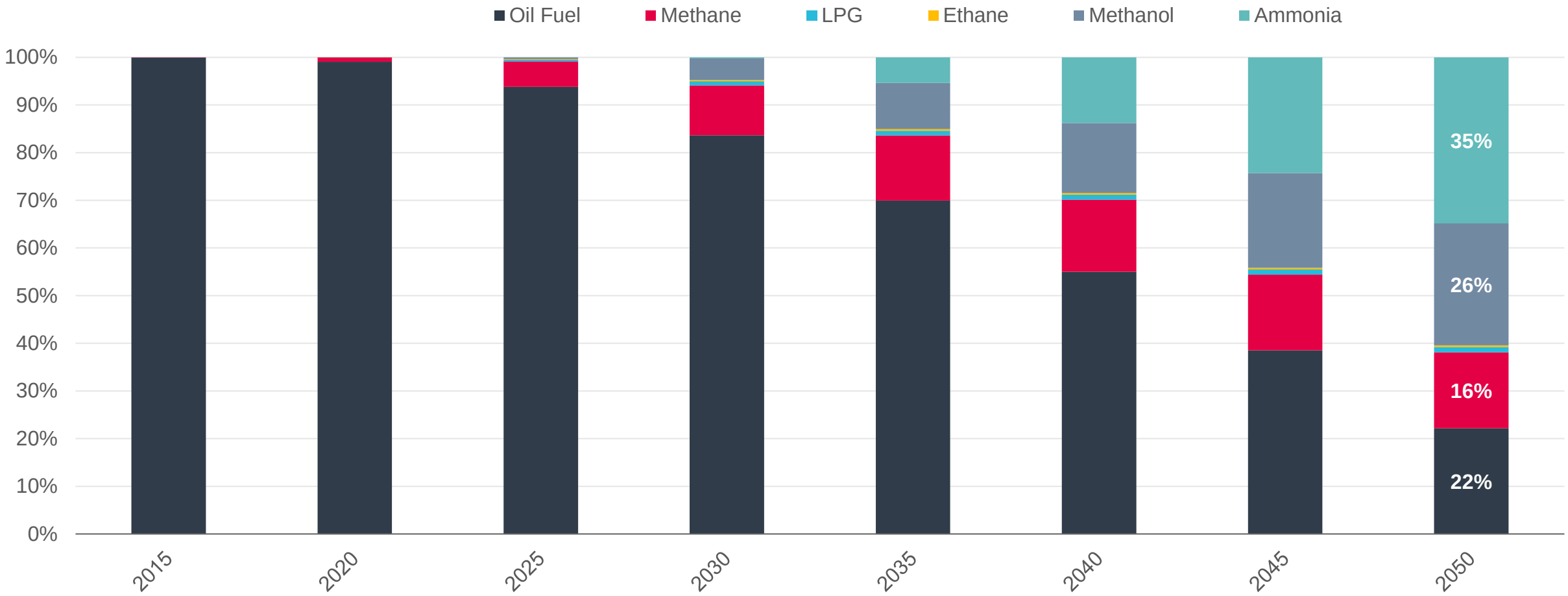
2s DF in 2024 (vessels)

Fuel Outlook

Fuel Outlook

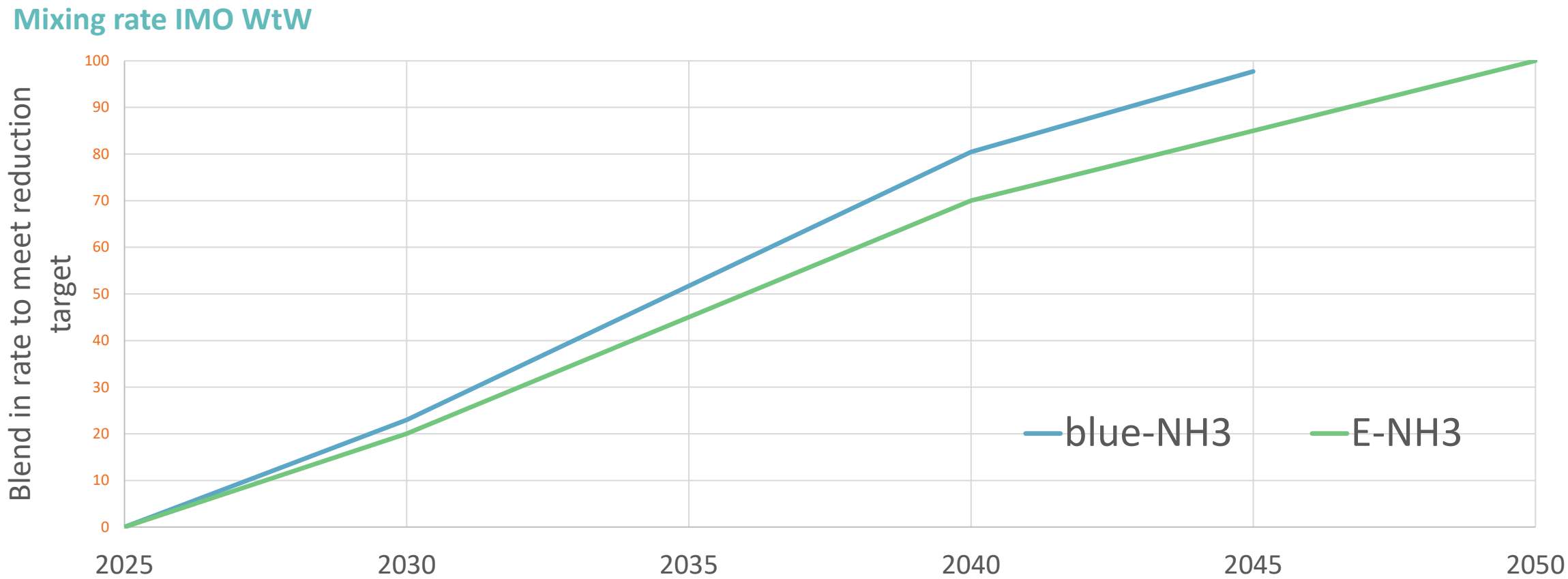
The demand for e-Fuels from shipping will be high

*After MEPC 80 scenario is Work in Progress and subject to changes



Both Blue and Green ammonia has a huge potential

Blue ammonia can be used until around 2045 (Fossile H_2)
e-Fuels are the only fuels that are truly scalable and can be used throughout and entirely from 2045 onwards

