MariNH$_3$

Clean, green ammonia engines for maritime

Achieving Near-Zero Tailpipe Emissions in a Lean-Burn Ammonia Fuelled SI Engine with an Integrated Cracker SCR System

Supported by: CIMAC INTERNATIONAL COUNCIL Power | Drives | Propulsion; Cambustion

Neeraj Kumar Yadav, Ajith Ambalakatte, Sikai Geng, Gagan Gopakumar Suja, Alexander Birch, Alasdair Cairns

University of Nottingham

Anthony Harrington, Jonathan Hall

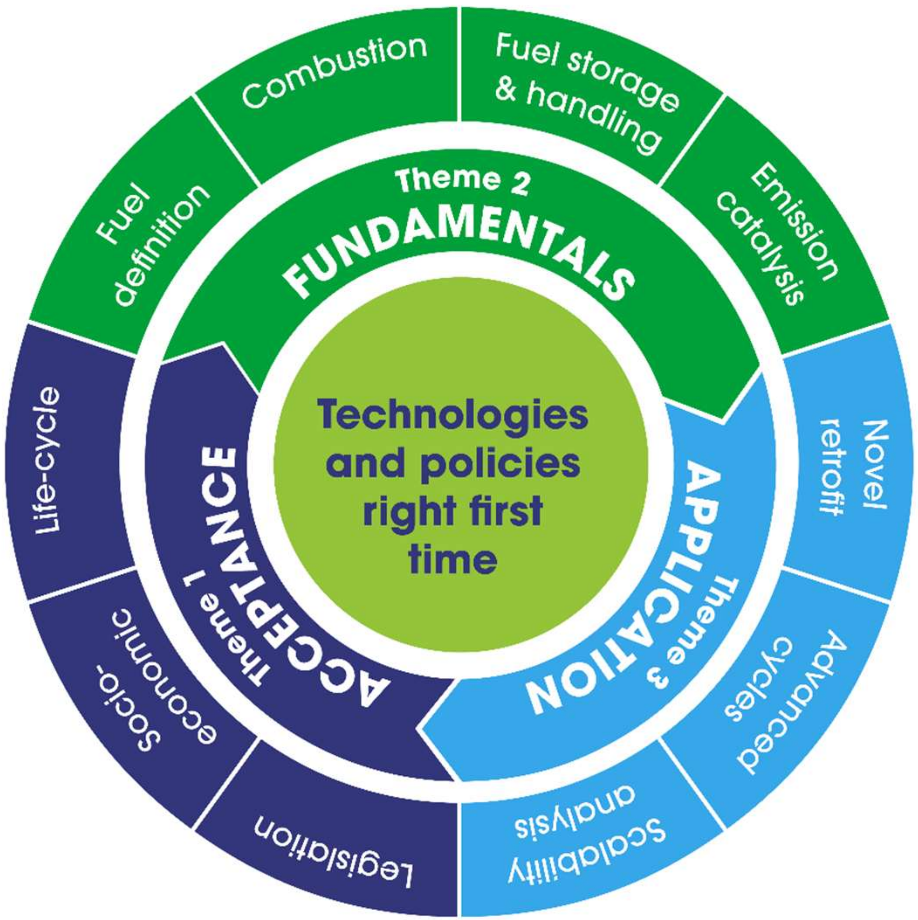
MAHLE Powertrain Ltd

The partnership: University of Nottingham UK | CHINA | MALAYSIA; UKRI Science and Technology Facilities Council; University of Birmingham; University of Brighton; Cardiff University Prifysgol Caerdydd

Funded by UKRI Engineering and Physical Sciences Research Council

MariNH3

Clean, green ammonia engines for maritime



The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by UKRI Engineering and Physical Sciences Research Council

Theme 3: Application

MariNH3
Clean, green ammonia engines for maritime

The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by UKRI Engineering and Physical Sciences Research Council

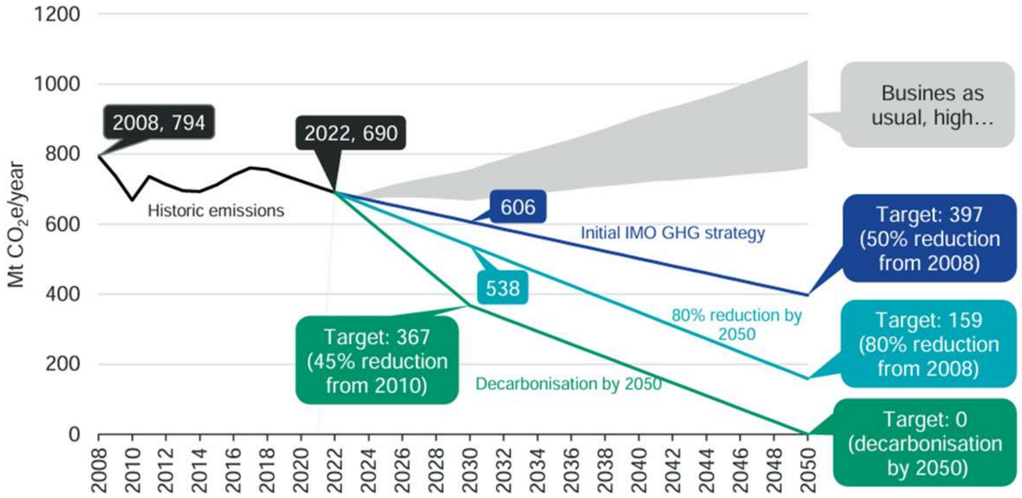
Roadmap to near-zero emissions

1. Why Ammonia?
2. Opportunities and Challenges?
3. Near-Zero Emissions Strategy
4. Validation and Development
5. Achieving Near-Zero Emissions

Why ammonia as fuel?

MariNH3
Clean, green ammonia engines for maritime

Decarbonisation of the industrial and marine sectors

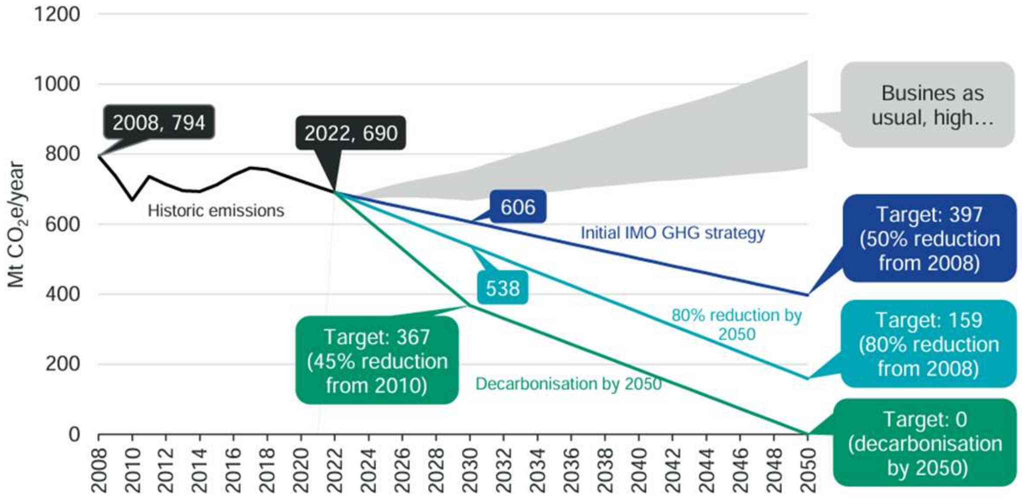


*Ricardo in association with DNV; 2023

Why ammonia as a fuel?

