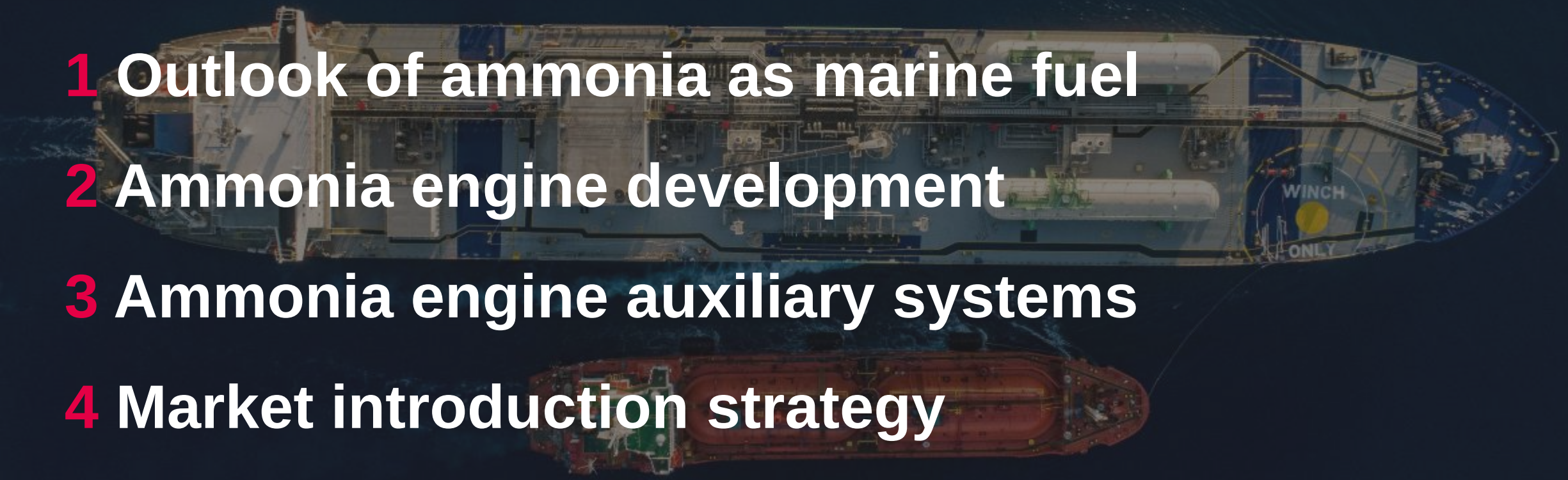
MAN Energy Solutions
Future in the making

MAN B&W ammonia engine development

Agenda



1 Outlook of ammonia as marine fuel

2 Ammonia engine development

3 Ammonia engine auxiliary systems

4 Market introduction strategy

5 Summary

1 Outlook of ammonia as marine fuel

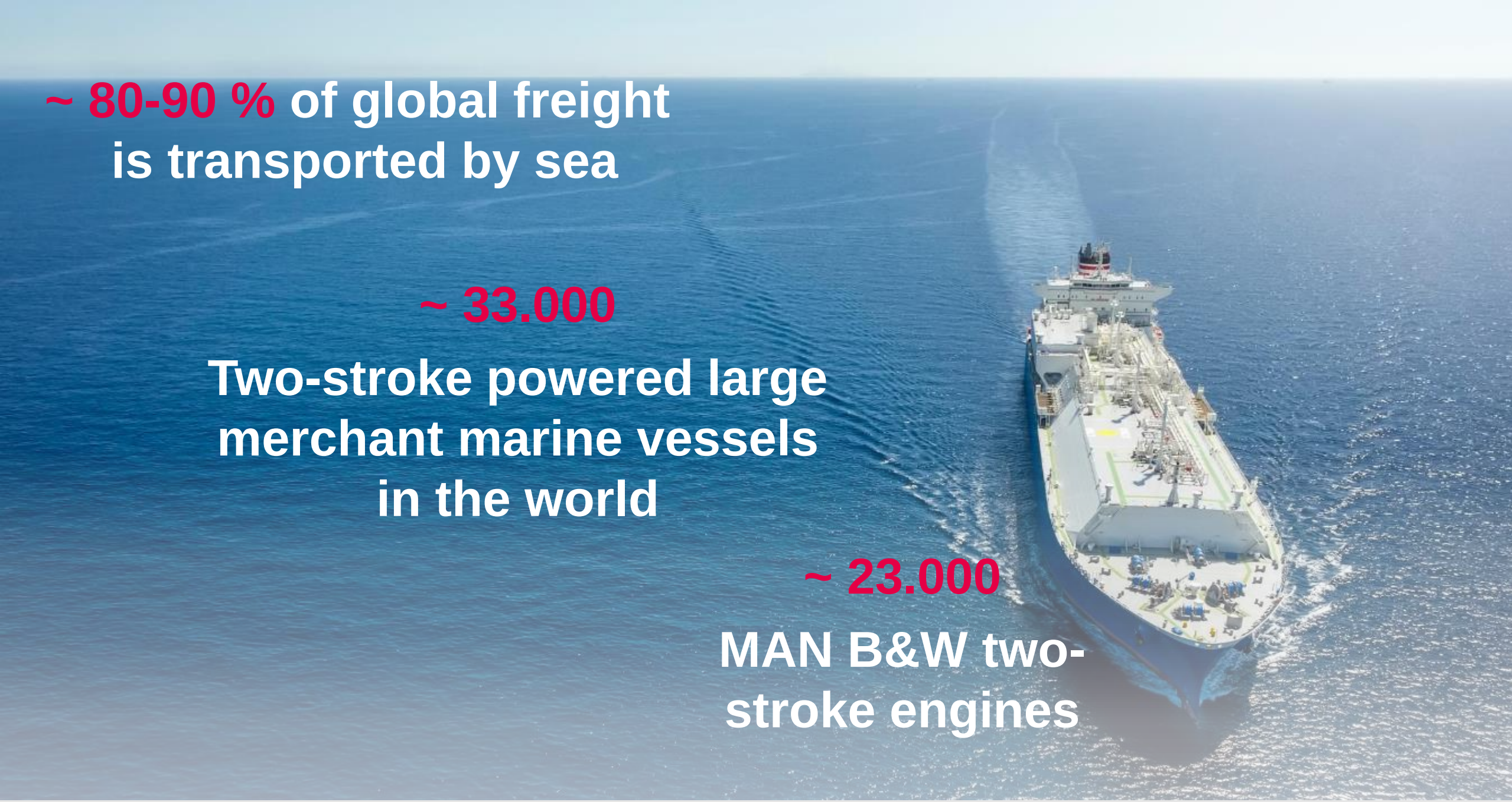
~ 80-90 % of global freight is transported by sea