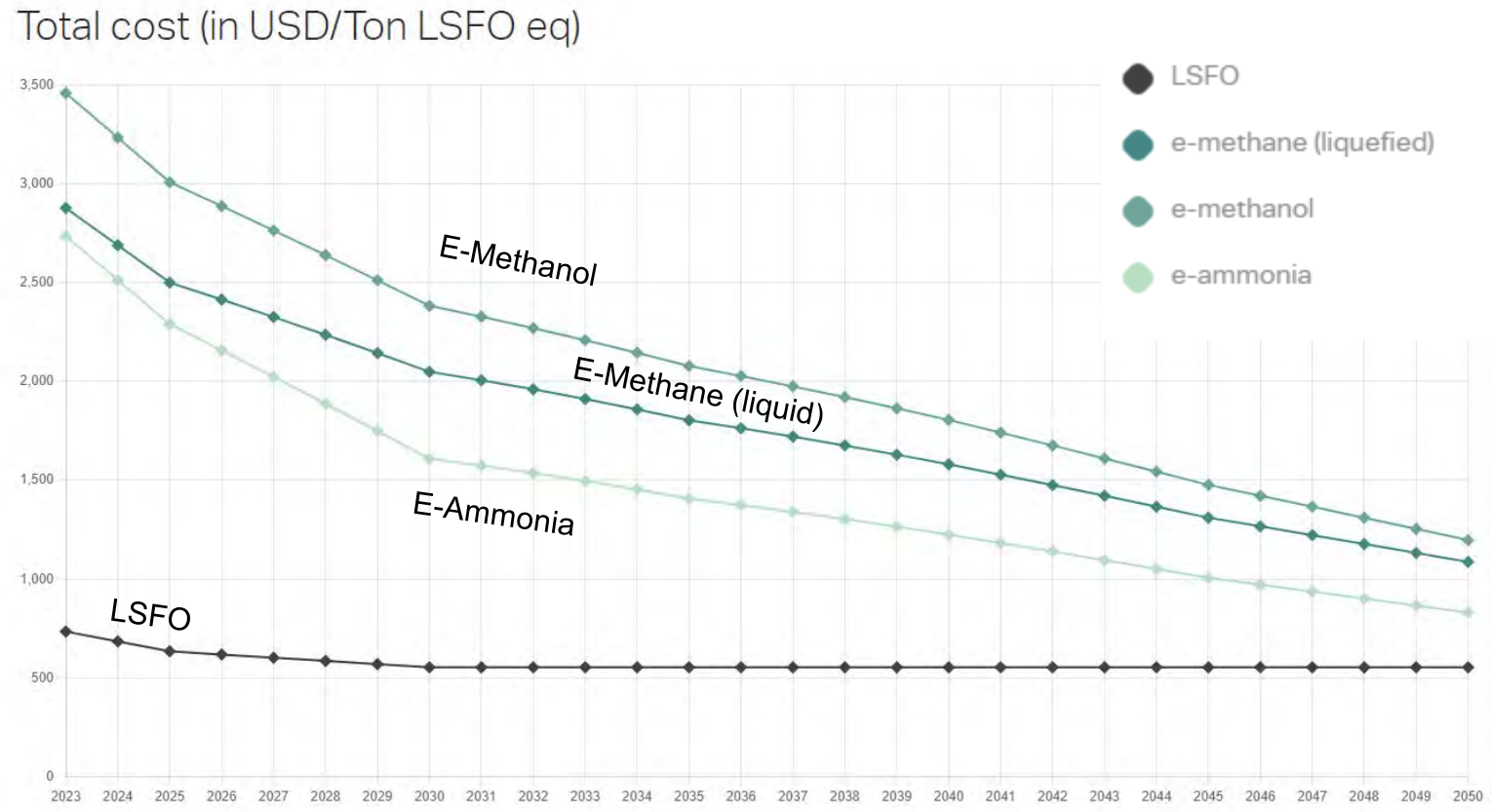


Price of e-Fuels?

It is not possible to foresee the market based prices of e-fuels, however looking into the production cost provides certain indicators.

- E-ammonia is expected to be the least costly energy dense e-fuel to produce compared to e-methanol and e-methane**.**

- E-ammonia is made from green Hydrogen and N_2, which is available in the atmosphere and cheaper to obtain than the biogenic CO_2 needed for carbon based e-Fuels.



Source: Maersk Mc-Kinney Møller Center for Zero Carbon Shipping https://www.zerocarbonshipping.com/cost-calculator/

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Unlocking the potential of ammonia as marine fuel

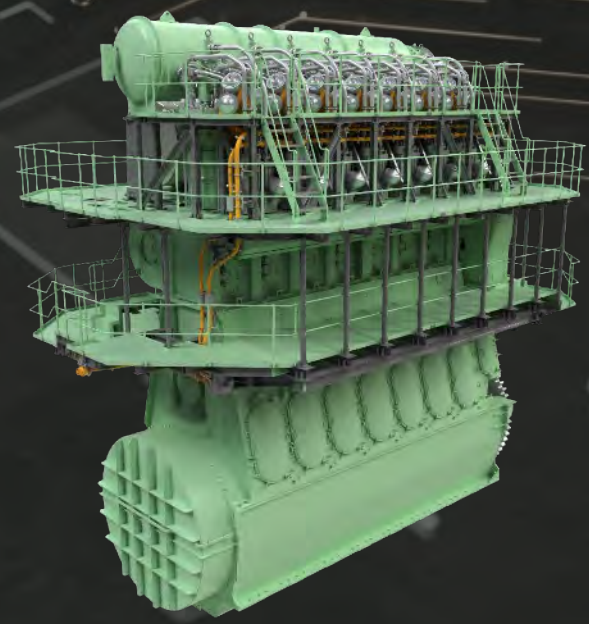
Important focus areas

Flamespeed

Auto ignition temperature

Combustion slip

N_2O



Foundation for design – HAZID & HAZOP

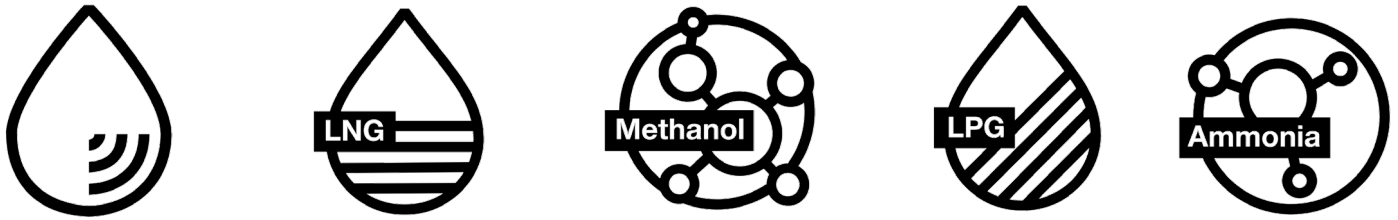
Risk assessment

- Failure Modes and Effects Analysis (FMEA) made in order to evaluate where and how components may fail and to assess the impact of different failures.
- Hazard identification (HAZID) and Hazard and Operability (HAZOP) assessments were made in order to live up to our own safety requirements.
- Experience from previous dual-fuel engine development projects.