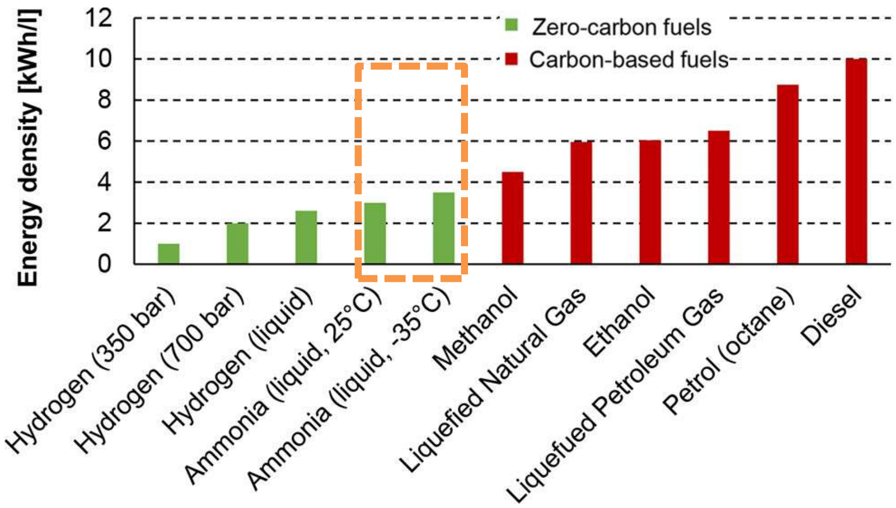
MariNH3
Clean, green ammonia engines for maritime

Decarbonisation of the industrial and marine sectors



*Ricardo in association with DNV; 2023

Ammonia as a fuel for marine engines



*Ammonia as a Carbon-Free Energy Carrier

The partnership

University of Nottingham UK | CHINA | MALAYSIA
Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by
Engineering and Physical Sciences Research Council

Opportunities and challenges

MariNH$_3$
Clean, green ammonia engines for maritime

Doesn’t produce CO_2 during burning

The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by UKRI Engineering and Physical Sciences Research Council

Opportunities and challenges

MariNH$_3$
Clean, green ammonia engines for maritime

Doesn't produce CO_2 during burning

Easy storage and handling

The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
UNIVERSITY OF BIRMINGHAM
University of Brighton
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
Funded by UKRI Engineering and Physical Sciences Research Council

Opportunities and challenges

MariNH3
Clean, green ammonia
engines for maritime

Doesn't produce CO_2 during burning

Easy storage and handling

Can produce hydrogen during cracking

The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by UKRI Engineering and Physical Sciences Research Council

Opportunities and challenges

MariNH3

Clean, green ammonia engines for maritime

Doesn't produce CO_2 during burning

Easy storage and handling

Can produce hydrogen during cracking

Slow combustion, NOx and N_2O emissions

Challenge: Achieving near-zero emissions while maintaining practical engine operation

The partnership

University of Nottingham UK | CHINA | MALAYSIA

UKRI Science and Technology Facilities Council

UNIVERSITY OF BIRMINGHAM

University of Brighton

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

Funded by UKRI Engineering and Physical Sciences Research Council

Opportunities and challenges

MariNH3
Clean, green ammonia engines for maritime

Doesn't produce CO_2 during burning

Easy storage and handling

Can produce hydrogen during cracking

Slow combustion, NOx and N_2O emissions

Unburned ammonia (Ammonia slip)

Challenge: Achieving near-zero emissions while maintaining practical engine operation

The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by
UKRI Engineering and Physical Sciences Research Council

Near-zero emission strategy

MariNH3
Clean, green ammonia engines for maritime

- Ammonia engines produce **NOx & unburned NH_3**
- SCR aftertreatment system **uses NH_3 to reduce NOx**

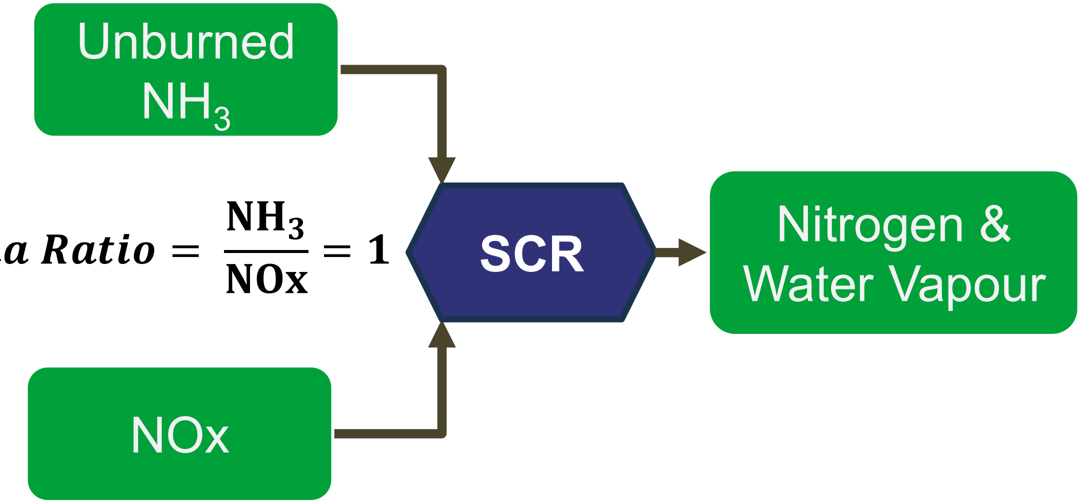
The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by UKRI Engineering and Physical Sciences Research Council

Near-zero emission strategy

MariNH$_3$
Clean, green ammonia engines for maritime

- Ammonia engines produce **NOx & unburned NH$_3$**
- SCR aftertreatment system **uses NH$_3$ to reduce NOx**

$$\boldsymbol{Alpha\ Ratio} = \frac{\mathbf{NH_3}}{\mathbf{NOx}} = \mathbf{1}$$



Near-zero emissions are theoretically possible when NH$_3$ and NOx are present in approximately equal amounts (NH$_3$ ppm = NOx ppm)) at engine out.

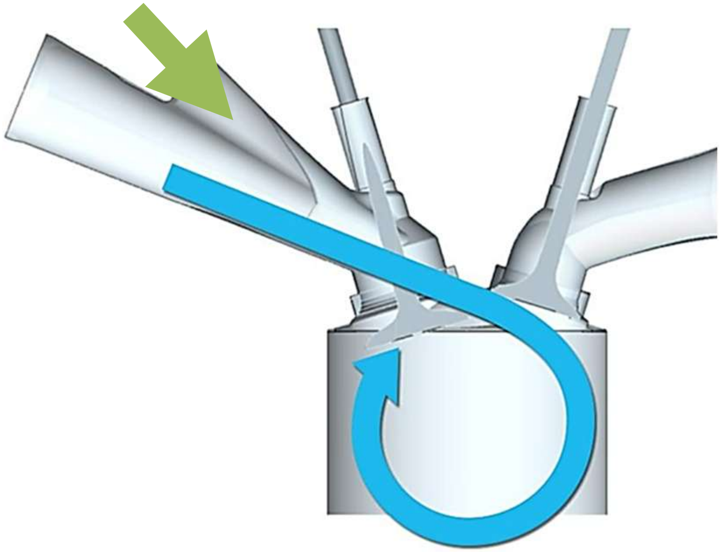
The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
UNIVERSITY OF BIRMINGHAM
University of Brighton
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
Funded by UKRI Engineering and Physical Sciences Research Council

Validation and development

MariNH3
Clean, green ammonia engines for maritime

Prior Work: Demonstration of α = 1 in a Lean-Burn Ammonia–Hydrogen SI Engine

PFI Hydrogen and Ammonia



MAHLE Single Cylinder Research Engine

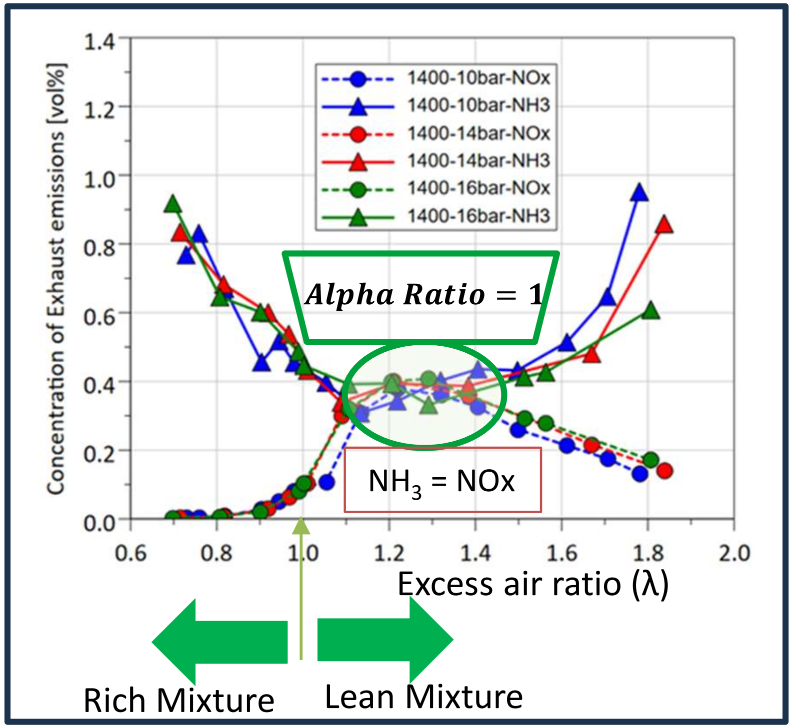
The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by UKRI Engineering and Physical Sciences Research Council

Validation and development

MariNH3
Clean, green ammonia engines for maritime

Prior Work: Demonstration of α = 1 in a Lean-Burn Ammonia–Hydrogen SI Engine

Ammonia-Hydrogen Co-Fuelling



Alpha ratio = 1 achieved **at λ = 1.2, H_2: 20 % by energy**

Validation and development

MariNH3
Clean, green ammonia engines for maritime

Validation of Alpha = 1 in lean burn SI engine

- ✓ Ammonia co-fuelling with bottled hydrogen in SI engine
- ✓ Equimolar NH_3/NOx (α) via H_2 share: External Hydrogen Required !!