~ 33.000

Two-stroke powered large merchant marine vessels in the world

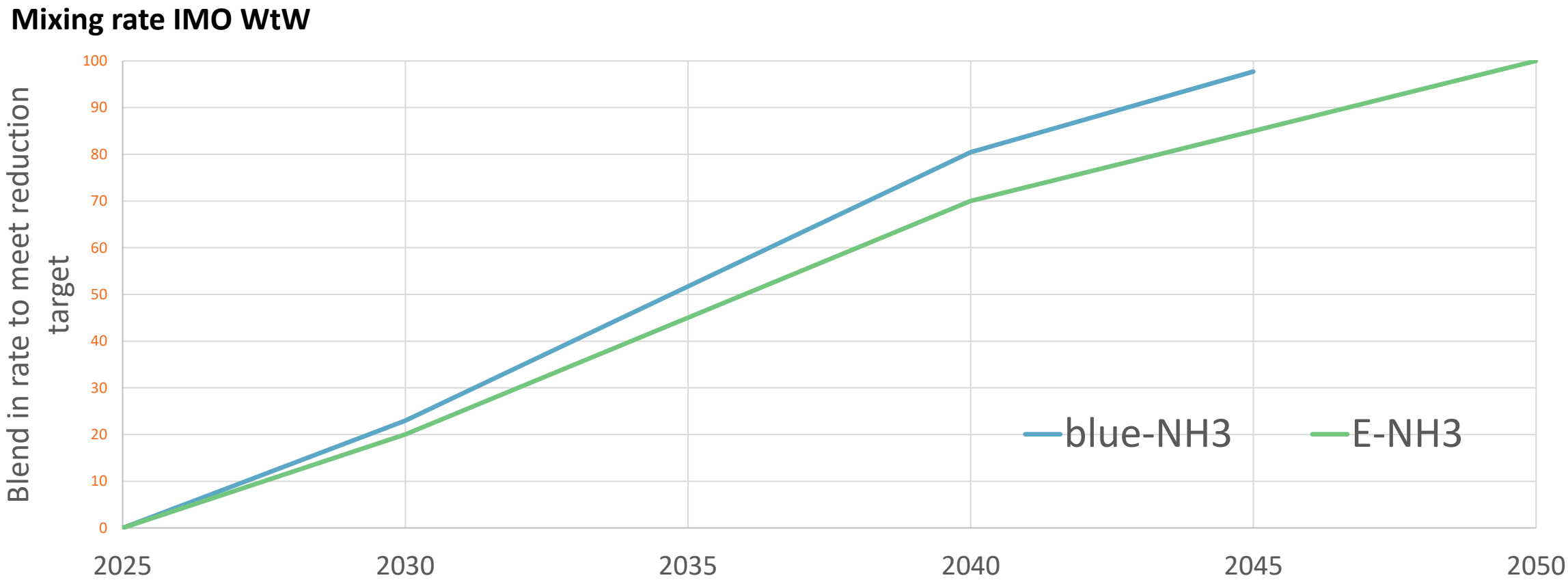
~ 23.000

MAN B&W two-stroke engines



Both Blue and Green ammonia has a huge potential

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



Powering sustainable shipping

Methane
ME-GI & ME-GA
>687 - 278

LPG
ME-LGIP
183

Ammonia
→

Methanol
ME-LGIM
>177

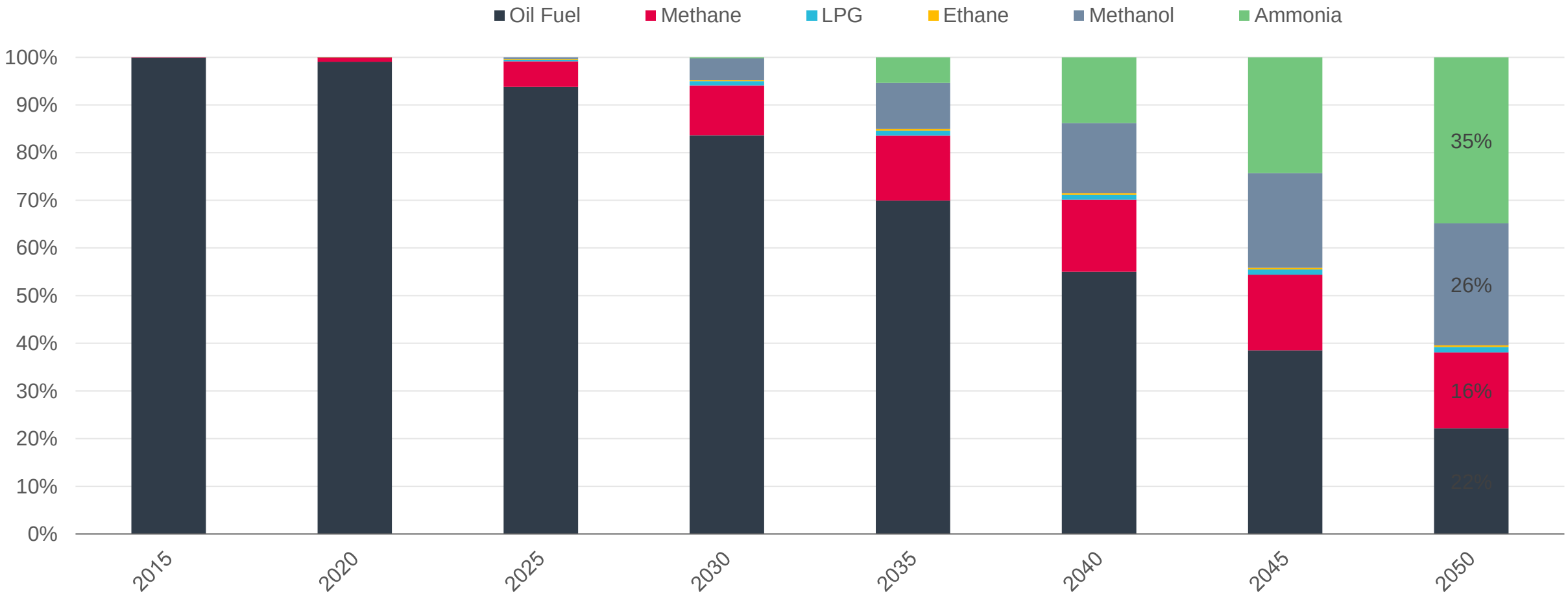
Ethane
ME-GIE
54

1380+

dual-fuel engine orders

Demand for e-Fuels from shipping will be high

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

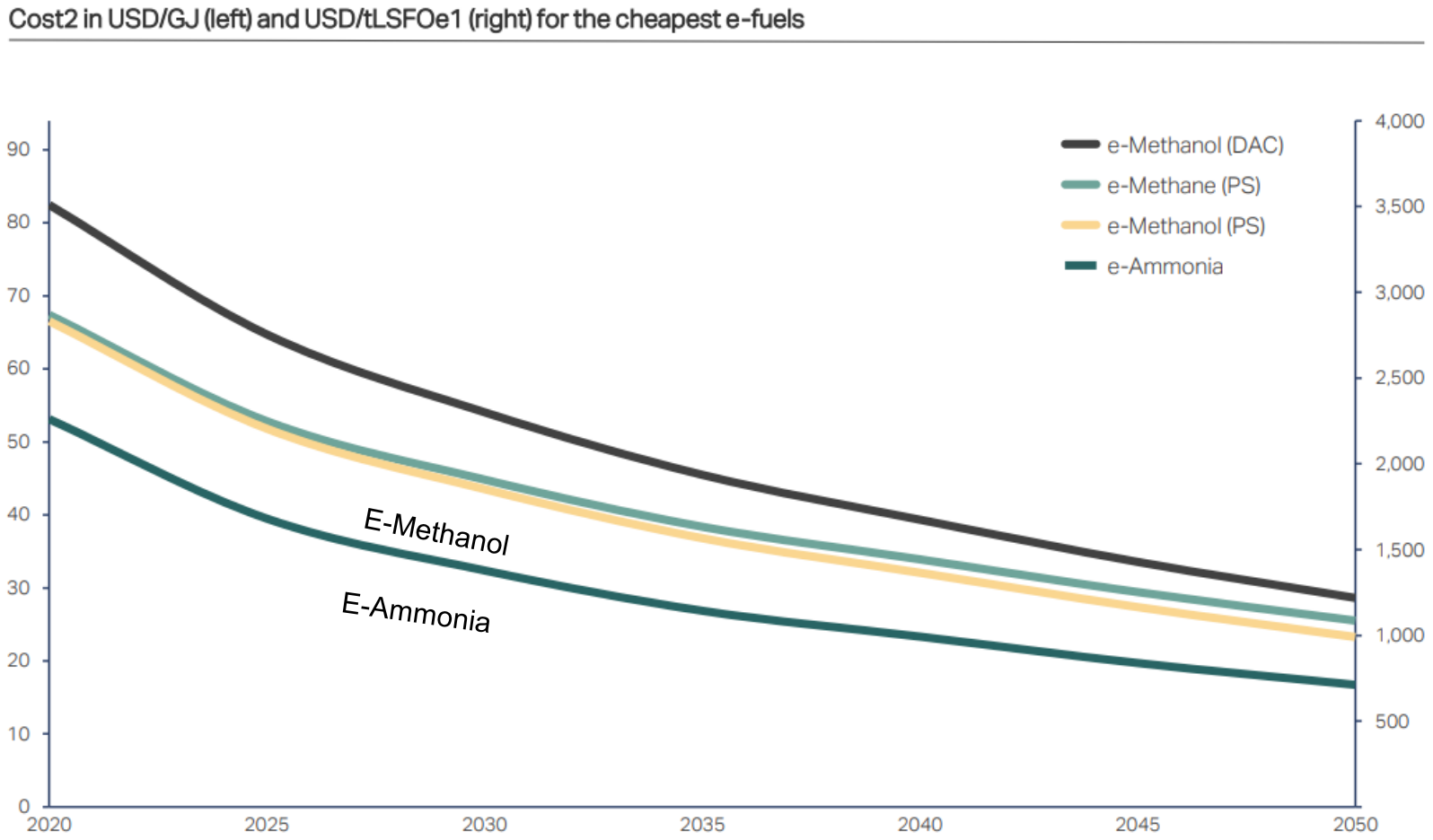


Price of e-Fuels?

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

Ammonia is expected to be the least costly energy dense e-fuel to produce.