More than 5,000 hours spent on FMEA, HAZID and HAZOP

Ammonia compared with other marine fuels

Characteristics of different fuel types

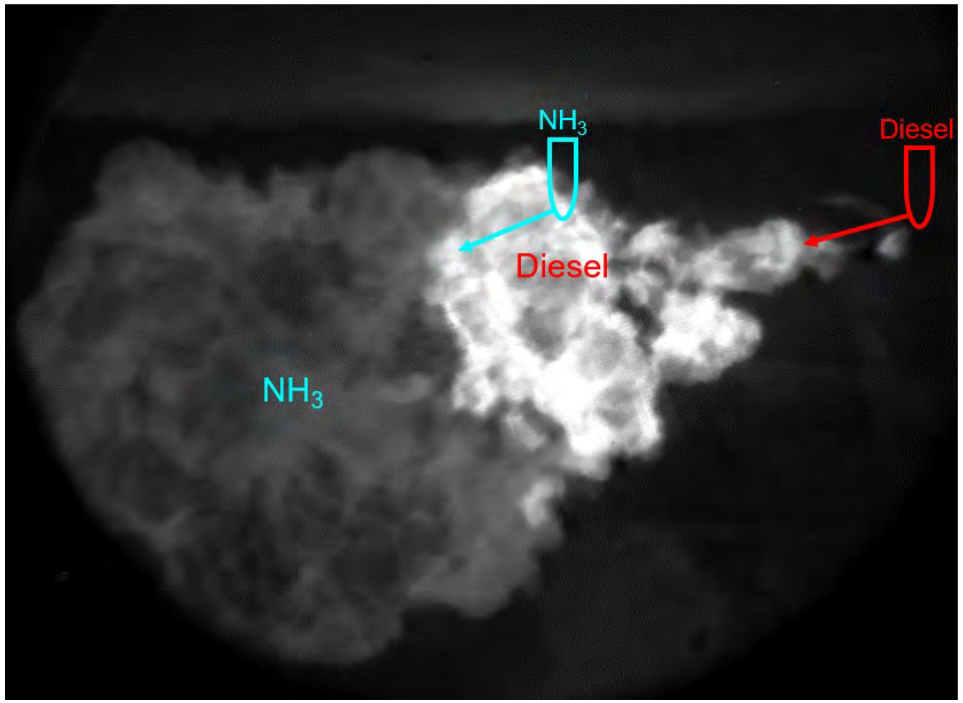


	MGO	LNG	Methanol	LPG	Ammonia
Density in liquid phase [kg/m³]	740	450	798	581	610
Lower calorific value [MJ/kg]	42.8	50.0	20.1	46.4	18.6
Autoignition temperature [°C]	260	587	470	455	**649**
Laminar flame speed [cm/s]	80	38	42	38	**7**

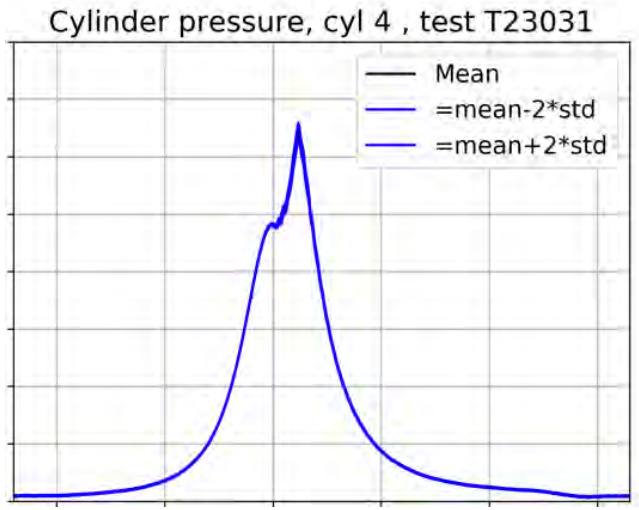
High-speed combustion camera

Part of the testing includes a high speed camera where we can precisely look into the cylinder and identify the combustion dynamics.

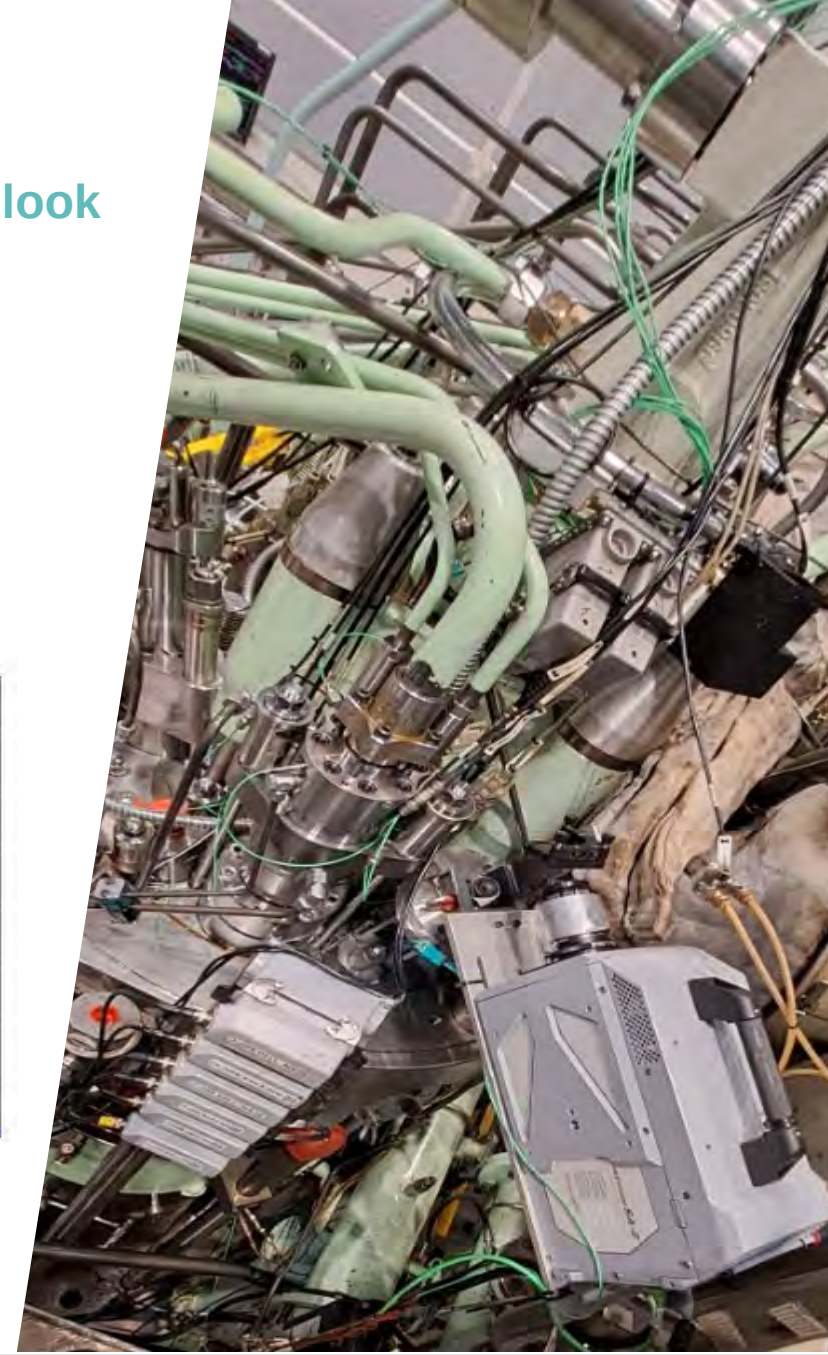
- Good visual confirmation of flame speed and ignition properties.