Mono-Fuel Ammonia Engine

Validation and development

MariNH$_3$
Clean, green ammonia engines for maritime

Validation of Alpha = 1 in lean burn SI engine

- ✓ Ammonia co-fuelling with bottled hydrogen in a spark ignition engine
- ✓ Equimolar NH_3/NOx (α) via H_2 share: External Hydrogen Required !!

Ammonia mono-Fuel E-cracker

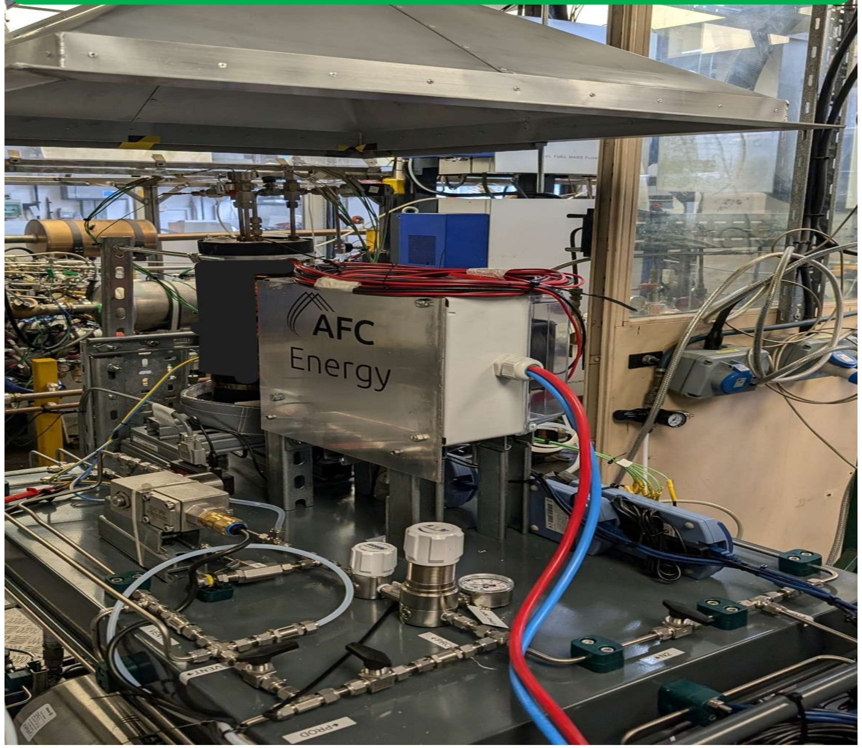
$$\text{(Ammonia) } 2NH_3 \xrightarrow{\text{cracker}} 3H_2 + N_2 \text{ (cracked gas)}$$

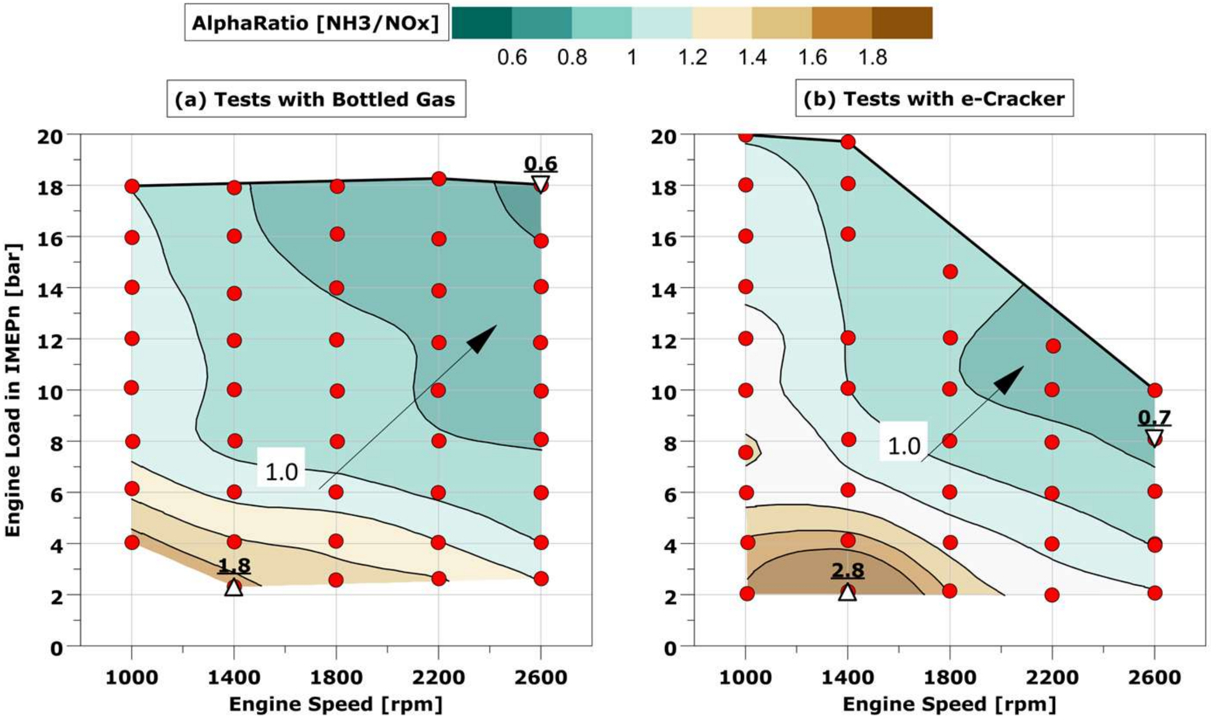
Mono-Fuel Ammonia Engine

Validation and development

MariNH3
Clean, green ammonia engines for maritime

Ammonia-Cracked co-fuelling for α = 1: Ammonia Mono Fuel





Alpha ratio = 1 achieved over a wide engine operating map

The partnership

University of Nottingham UK | CHINA | MALAYSIA

UKRI Science and Technology Facilities Council

UNIVERSITY OF BIRMINGHAM

University of Brighton

CARDIFF UNIVERSITY PRIFYSGOL CAERDYD

Funded by UKRI Engineering and Physical Sciences Research Council

Validation and development

MariNH$_3$
Clean, green ammonia engines for maritime

Validation of Alpha = 1 in lean burn SI engine

- ✓ Ammonia co-fuelling with bottled hydrogen in SI engine
- ✓ Equimolar NH_3/NOx (α) via H_2 share: External Hydrogen Required !!

Ammonia mono fuel E-cracker

- ✓ Cracked gas (N_2+H_2) co-fuelling in SI engine
- ✓ α = 1 across the full engine map. Electrical Power for Cracking!

Mono-Fuel Ammonia Engine

The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by UKRI Engineering and Physical Sciences Research Council

Validation and development

MariNH3
Clean, green ammonia engines for maritime

Validation of Alpha = 1 in a lean burn SI engine

- ✓ Ammonia co-fuelling with bottled hydrogen in a spark ignition engine
- ✓ Equimolar NH_3/NOx (α) via H_2 share: External Hydrogen Required !!

Ammonia mono fuel E-cracker

- ✓ Cracked gas (N_2+H_2) co-fuelling in SI engine
- ✓ α = 1 across the full engine map. Electrical Power for Cracking!