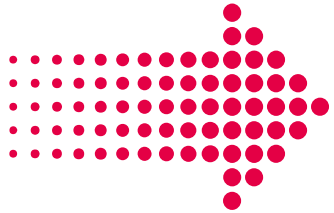
E-ammonia is made from green hydrogen and N_2, which is available in the atmosphere and cheaper to obtain than the biogenic CO_2 needed for carbon based e-Fuels.



Source: Maersk Mc-Kinney Møller Center for Zero Carbon Shipping https://cms.zerocarbonshipping.com/media/uploads/documents/Fuel-Options-Position-Paper_Oct-2021_final_2022-06-07-102920_edoy.pdf page 58

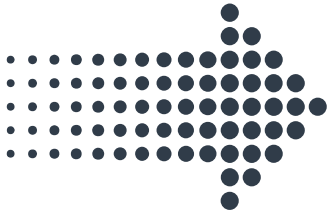
2 Ammonia engine development

R&D timeline



2019

✓ combustibility investigation.

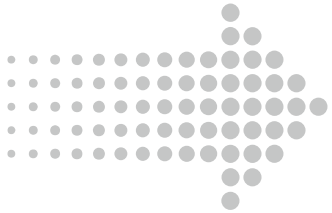


2020

✓ 4T50ME-X test engine received.

✓ HAZID on engine concept.

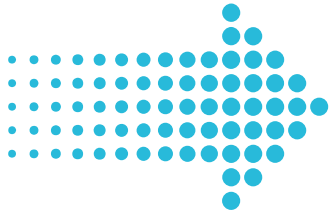
✓ Combustion chamber evaluation based on simulations.



2021

✓ Engine concept defined based on R&D and simulations.

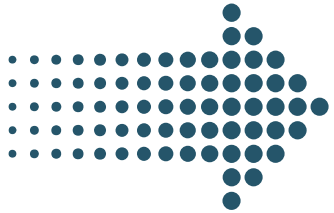
✓ Ammonia fuel supply & auxiliary systems specified.



2022

✓ Ammonia fuel supply & auxiliary systems installed at RCC.

✓ 1 cylinder engine and auxiliary system preparation at RCC.



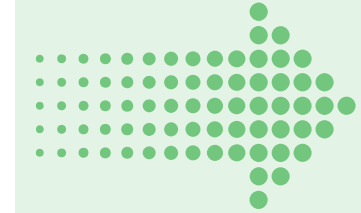
2023

✓ 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.

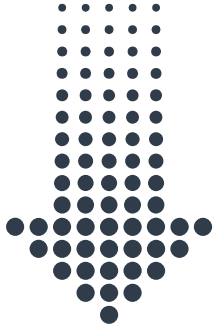
- 1st ammonia fueled engine delivery.

R&D timeline

2024 – a year full with planned R&D activities

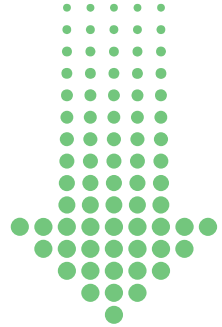
Full engine test in Research Centre Copenhagen

- Installation of engine components.
- R&D engine testing including:
  - Performance.
  - Emissions.
  - Control concept.



S60 R&D test

- Test of commercial engine design.
- Test of engine concept.
- Performance and emission analysis.
- Commercial auxiliary systems testing.



First commercial engine delivery

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

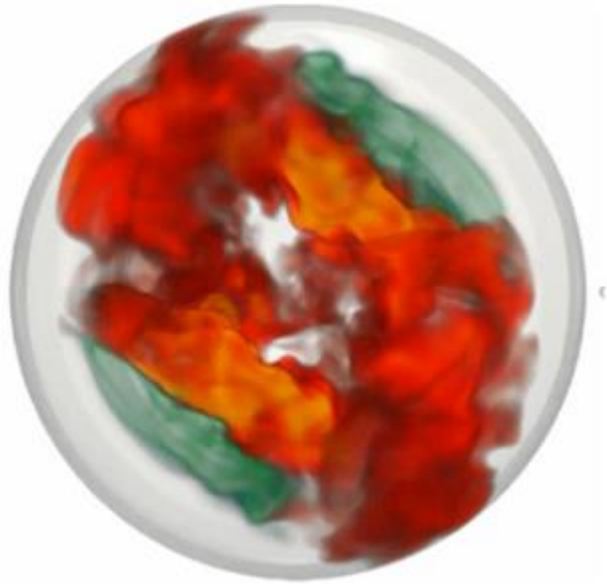
Key combustion challenges with ammonia as a fuel

Emissions

N_2O

& NH3

Difficult to ignite and slow to burn



Ammonia compared with other marine fuels

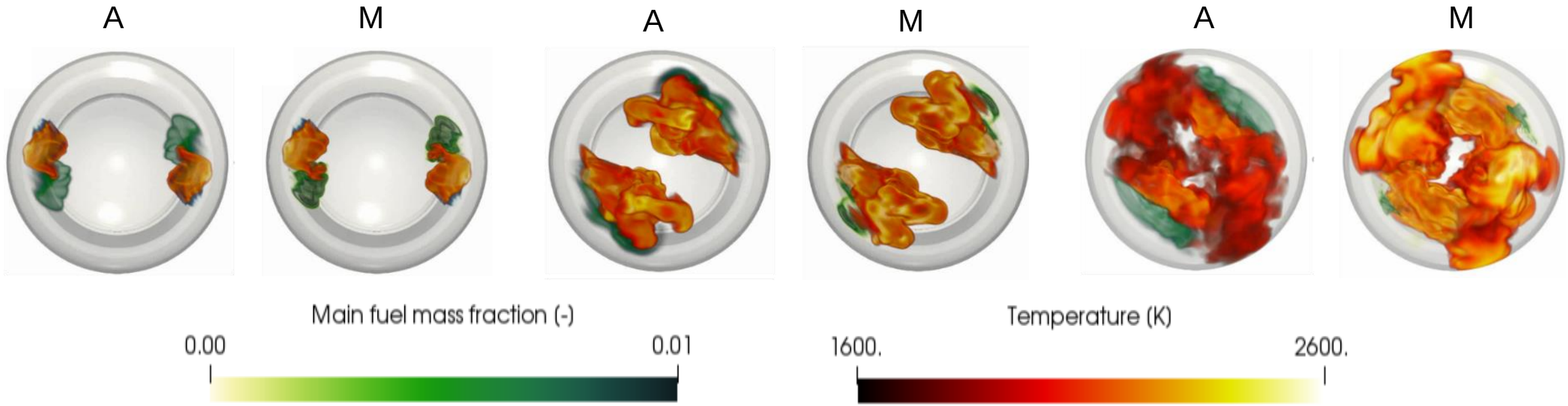
	MGO	LNG	Methanol	LPG	Ammonia
Density in liquid phase [kg/m^3]	740	450	798	581	610
Lower calorific value [MJ/kg]	42.8	50.0	20.1	46.4	18.6
Autoignition temperature [°C]	260	587	470	455	**649**
Laminar flame speed [cm/s]	80	38	42	38	**7**