Installation of high-speed camera



Combustion graph

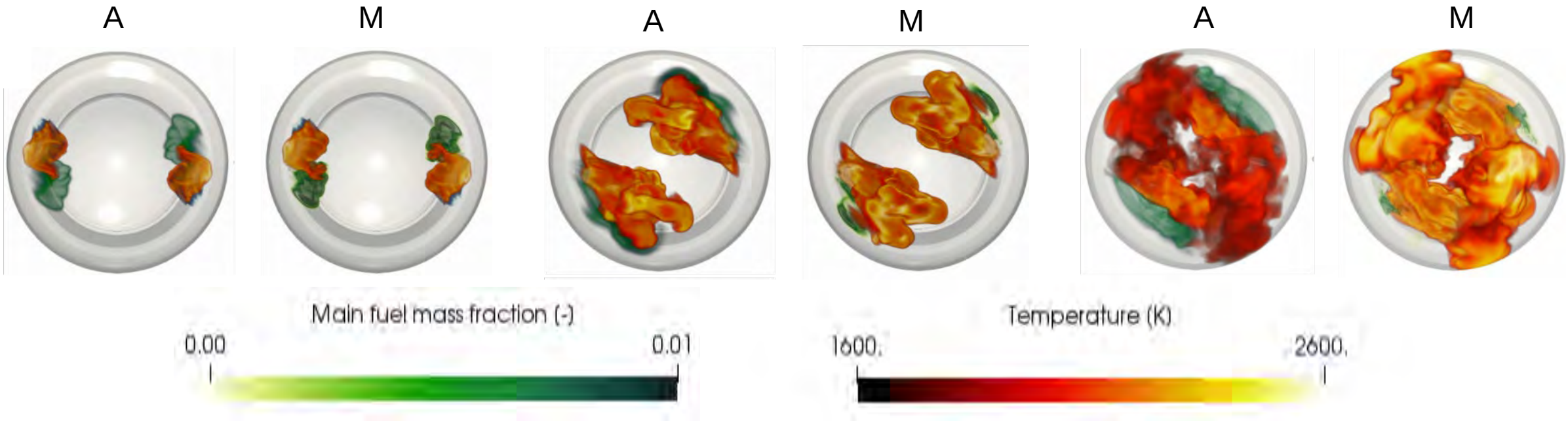


Computational Fluid Dynamics (CFD) Simulations

Comparison between ammonia and methanol combustion

Evaluation and design by CFD analysis

- Flamespeed is 6 times lower for ammonia (cm/s).
- Autoignition temperature is 33% higher for ammonia.
- Two-stroke slow speed engines however manages these properties very well.



A = Ammonia M = Methanol

Two-stroke ammonia engine combustion

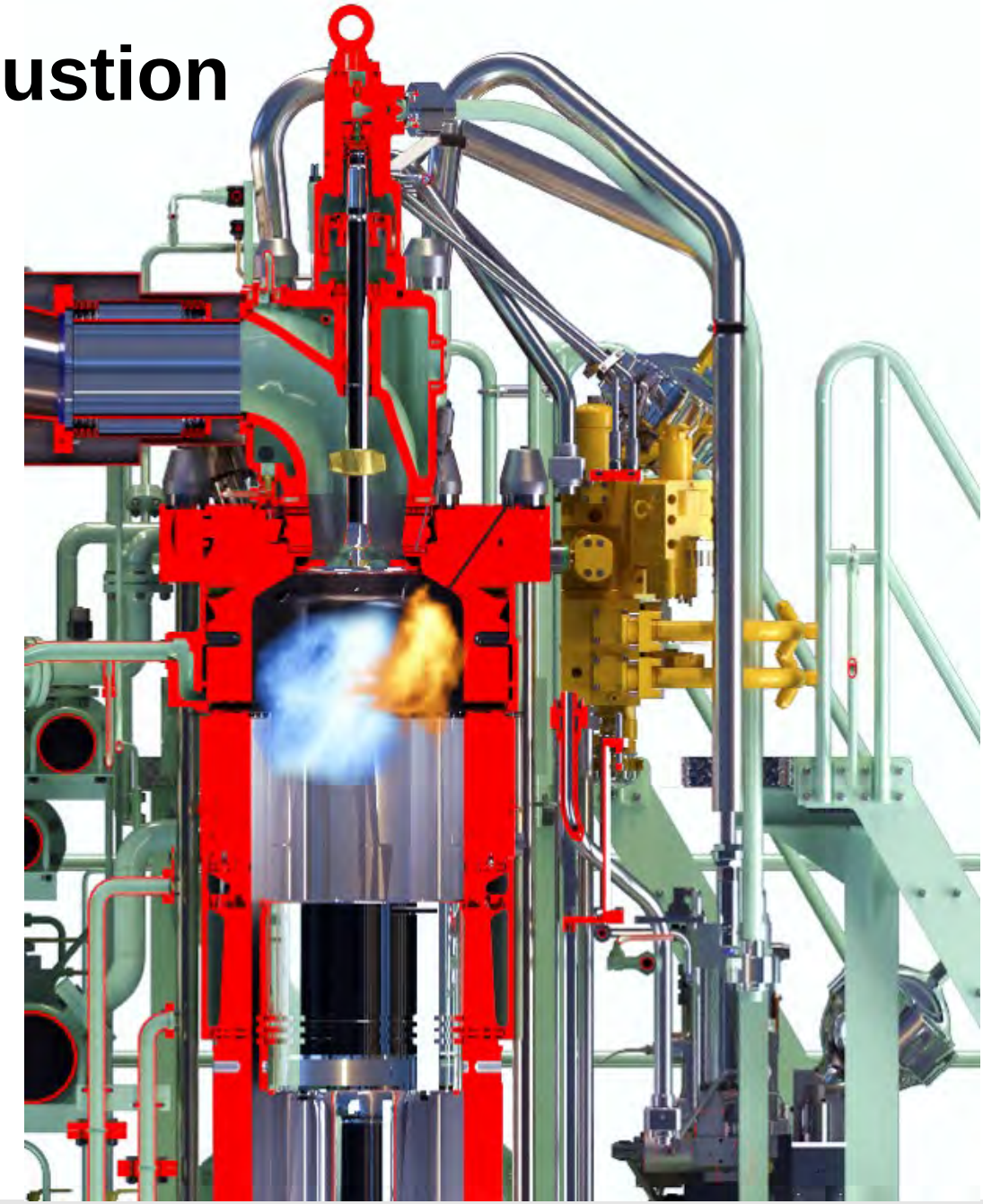
The MAN B&W ME-LGIA design philosophy

“Ammonia mode”:

- Small pilot flame needed.
- Target of 5% **S**pecific **P**ilot **O**il **C**onsumption at 100% load for L1-rated engines has been reached.
- Potential for further reductions, however 4-cylinder testing will showcase the full potential. The initial ME-LGIA engines will have 5% SPOC.
- We target to obtain same heat rate as “fuel oil mode”.