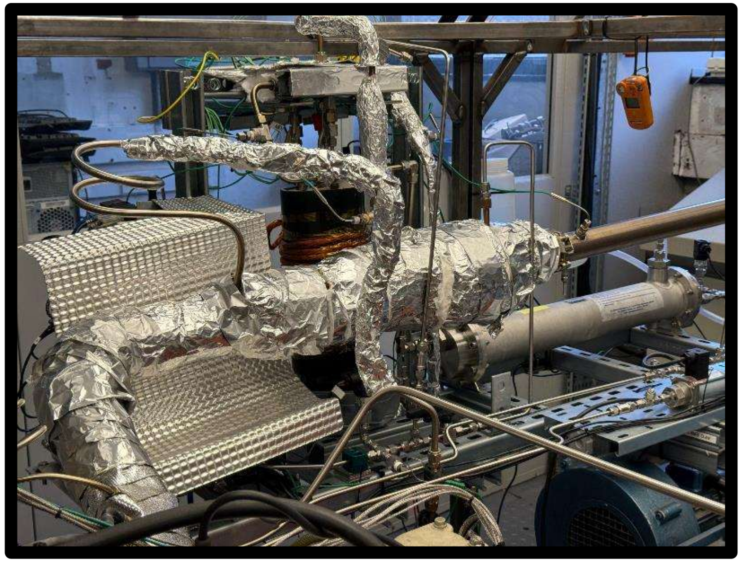
E-Cracker + thermal recuperator

Mono-Fuel Ammonia Engine

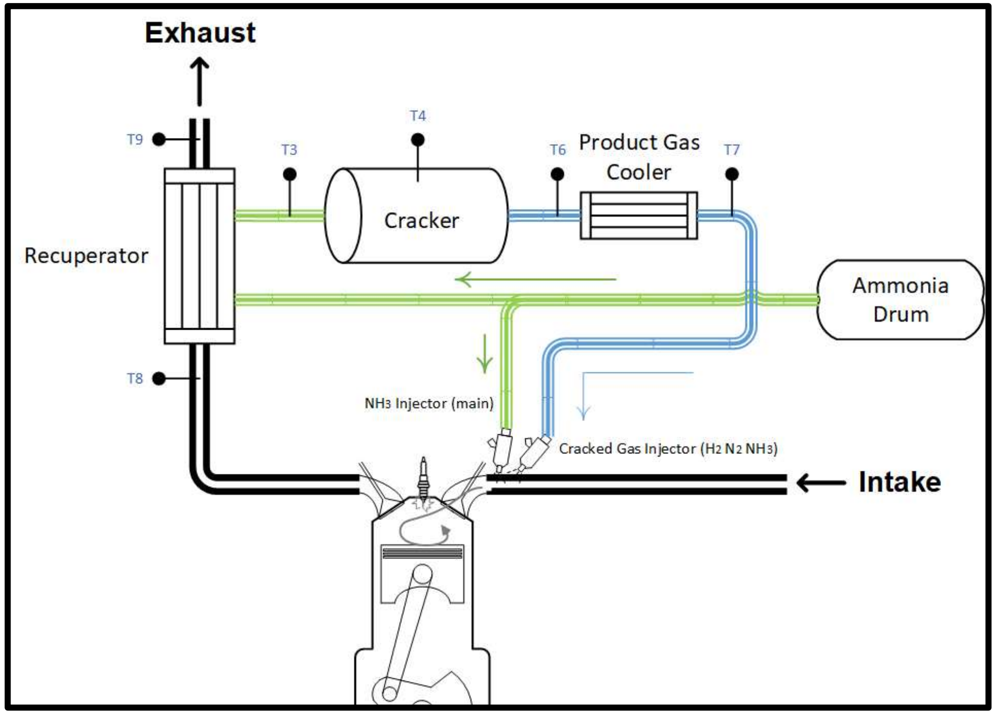
Validation and development

MariNH3
Clean, green ammonia engines for maritime

Integrated cracker with exhaust heat recovery



- Integrated cracker with exhaust heat recovery



Alpha ratio = 1 achieved over a wide engine operating map

Validation and development

MariNH3
Clean, green ammonia engines for maritime

Validation of Alpha = 1 in a lean burn SI engine

- ✓ Ammonia co-fuelling with bottled hydrogen in a spark ignition engine
- ✓ Equimolar NH_3/NOx (α) via H_2 share: External Hydrogen Required !!

Ammonia mono fuel E-cracker

- ✓ Cracked gas (N_2+H_2) co-fuelling in SI engine
- ✓ α = 1 across the full engine map. Electrical Power for Cracking!

E-Cracker + thermal recuperator

- ✓ Exhaust waste heat recovered
- ✓ α = 1; Power demand reduced by up to 35 %

Mono-Fuel Ammonia Engine

The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by UKRI Engineering and Physical Sciences Research Council

Validation and development

MariNH$_3$
Clean, green ammonia engines for maritime

Validation of Alpha = 1 in a lean burn SI engine

- ✓ Ammonia co-fuelling with bottled hydrogen in a spark ignition engine
- ✓ Equimolar NH_3/NOx (α) via H_2 share: External Hydrogen Required !!

Ammonia mono fuel E-cracker

- ✓ Cracked gas (N_2+H_2) co-fuelling in SI engine
- ✓ α = 1 across the full engine map. Electrical Power for Cracking!

E-Cracker + thermal recuperator

- ✓ Exhaust waste heat recovered
- ✓ α = 1; Power demand reduced by up to 35 %

Achieving near-zero emission

Does α ≈ 1 deliver near-zero tailpipe emissions?
Does **engine architecture** reduce the hydrogen required?
Can it be scaled to a practical marine application?