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 LGI combustion principle

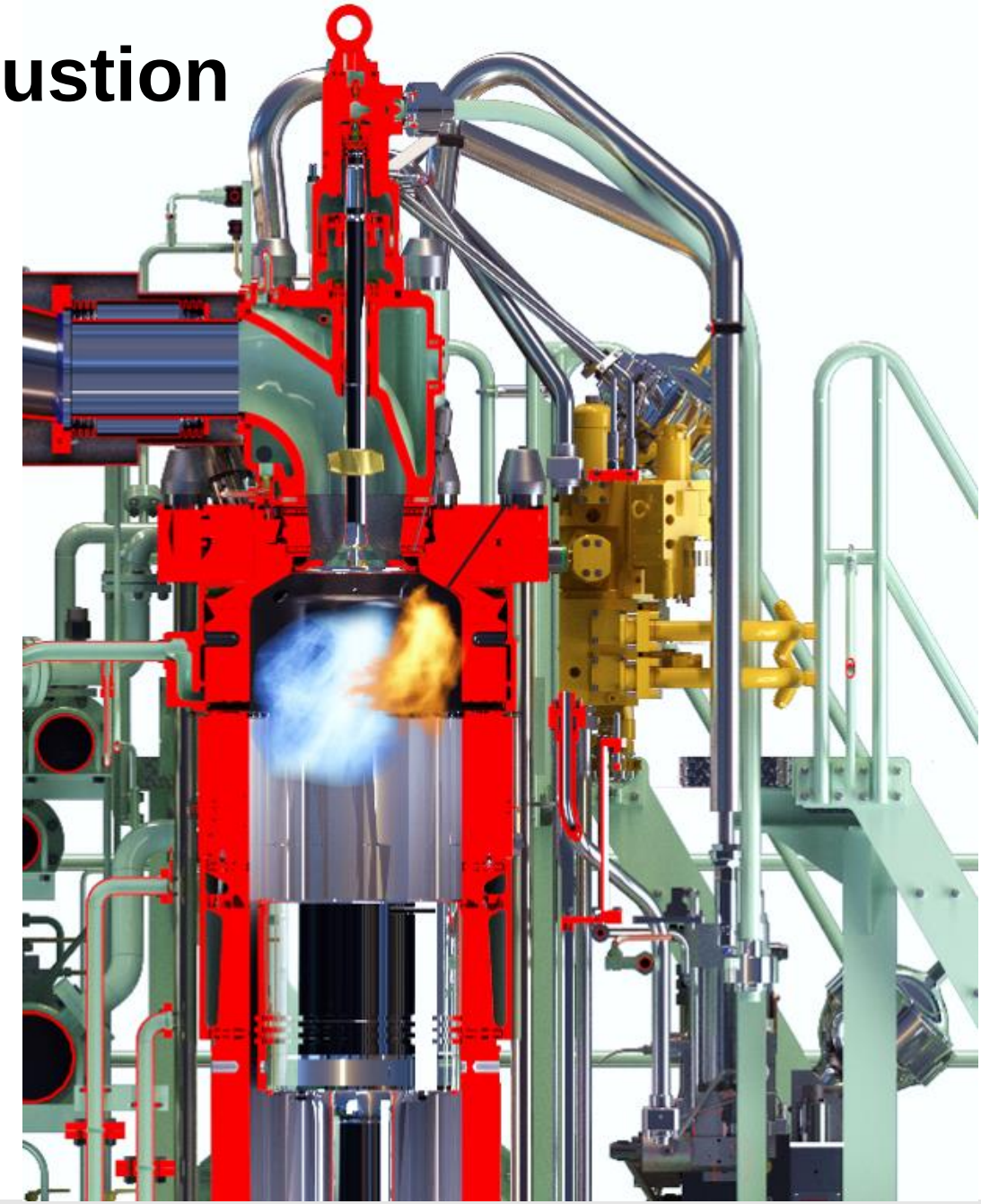
The MAN B&W ammonia engine design philosophy

“Ammonia mode”:

- Small pilot flame needed to start ammonia combustion.
- Initial tests conducted with 10-15% pilot as a first step → R&D target of 5% pilot oil at 100% load for L1-rated engines is already within reach.
- We target for 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

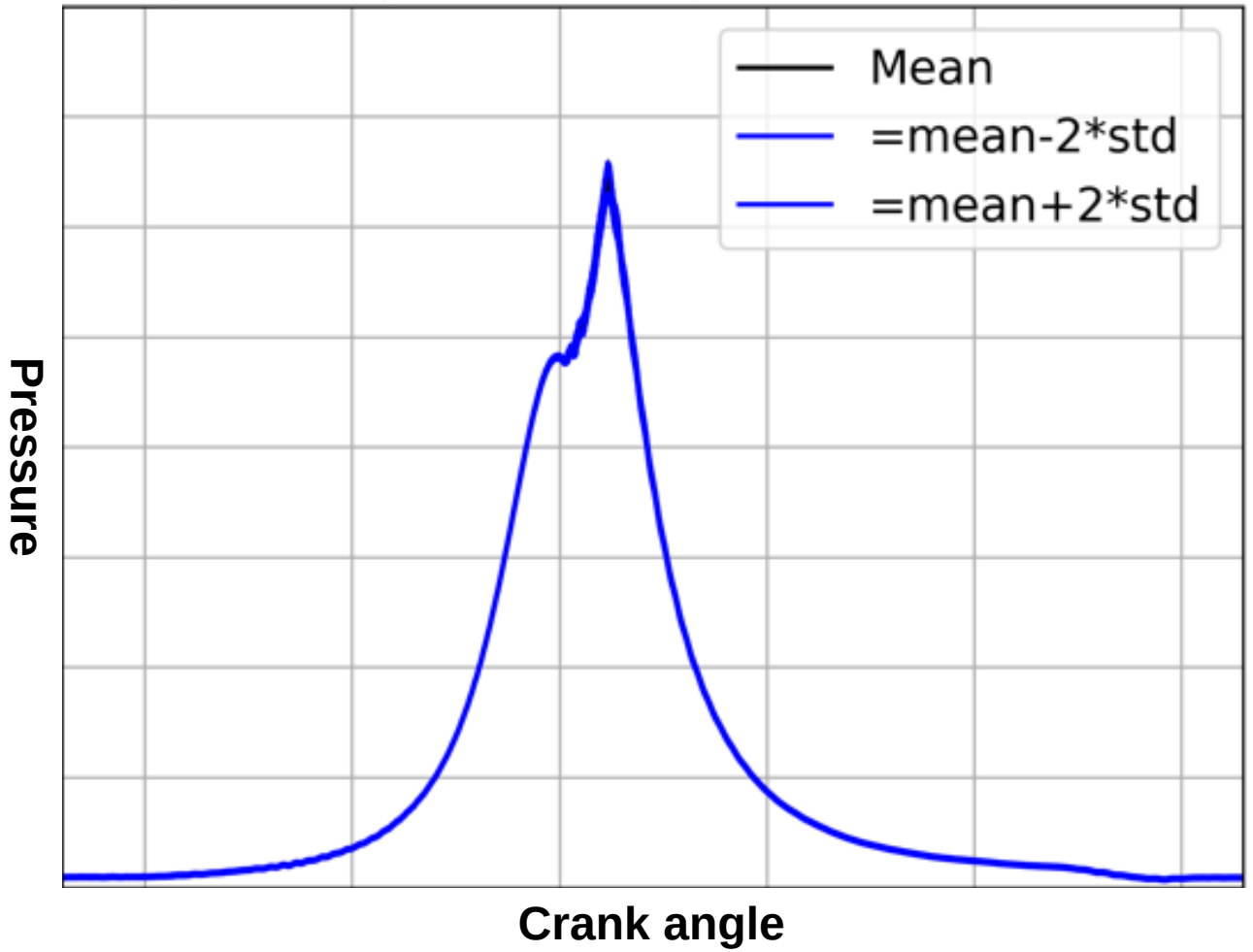
1) 3rd of July 2023: First ammonia combustion in our test engine no. 1#
2) Over 200 tests have already been completed.
3) Engine testing includes both performance and emissions tests in many load points.
4) Cylinder no. 4 is operated on ammonia and 100% load is obtained.
5) Pilot oil energy fractions similar to other LGI engines.
6) N_2O is handled by engine tuning.
7) Very low NOx emissions.
8) Ammonia slip measures still under investigation

Ammonia combustion

Diesel cycle ammonia combustion

Cylinder pressure is following the Diesel principle

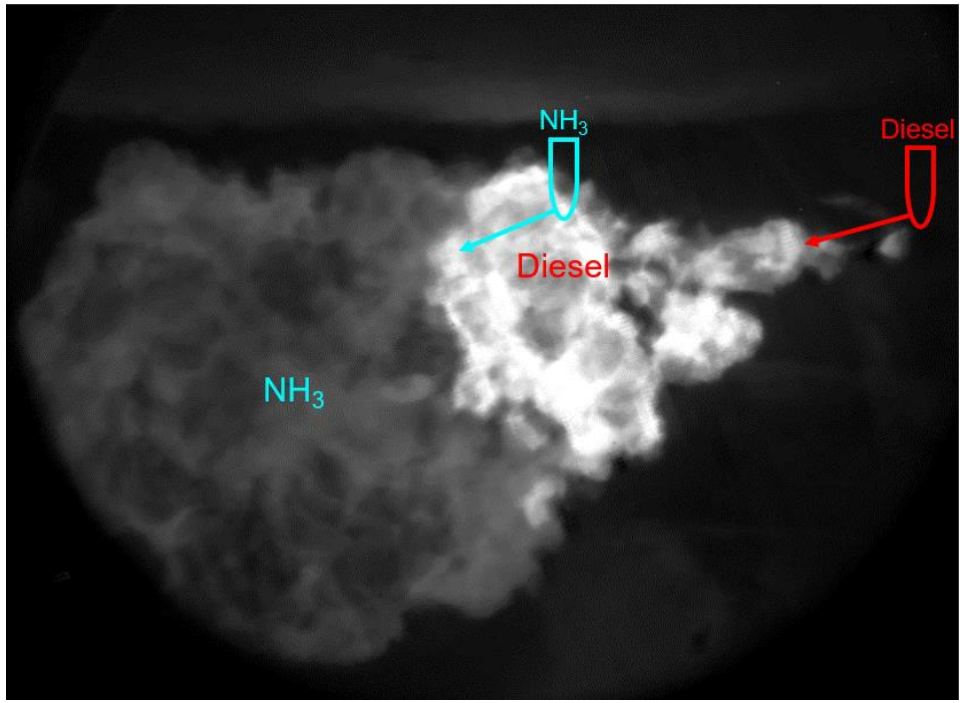
1) Combustion has good stability behavior and acts like other fuels of hydrocarbon origin.
2) Robust compression and expansion curves.
3) Mean statistical analysis indicate very good combustion stability on a cycle-to-cycle pressure variation as measured during engine testing operation.