“Fuel oil mode”:

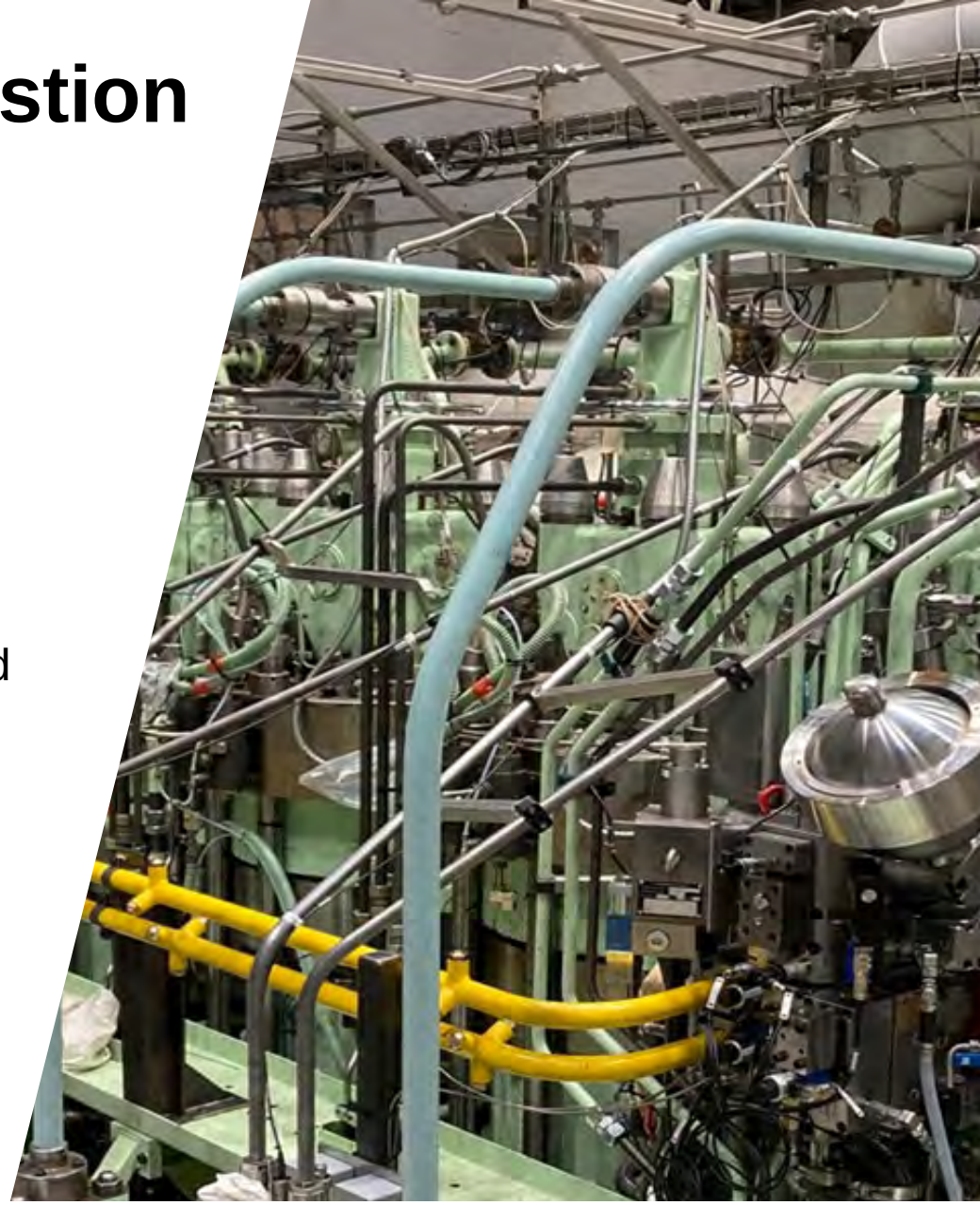
- We target identical performance as a conventionally fueled Diesel engine.



Two-stroke ammonia engine combustion

Status on the ammonia engine testing

- 3rd of July 2023: First two-stroke ammonia combustion
- Over 300+ tests completed
- 175.000+ engineering hours in total
- 5.000 hours on FMEA / HAZID / HAZOP
- Performance and emissions tests in load points from 10-100% load
- Pilot oil energy fractions similar to other LGI engines
- N_2O emissions are very low and are handled by engine tuning
- NO_x emissions approximately 40% lower than conventional fuel oil (Can be adjusted according to final engine tuning)
- Ammonia slip is minimized by design and performance modifications



4 cylinder 50-bore test engine at RCC

4X50 ME-C10.5-LGIA at RCC

4 cylinder test engine at the Research Center Copenhagen (RCC)