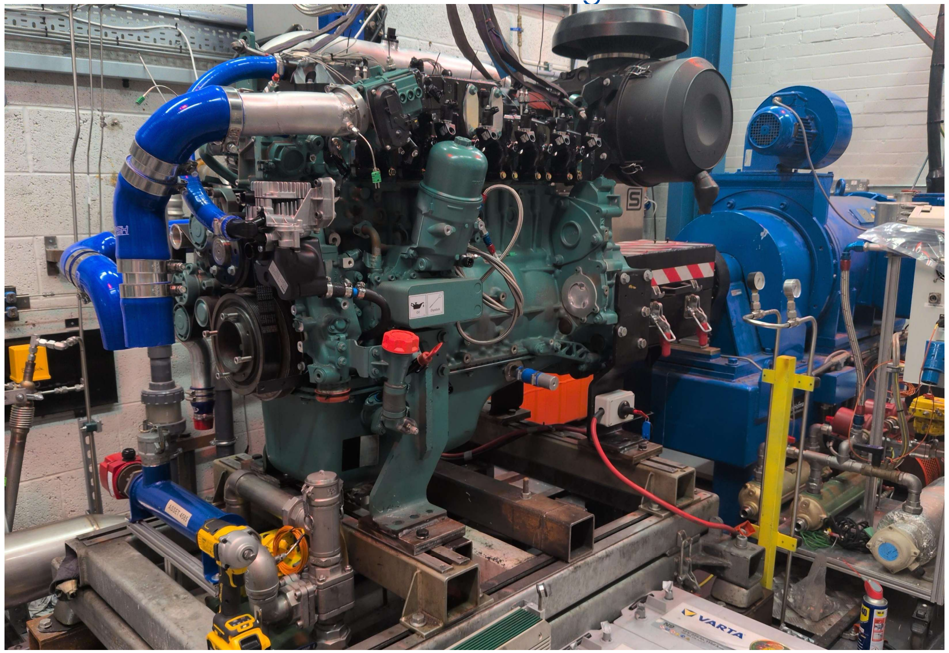
Mono-Fuel Ammonia Engine

Achieving near-zero emissions

MariNH₃
Clean, green ammonia engines for maritime

Engine hardware

Single-Cylinder Research Engine (High Tumble)
Compression Ratios: 12.5 and 17.5



VOLVO D8 Heavy-duty
200 kW Demonstrator Engine

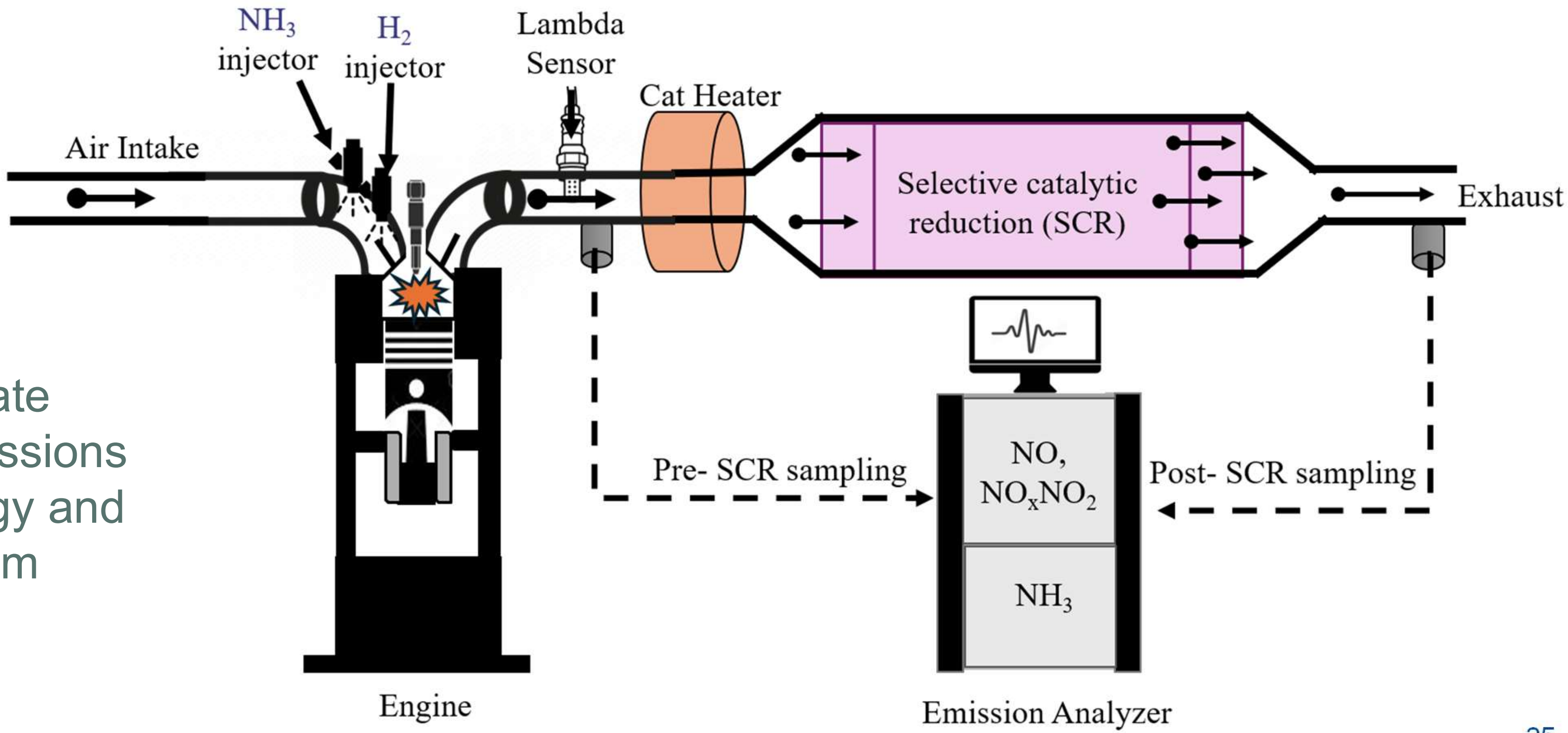
Scaling up to marine applications

The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
UNIVERSITY OF BIRMINGHAM
University of Brighton
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
Funded by
UKRI Engineering and Physical Sciences Research Council

Achieving near-zero emissions

MariNH3
Clean, green ammonia
engines for maritime

Integrated Near-Zero Emissions System



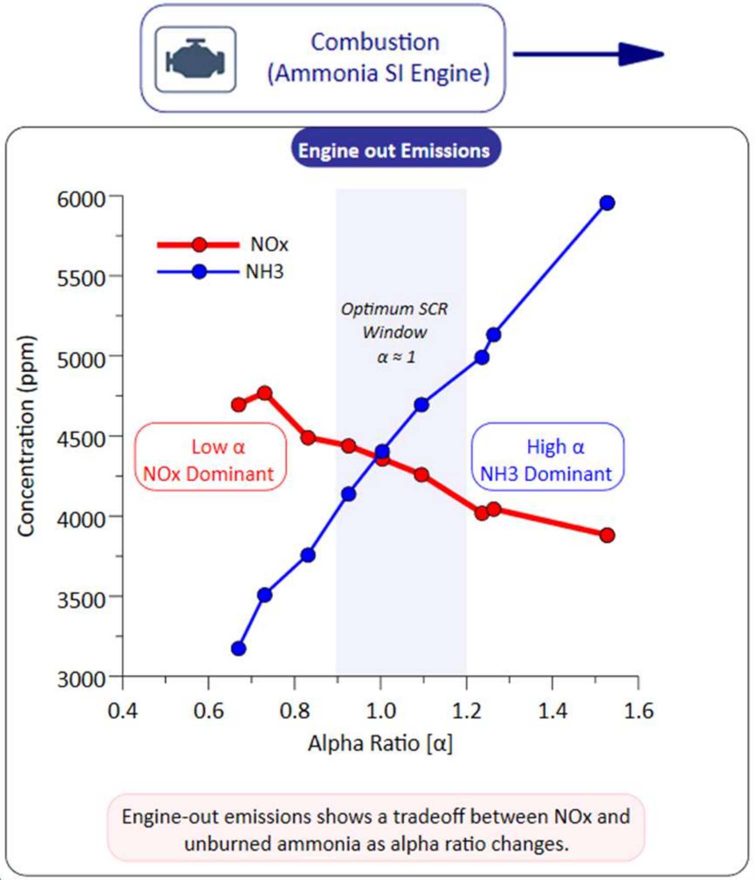
Objective: Demonstrate near-zero tailpipe emissions using the **α ≈ 1** strategy and a standard SCR system

The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
UNIVERSITY OF BIRMINGHAM
University of Brighton
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
Funded by UKRI Engineering and Physical Sciences Research Council

Achieving near-zero emissions

MariNH3
Clean, green ammonia engines for maritime

Experimental validation of the α ≈ 1 strategy



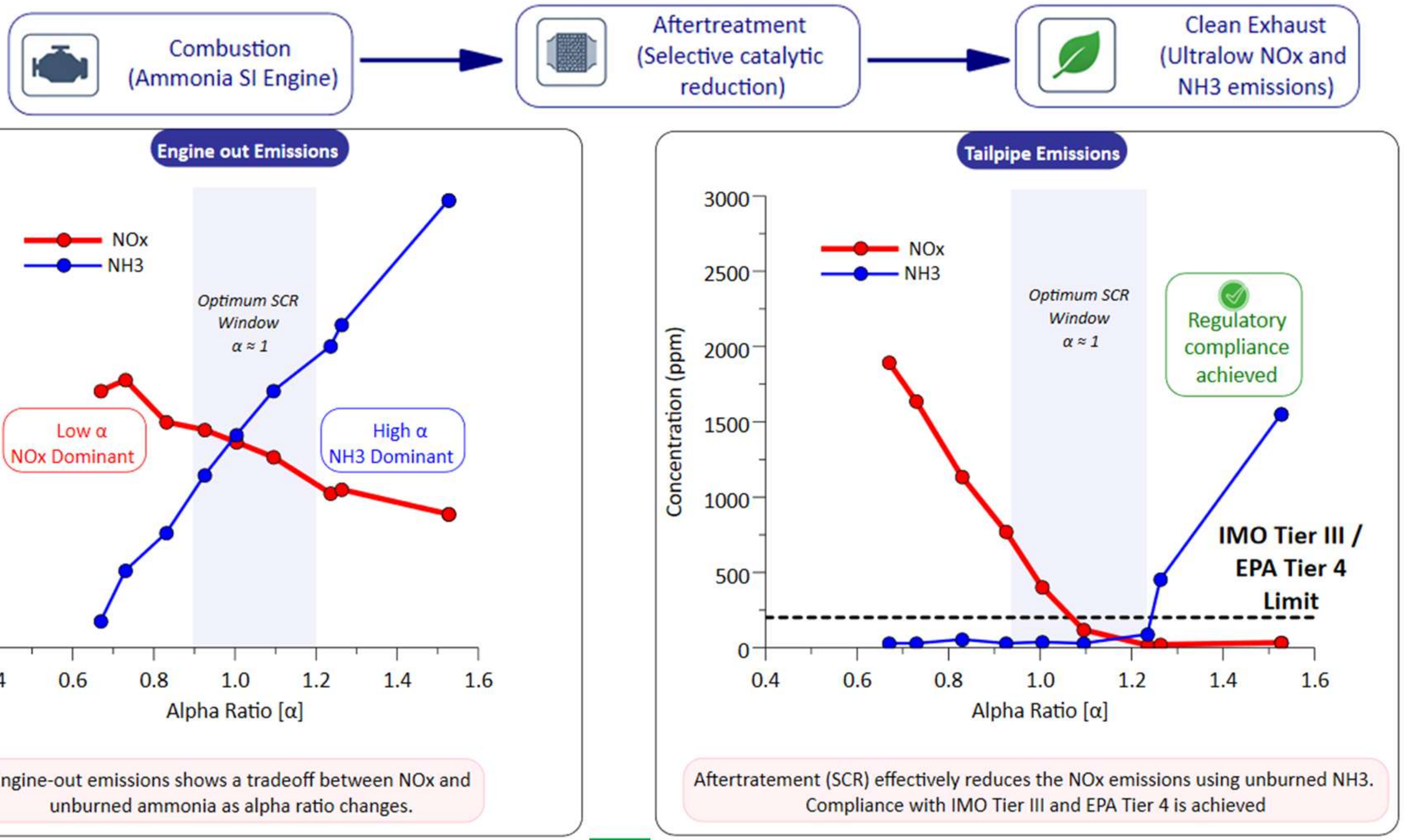
The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by UKRI Engineering and Physical Sciences Research Council