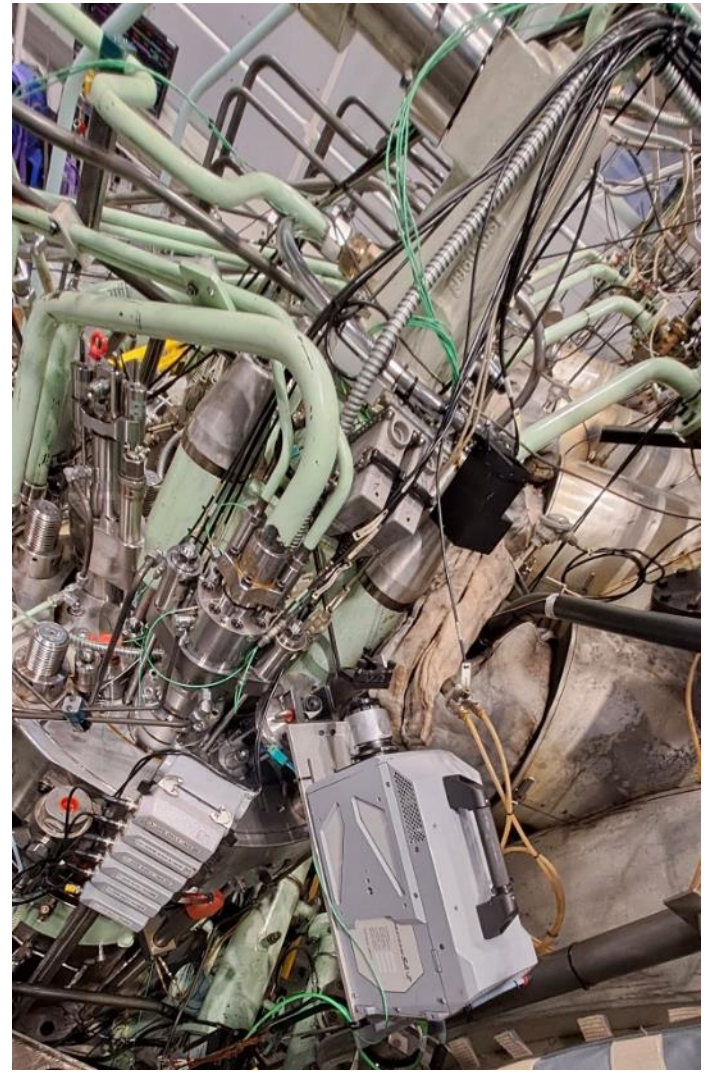


High-speed combustion camera

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.