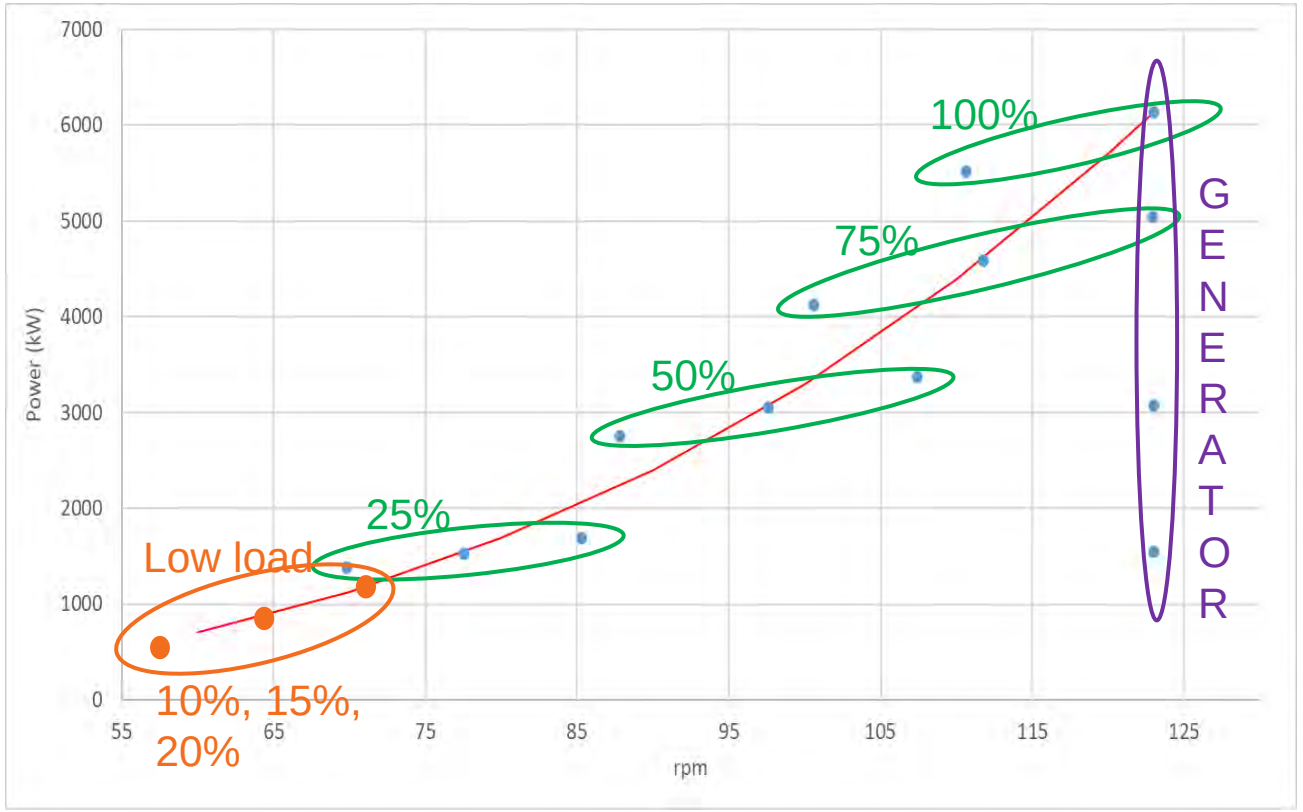
RCC engine is currently being re-build to a full-scale four-cylinder ME-LGIA engine.

Expected re-start of testing sometime in October.

M/E tests at both light & heavy running and generator curve

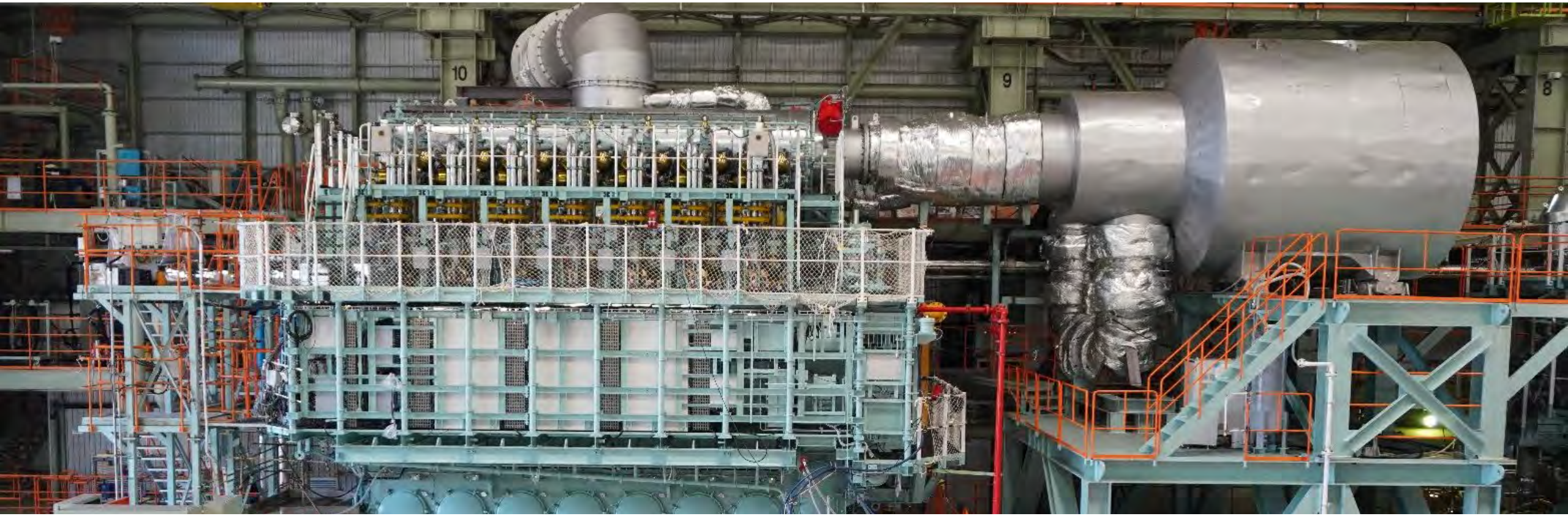
Engine testing includes the propeller curve and light and heavy running points for each given load.

- In additional a PTO effect is simulated and tested.
- The tests are including operational screening.
- Combustion is confirmed stable on all test points.



7S60ME-C10.5 LGI-A at Mitsui

Full scale 2 stroke test engine at Mitsui (MES) Japan



7S60ME-C10.5-LGIA at MES has been operated on Diesel.

Currently the ammonia auxiliary systems are being fianalized. Expected start October/November.

Engine emissions

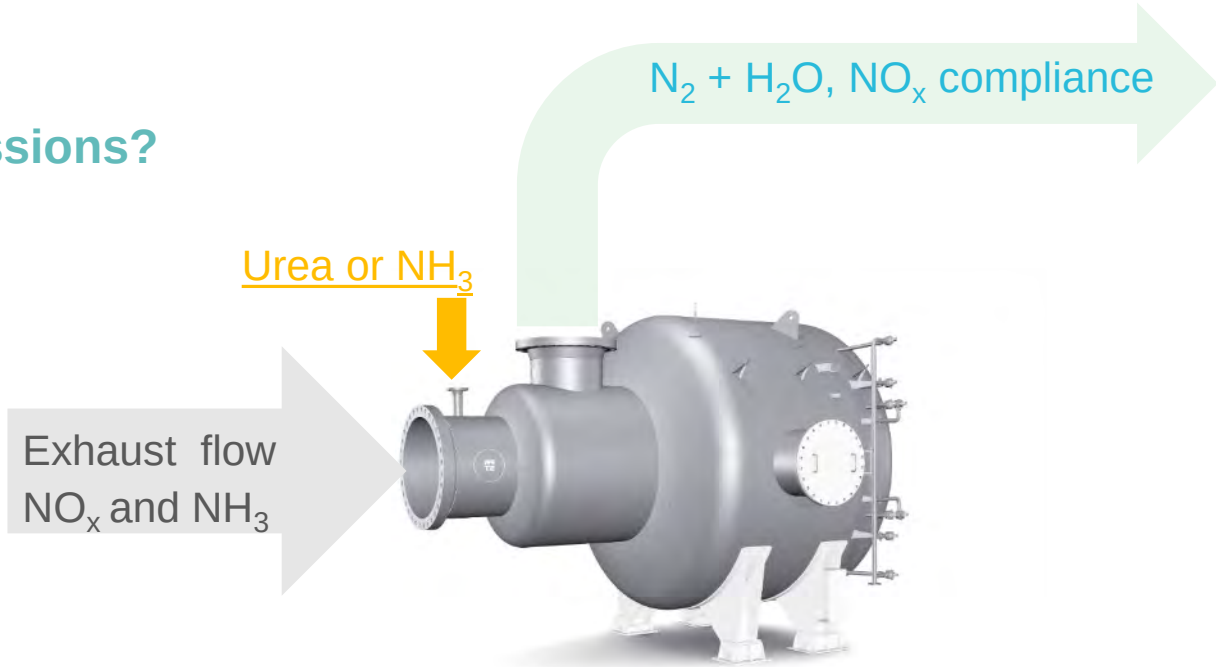
How do we handle potential Nitrous Oxide (N_2O) emissions?