Achieving near-zero emissions

Experimental validation of the α ≈ 1 strategy

MariNH3

Clean, green ammonia engines for maritime



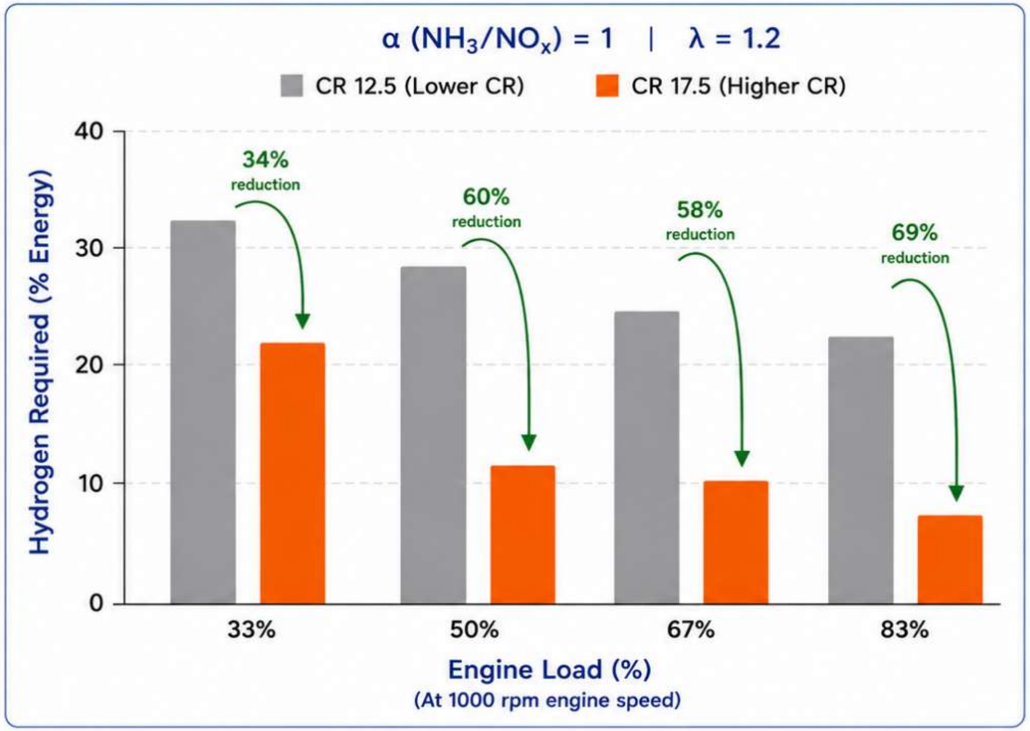
Near-zero tailpipe **NOx and NH_3** emissions were achieved at **α ≈ 1 - 1.1** using a standard SCR system

The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by UKRI Engineering and Physical Sciences Research Council

Achieving near-zero emissions

Enhancing the strategy through engine architecture: High compression ratio high tumble effect

MariNH3
Clean, green ammonia engines for maritime



Up to 70% Less Hydrogen Required

while maintaining α ≈ 1

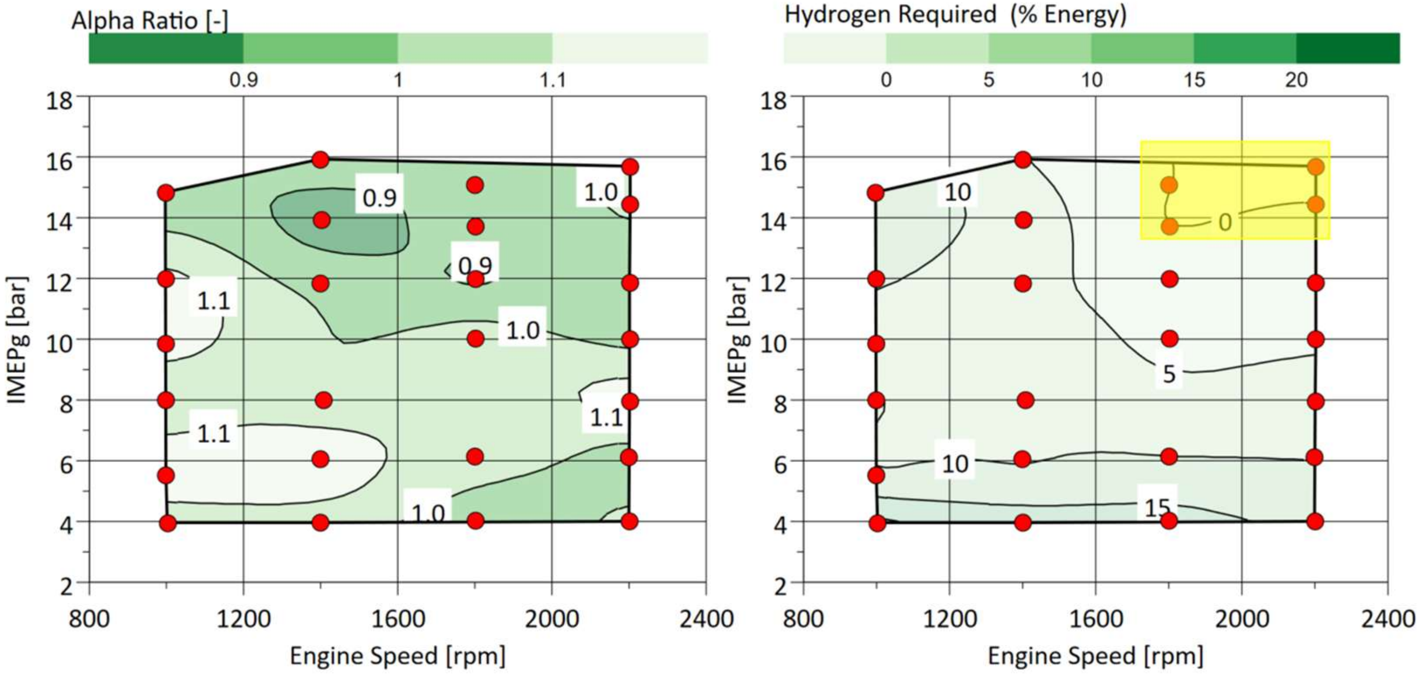
- Maintains α ≈ 1 (Near-zero emissions)
- Smaller ammonia cracker required
- Lower parasitic energy consumption
- Improves feasibility of mono-fuel ammonia engines

Near-zero emissions achieved with up to 70% lower hydrogen demand.

Achieving near-zero emissions

High compression ratio: Whole engine operating map with hydrogen requirement

MariNH3
Clean, green ammonia engines for maritime



Results obtained using a high-compression-ratio (CR 17.5), high-tumble research engine.