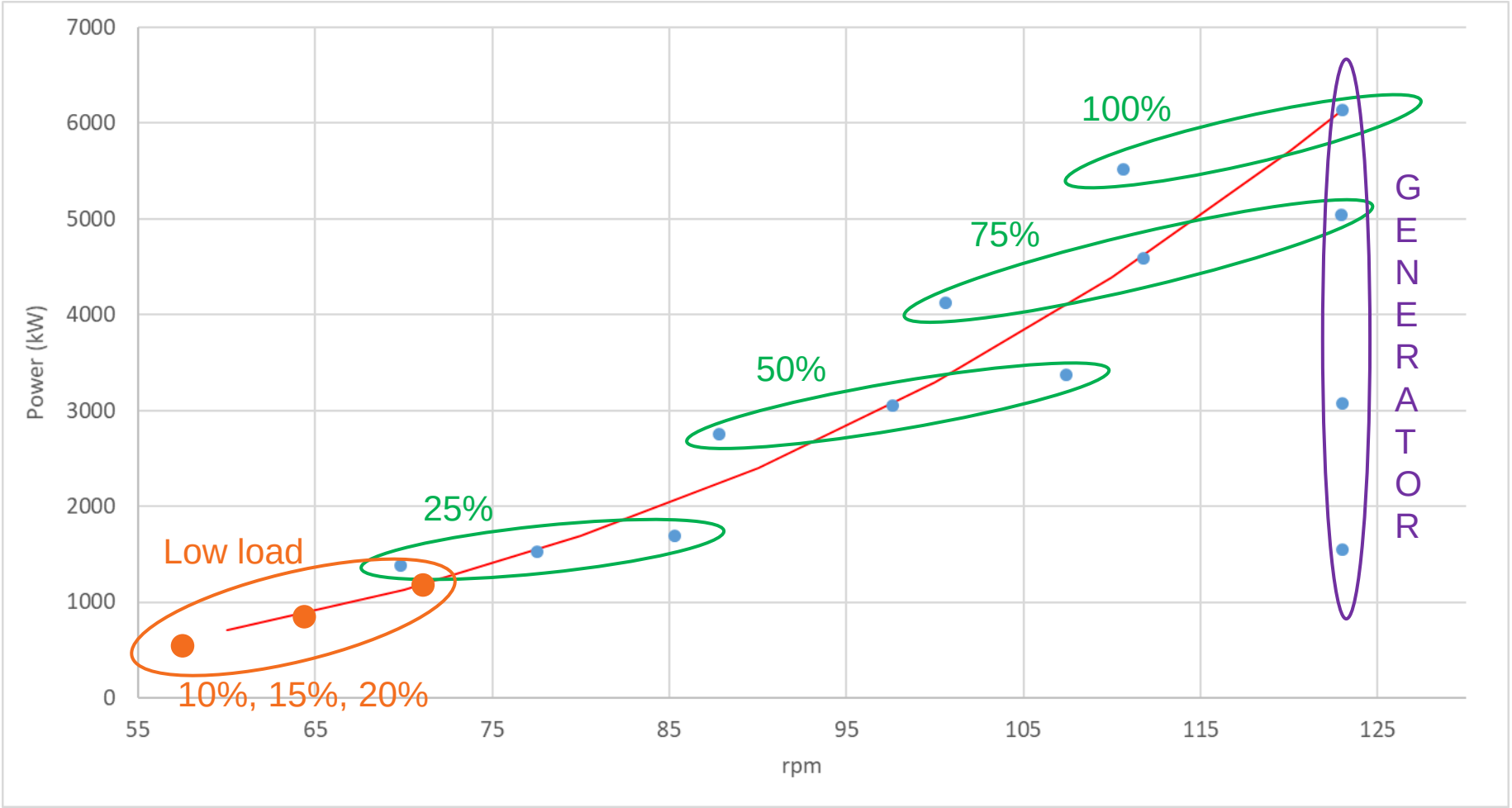


Installation of high-speed camera

Engine testing at both light & heavy running and generator curve

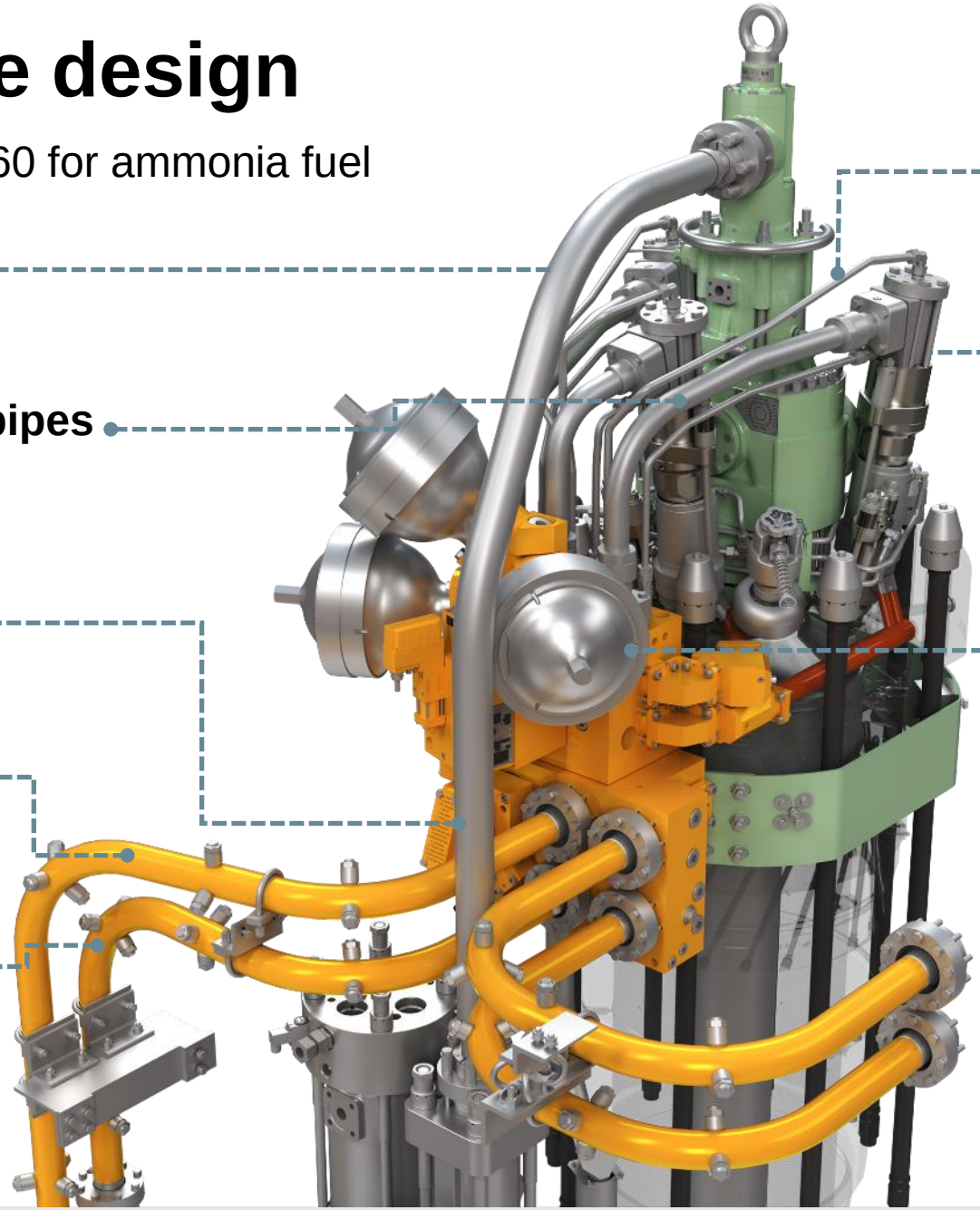
Engine testing includes not only the propeller curve but both light and heavy running points for each given load.

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



Ammonia engine design

The LGI injection system on S60 for ammonia fuel



Hydraulic oil

High pressure hydraulic oil pipes

Hydraulic control valves

Ammonia double-walled pipe inlet

Ammonia double-walled pipe outlet

De-aeration point

Fuel Booster Injection Valve

Hydraulic accumulator

Preliminary ammonia engine design on a 7S60 engine

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.

Engine emissions

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

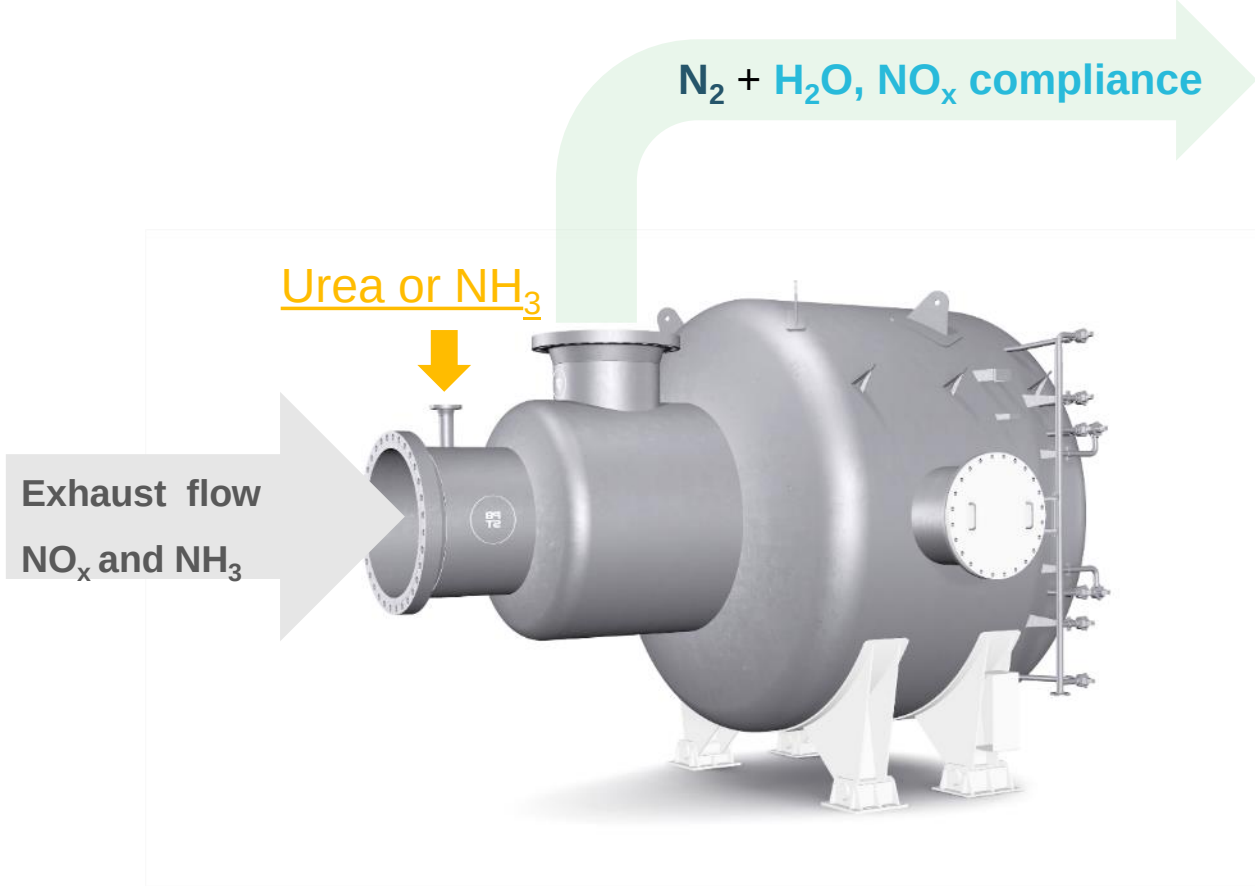
N_2O is a very potent GHG with GWP of 298.

It will also be accounted in on-going adopted regulations

- Nitrous oxide (N_2O) will be removed by engine tuning.

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.
- Known SCR technology is suitable and MAN HP-SCR reactor can be applied.



Ammonia engine development

Materials

Fuel Supply System

- 316L steel is recommended.
- To be welded with backing gas / pickling.

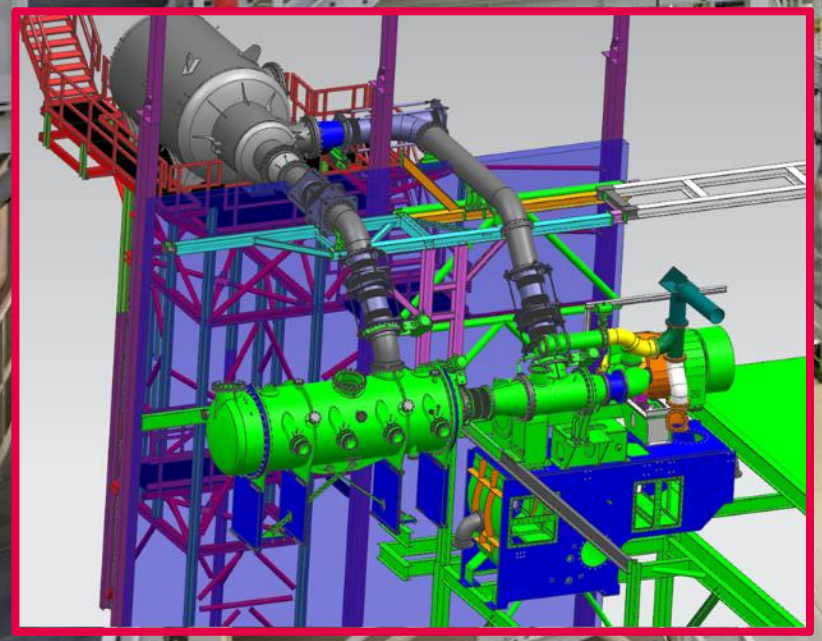
LGI injection system

- Current materials expected to perform satisfactorily.