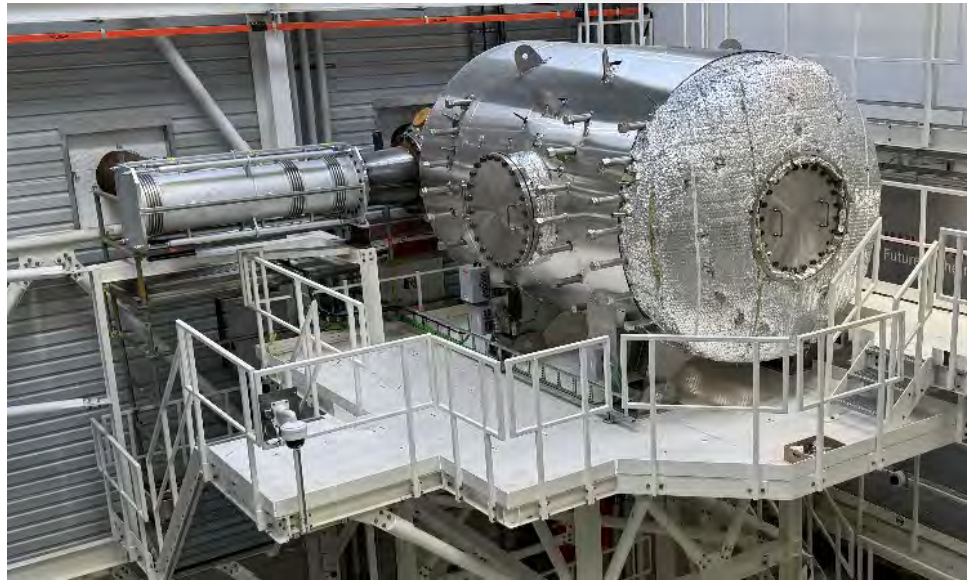
I. N_2O is a very potent GHG with GWP of 298 and will be accounted in on-going adopted regulations

- N_2O will be removed by engine tuning alone, and emission levels are extremely low.
- Exact levels will be published to market after four-cylinder testing.

II. Ammonia slip and NOx emissions

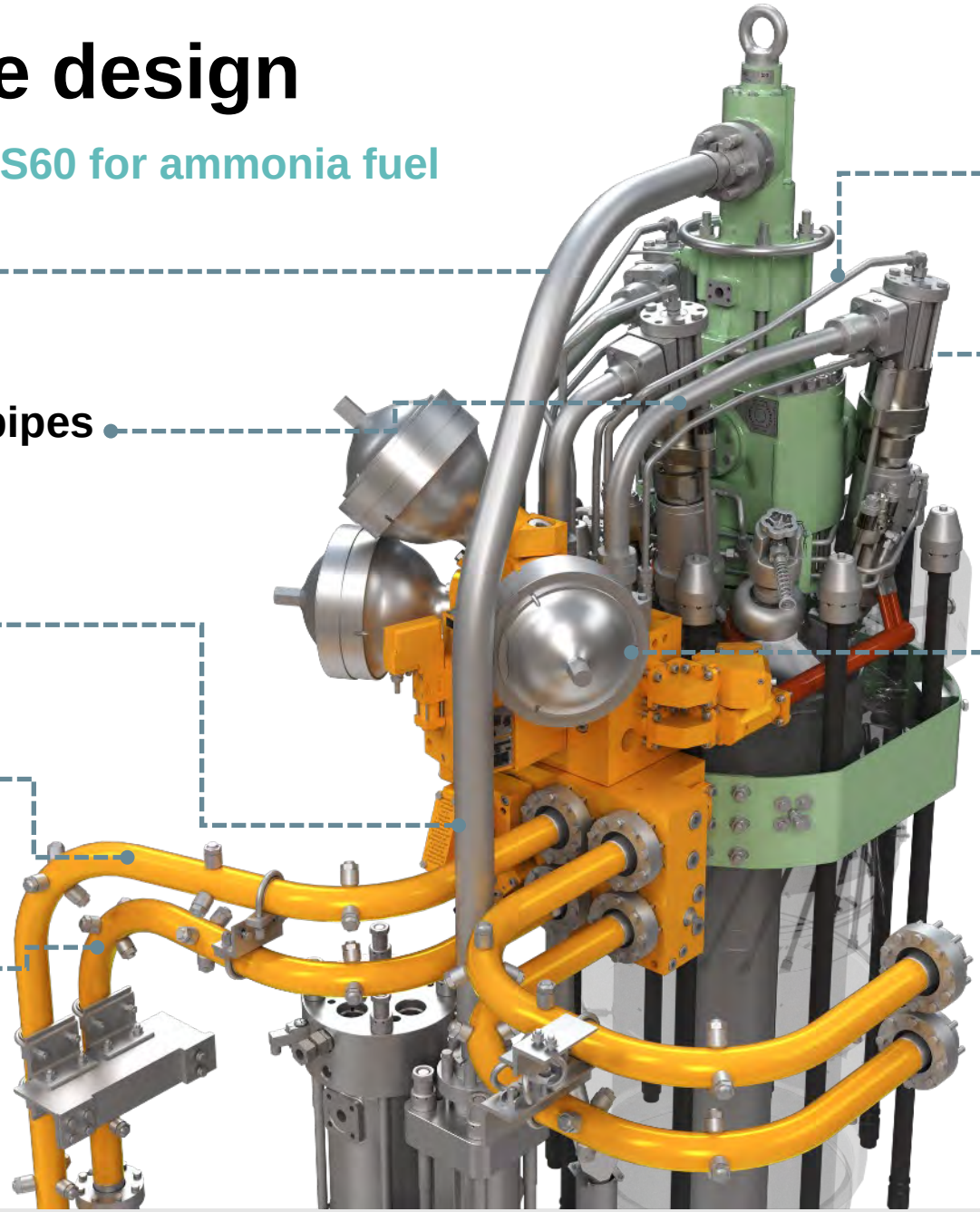
- Unburned NH_3 and NO_x is removed in the SCR reactor
- Dosing of additional ammonia to SCR reaction if needed.
- Four cylinder testing will be used to find balance between NH_3 slip and NO_x





Ammonia engine design

The LGI injection system on S60 for ammonia fuel



Ammonia injection valve

Fuel Booster Injection Valve – Ammonia (FBIV-A) – ongoing development

- Basic design concept known from our methanol and LPG fuelled engines.
- High pressure hydraulic oil acting on top of a piston to increase ammonia pressure from 83 bars to around 650 bar injection pressure.
- Ammonia supplied via lance in cylinder cover and sleeve to FBIV-A.