Hydrogen requirement

α ≈ 0.9 – 1.1 is maintained across the operating range

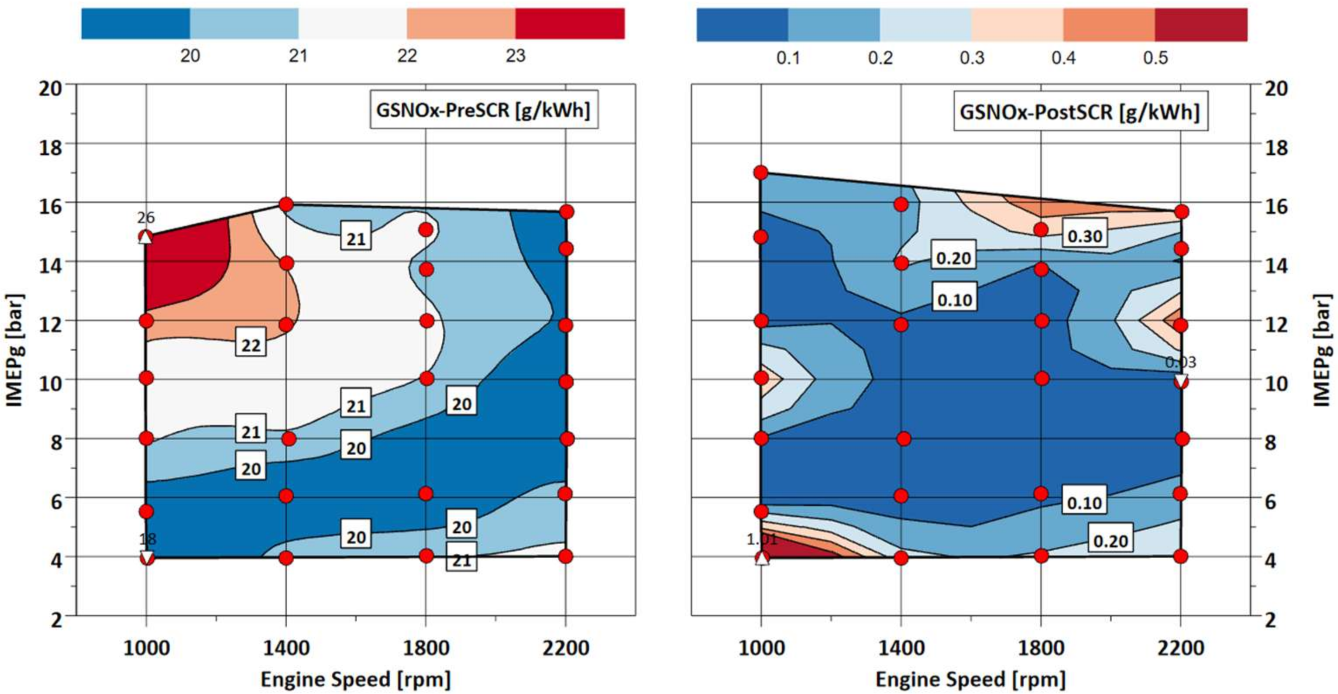
Hydrogen demand is substantially reduced at high load and speed

Reduced hydrogen demand enables greater hydrogen availability during **transient operation**

Achieving near-zero emissions

MariNH3
Clean, green ammonia engines for maritime

IMO Tier III	Euro 7 WHSC	EPA Tier 4
2.0 (2000 rpm)	0.2	0.4



NOx emissions

Compliant with **IMO Tier III** across the full operating range

Meets **EPA Tier 4** limits at most operating points

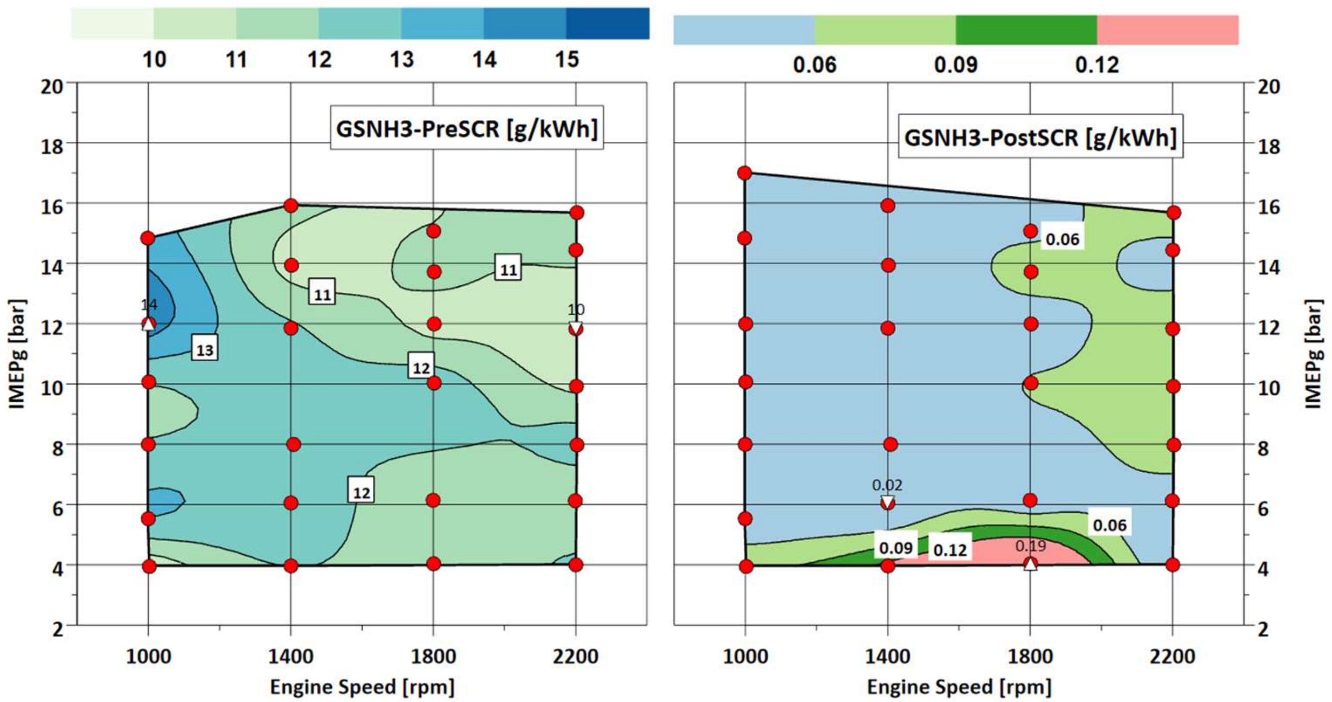
NOx conversion efficiency > **98 %**

The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by UKRI Engineering and Physical Sciences Research Council

Achieving near-zero emissions

MariNH3
Clean, green ammonia engines for maritime

IMO Tier III	Euro 7 WHSC	EPA Tier 4
NA	0.06 g/kWh	10ppm*



Ammonia emissions

Post-SCR Ammonia emissions are within **Euro 7 WHSC** limits at most operating points

NH_3 utilization efficiency > **98 %**

The partnership

University of Nottingham UK | CHINA | MALAYSIA

UKRI Science and Technology Facilities Council

University of Birmingham

University of Brighton

Cardiff University Prifysgol Caerdydd

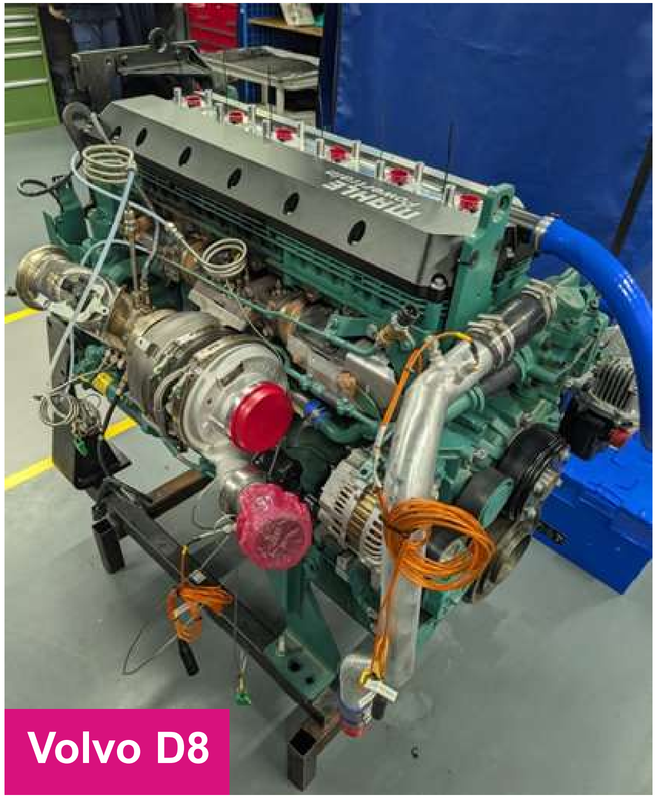
Funded by UKRI Engineering and Physical Sciences Research Council