Elastomers

- Suitable material found for both O-rings and accumulators.

Stress corrosion cracking is solved by the industry already, by requiring small amount of water in the ammonia and requirements to the steel grades, welding procedures etc.



Installation of HP-SCR

Unique and breakthrough R&D progress

100,000 man hours completed

- 37 patent applications filed around ammonia engine development.
- 4 additional applications in the filing process.
- 6 patents granted.

2020

- First 2 patent applications for ammonia engine filed.
- 2 patents registered.

2021

- 7 patents applications filed.
- 4 patents registered.

2022

- 15 additional patent applications filed.

2023

- 9 more patent applications are filled.
- 4 more patent applications are pending filing (Q2**).**

2024

Well-engineered and unique MAN B&W ammonia engine.

3 Ammonia engine auxiliary systems and safety

The challenges of using ammonia as a marine fuel

Engine design reliability

Is the ammonia engine design reliable and safe enough to avoid incidents?

Extra auxiliary systems

The level of safety meassures required for engine and auxiliary systems are unlike anything we have ever worked with before.

The human factor

Is the safety by design enough to eliminate errors caused by wrong operation / handling?

Foundation for design - Risk Assessment – 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 4,000 hours spent on FMEA, HAZID and HAZOP**

Ammonia engine auxiliary systems at RCC

Ammonia service tank

Ammonia supply and recirculation system

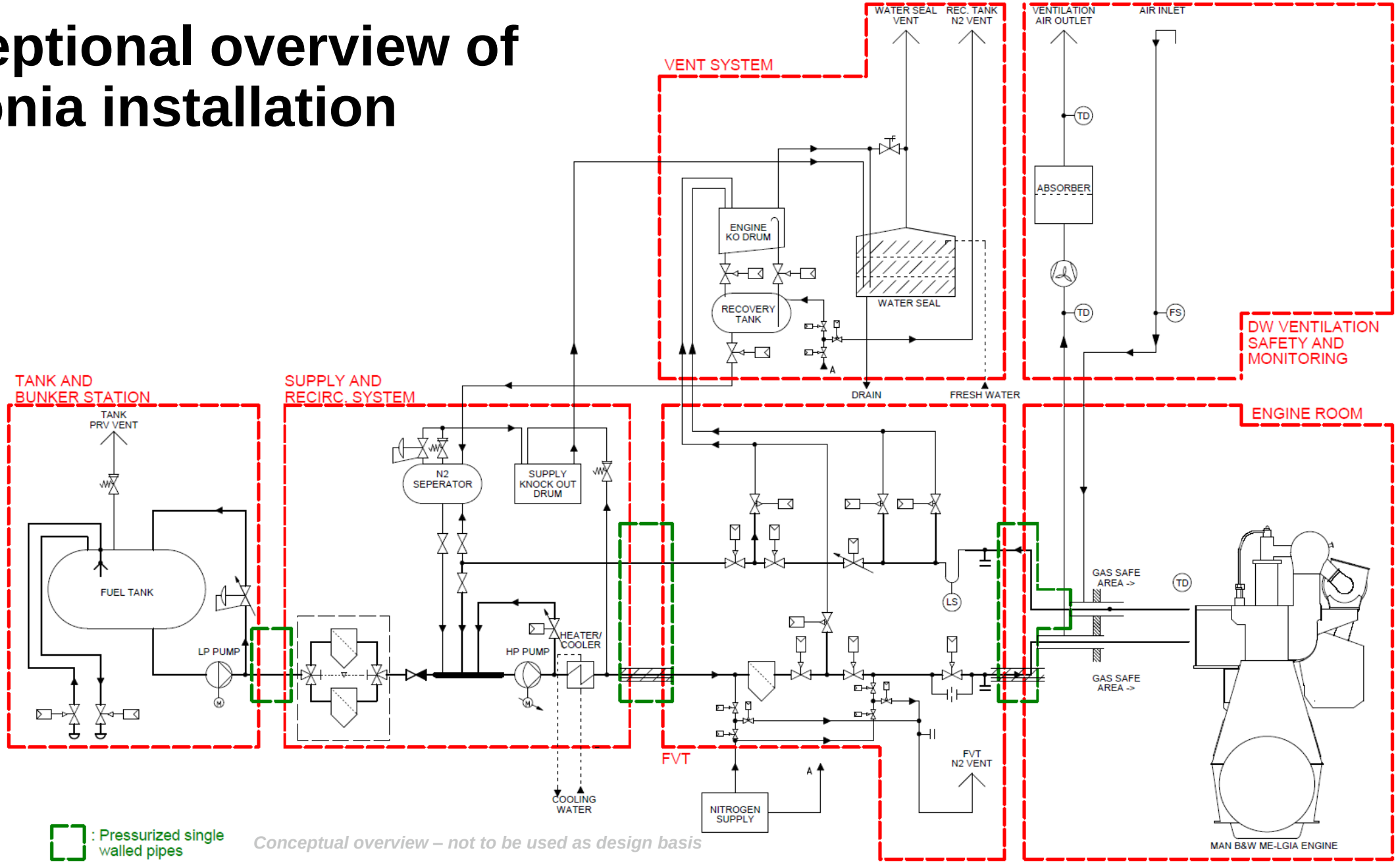
Fuel valve and return train

Nitrogen purging

Double wall ventilation and absorber

Ammonia catch system

Conceptional overview of ammonia installation



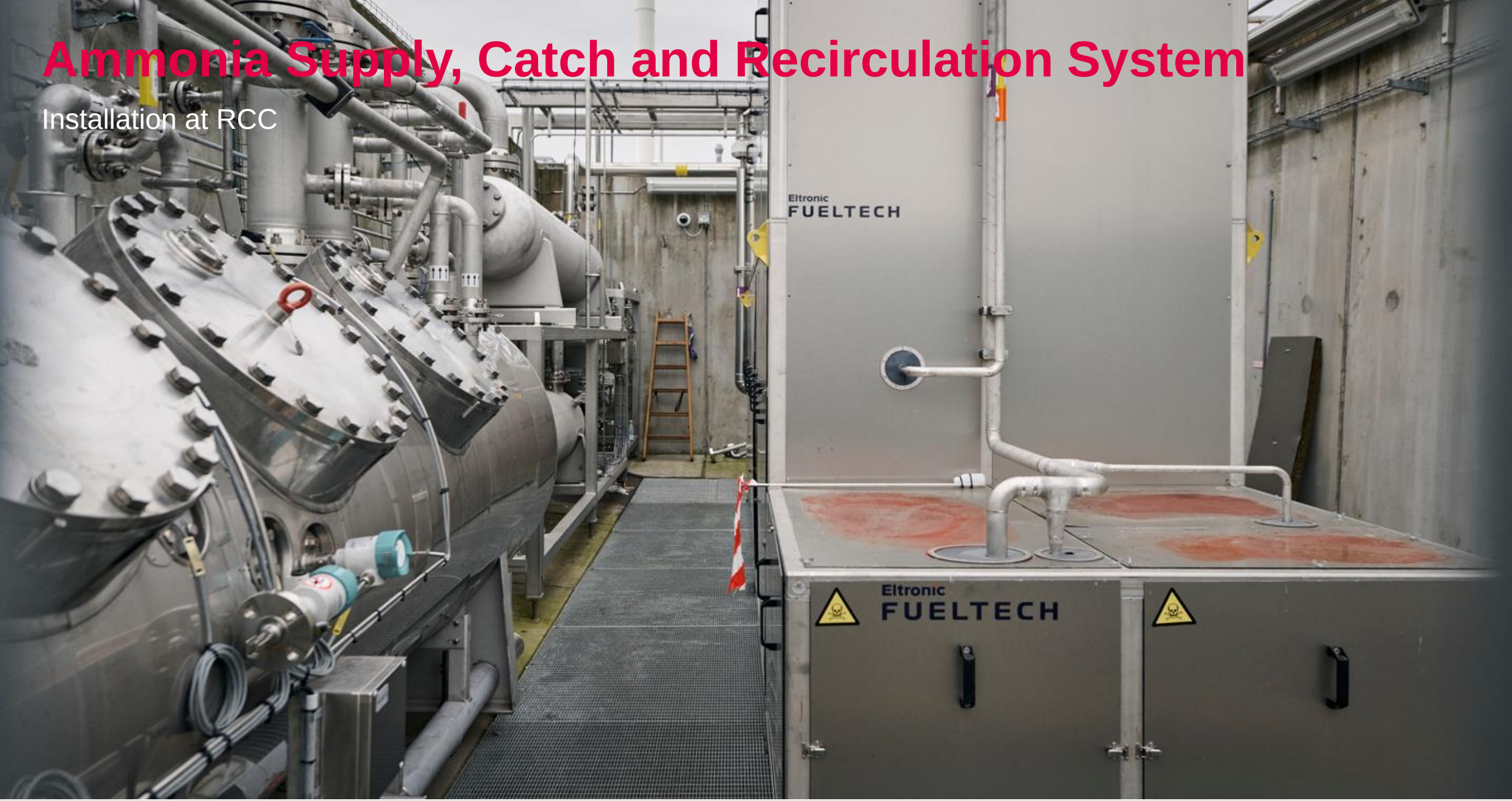
Ammonia Catch System

Basic principles

- Designed to avoid direct ammonia vapours to atmosphere when purging.
- Is designed to only release vapours of ammonia up to 5 ppm.
- We have been able to test the system with blow down equivalent to a full engine shutdown due to a test rig set up.
- Approx. skid size: Length: 7m - Width: 2,5m - Height: 3,5m.
- Accumulated water/ammonia mixture to be discharged as chemical waste based on existing regulations.

Ammonia Supply, Catch and Recirculation System

Installation at RCC



Double wall safety concept

Purpose

- Enable detection of inner pipe leaks.
- Enable verification of outer pipe tightness.

System specification

- Dry ventilation air.
- Air change between 30 and 45 times/hour.
- Additional absorber installed to handle leaks to outer pipe with the use of water.

Status of auxiliary systems at RCC

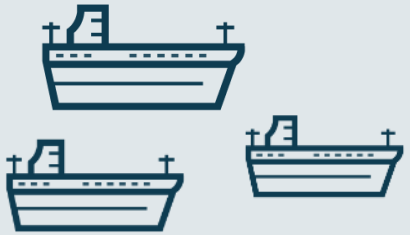
- Frequent bunkering operations on weekly basis are performed trouble free.
- Tank and bunkering systems are working as per design.
- Supply and return system along with fuel valve train requires refinement based on learnings.
- Ammonia catch system is working well.