Ammonia engine auxiliary systems

Setup at the Research Center Copenhagen

Ammonia service tank
5000l

Ammonia supply
and recirculation system
(FGSS)

Fuel valve and return train
(FVT)

Double wall ventilation
and absorber

Nitrogen purging

Ammonia catch system
Max. 20ppm to atmosphere

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R&D timeline

From cradle to … today

2019

- ✓ combustibility investigation.

2020

- ✓ 4T50ME-X test engine received.
- ✓ HAZID on engine concept.
- ✓ Combustion chamber evaluation based on simulations.

2021

- ✓ Engine concept defined based on R&D and simulations.
- ✓ Ammonia fuel supply & auxiliary systems specified.

2022

- ✓ Ammonia fuel supply & auxiliary systems installed at RCC.
- ✓ 1 cylinder engine and auxiliary system preparation at RCC.

2023

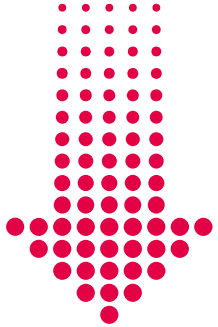
- ✓ 1st bunkering of ammonia at RCC.
- ✓ 1 cylinder two-stroke ammonia combustion at RCC.
- ✓ Full scale design work. (on-going)
- ✓ Installation of emission after-treatment (HP-SCR).

2024

- Full scale engine test at RCC evaluated for 1st commercial design.
- 1st ammonia fueled engine ready for delivery.

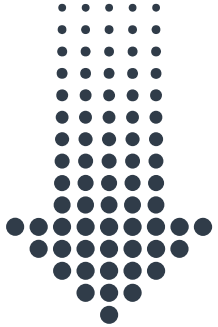
R&D timeline

2024 – A year full with R&D activities



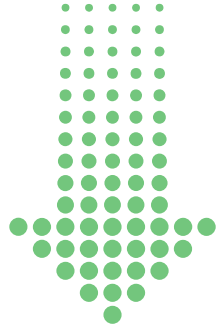
Full engine test in Research Centre Copenhagen

- Installation of engine components (full scale testing)
- Expected full engine testing by end of October.
- R&D engine testing including:
  - Performance.
  - Emissions.
  - Control concept.



7S60 R&D test

- Test of commercial engine design. Ammonia running scheduled to start in Q4.
- Test of engine concept.
- Performance and emission analysis.
- Commercial auxiliary systems testing.



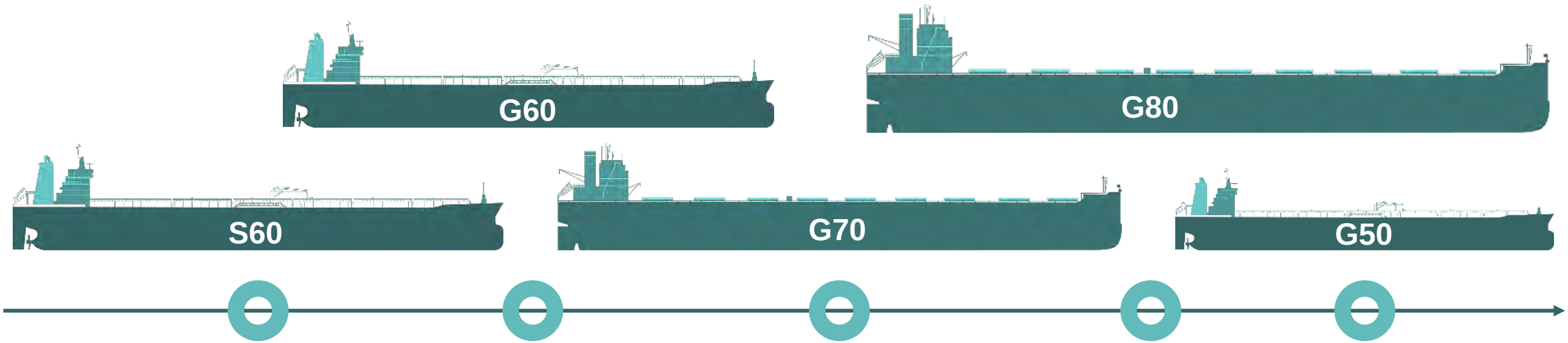
First commercial engine ready for delivery

- Full scale engine test evaluated for 1st commercial design.
- Test of engine and software.
- Planned factory acceptance test.

Ammonia engine market introduction

MAN B&W ME-LGIA market matters

- Working diligently on pilot projects with VLAC, Bulkers and PCTCs
- Press Releases highlighting involved parties and project details will be made upon the signing of the ammonia option in the ammonia pilot shipbuilding projects
- Full release of **G50, S60, G60, G70** and **G80 ME-LGIA** to the market as soon as the first vessel or vessels have demonstrated positive seagoing service experience operating on Ammonia. As such the actual **time schedule will be pending shipyard delivery schedule**. A best guess time estimate for sales release of these engines is **end of 2026**



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MAN B&W ME-LGIA status

- Ammonia is a **great fuel** in slow speed two-stroke engines
- Combustion stability **similar to fuel oil**
- N_2O emission levels are **negligible**
- NOx emission levels **are 40% lower than fuel oil**
- Pilot oil amount **similar to methanol and LPG**
- Toxicity challenges of ammonia is being handled with **success** in our RCC in the middle of Copenhagen
- **However,** in order to safeguard the uptake of ammonia as marine fuel, we have a **responsible** implementation plan with a number of pilots going into service to obtain service experience prior to full sales release to market
- **MAN Energy Solutions is the market leading** for two-stroke ammonia engine development with dedicated two-stroke ammonia combustion on-going for more than 12 months, with a dual-fuel concept of which we have a decade of experience.

MAN Energy Solutions
Future in the making

Thank you very much!

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This data serves informational purposes only and is especially not guaranteed in any way.
Depending on the subsequent specific individual projects, the relevant data may be subject to changes and will be assessed and determined individually for each project. This will depend on the particular characteristics of each individual project, especially specific site and operational conditions.