- For safe and reliable installation.
  MAN Energy Solutions requires first time approval of major auxiliary systems.

4 Market introduction strategy

Two-stroke ammonia engine main development timeline

R&D development
Copenhagen

First engine delivery
2024



Positive seagoing experience
of pilot projects 2026-2027

Full sales release

Ensure a safe and reliable introduction of ammonia as marine fuel

A successful introduction of ammonia as a marine fuel

1. Usually engines are introduced for full-sales release prior to seagoing experience.
2. This is possible because of vast experience with the fuels as well as engine and auxiliary system designs.
3. Such experience does not exist for ammonia engines and auxiliary systems.
4. MAN Energy Solutions therefore want to obtain positive seagoing experience from a number of MAN B&W ammonia engine before it is released for full sales in the engine catalogue.
5. Service experience will be started from around first half of 2026.
6. Such service experience will be used to introduce potential design updates/improvements for main- and auxiliary systems if needed.

Engine connectivity

An important element for future development and improvements.

Spot trends through data visualisation before operation is impacted.

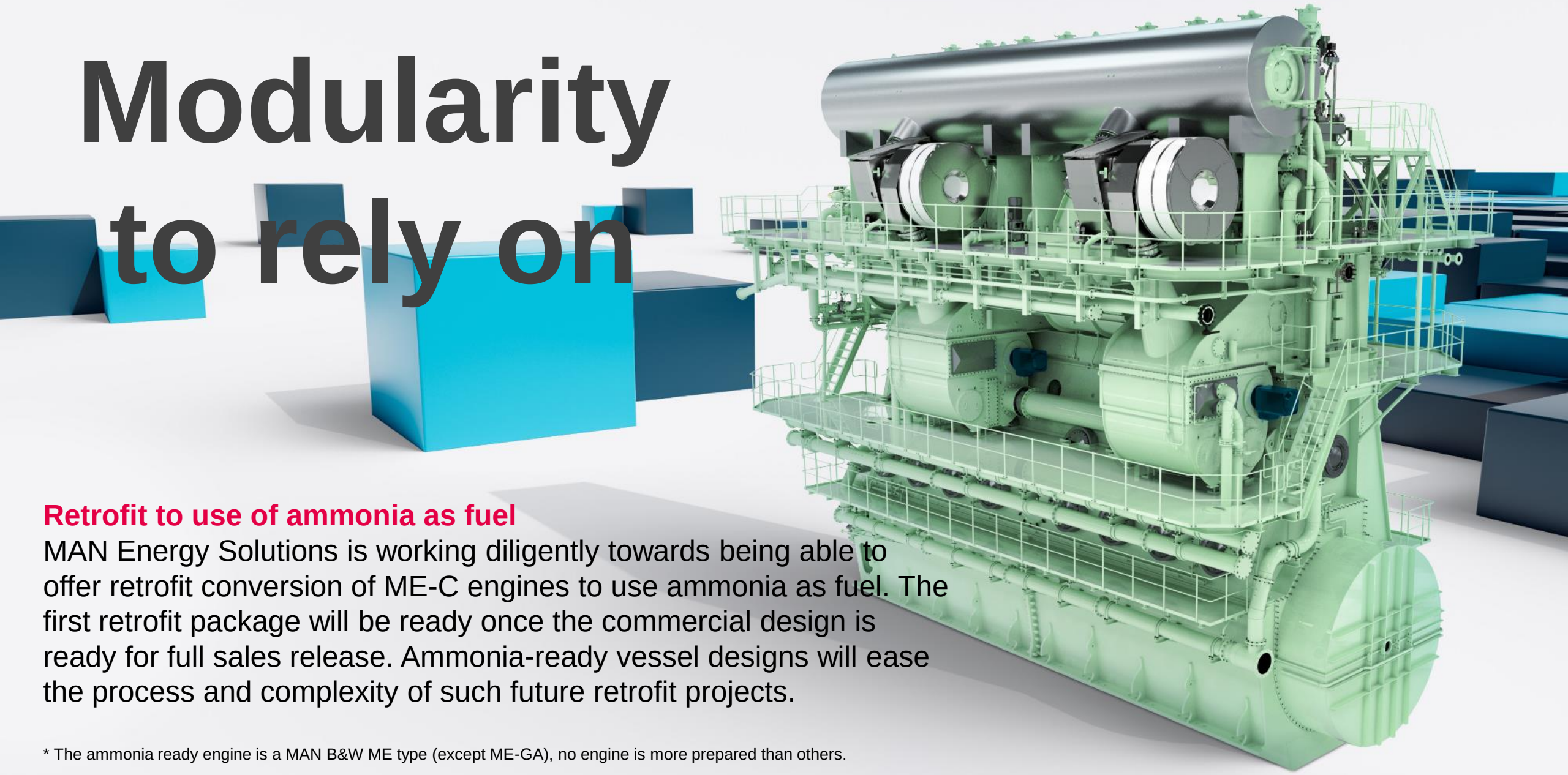
Initiate root cause analysis immediately without crew interaction.

Minimise required crew interaction.

Through connectivity and engine data monitoring, we want to remove unscheduled activities by detecting faults before they become failures

Note: Fault: Asset is still operational vs Failure: Asset stops being operational

Modularity to rely on



Retrofit to use of ammonia as fuel

MAN Energy Solutions is working diligently towards being able to offer retrofit conversion of ME-C engines to use ammonia as fuel. The first retrofit package will be ready once the commercial design is ready for full sales release. Ammonia-ready vessel designs will ease the process and complexity of such future retrofit projects.

* The ammonia ready engine is a MAN B&W ME type (except ME-GA), no engine is more prepared than others.

5 Summary

Summary

Ammonia engine development

- ✓ **More than 100,000 R&D man hours completed for the MAN B&W ammonia engine development.**
- ✓ **More than 4,000 hours alone for identification of hazards and risks on our engine and auxiliary system designs.**
- ✓ **Very promising results from initial engine combustion testing.**
- ✓ **High expectations to ammonia as a marine fuel due to high PtX efficiency and thereby lower production cost.**
- ✓ **First MAN B&W ammonia engine size is 60-bore.**
- ✓ **Seagoing experience before full sales release in order to safeguard the use of ammonia as a marine fuel.**

Disclaimer

All data provided in this document is non-binding.
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.

MAN Energy Solutions
Future in the making

Thank you very much!