Achieving near-zero emissions

VOLVO D8 Heavy-duty: *200 kW Demonstrator Engine*

MariNH$_3$
Clean, green ammonia engines for maritime

- Volvo D8 engine was converted into a SI system.
  - PFI Hydrogen & Ammonia
- Combined with a Modular SCR system
  - 3 SCR Blocks + ASC catalyst
- Validate the Alpha = 1 Lean operating strategy in a Multi-cylinder engine.

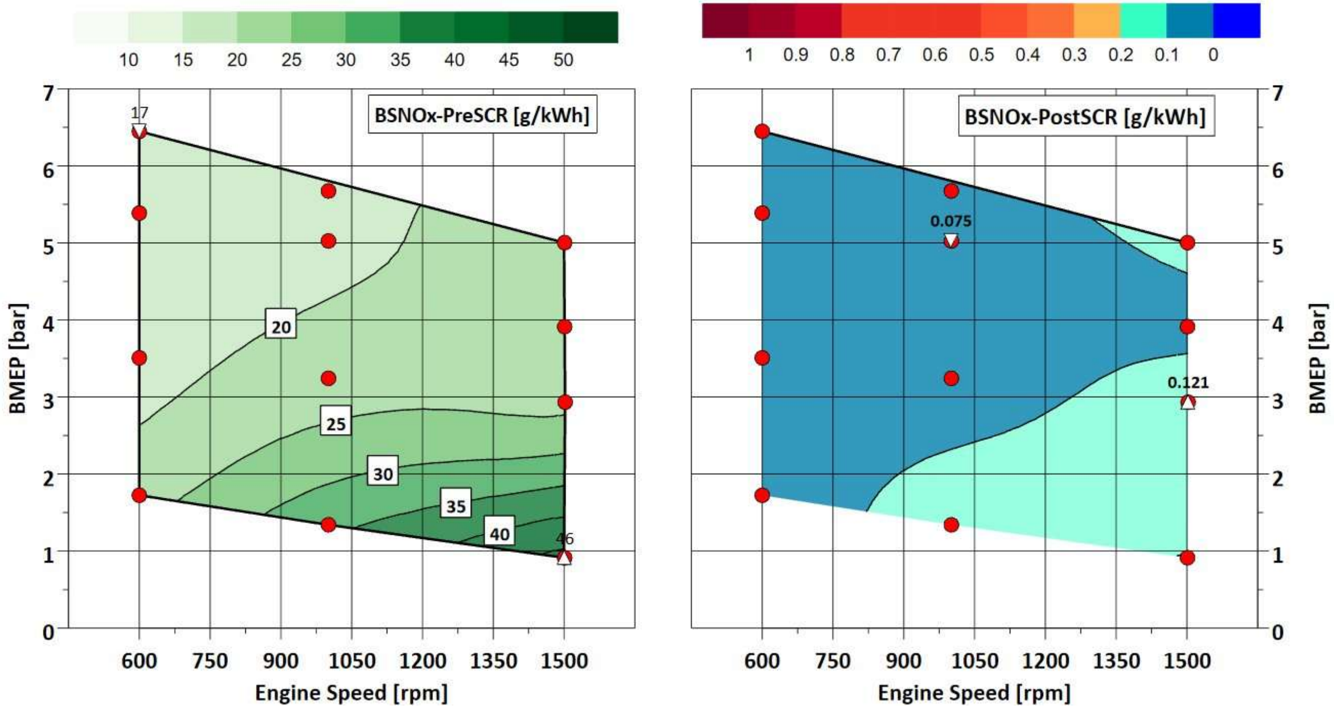


Achieving near-zero emissions

VOLVO D8 Heavy-duty: *200 kW Demonstrator Engine*

MariNH3
Clean, green ammonia engines for maritime

IMO Tier III	Euro 7 WHSC	EPA Tier 4
2.0 (2000 rpm)	0.2	0.4



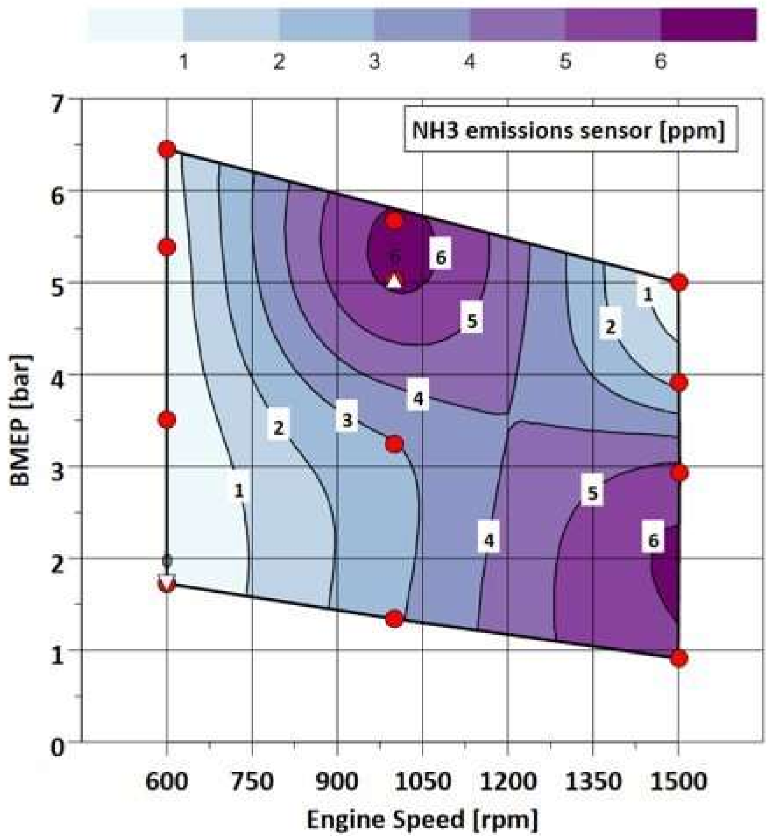
NOx emissions

- Pre-SCR NOx emissions **20 times** that of IMO tier III limits
- Emissions measurements post-SCR show a max of 0.121 g/kWh
  - **16 times below IMO limits**
  - **3.5 times below EPA Tier 4 limits**
  - **1.6 times below Euro 7 WHSC limits**
- Very-low speed and low load operation

Achieving near-zero emissions

VOLVO D8 Heavy-duty: *200 kW Demonstrator Engine*

MariNH3
Clean, green ammonia engines for maritime



IMO Tier III	Euro 7 WHSC	EPA Tier 4
NA	0.06 g/kWh	10ppm*

Unburned ammonia emissions

- Post SCR ammonia emissions less than **10ppm** throughout the tested area
- Ammonia emissions below **EPA Tier 4 emissions**
- N_2O emissions were monitored and were below 100 ppm for the investigated conditions

The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
UNIVERSITY OF BIRMINGHAM
University of Brighton
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD
Funded by UKRI Engineering and Physical Sciences Research Council

Conclusions

MariNH3
Clean, green ammonia engines for maritime

01 Near-zero tailpipe emissions achieved **(>98% NOx and >99% NH_3 conversion)**, meeting **IMO Tier III and EPA Tier 4** requirements.

02 Post-SCR NOx emissions were up to **16 × lower than IMO limits**, **3.5× lower than EPA Tier 4** limits, and **1.6 × lower than Euro 7 WHSC** limits.

03 Operating the engine at an **Alpha ratio of 1-1.2** results in the **>98% simultaneous reduction of engine-out NOx and Unburned Ammonia**

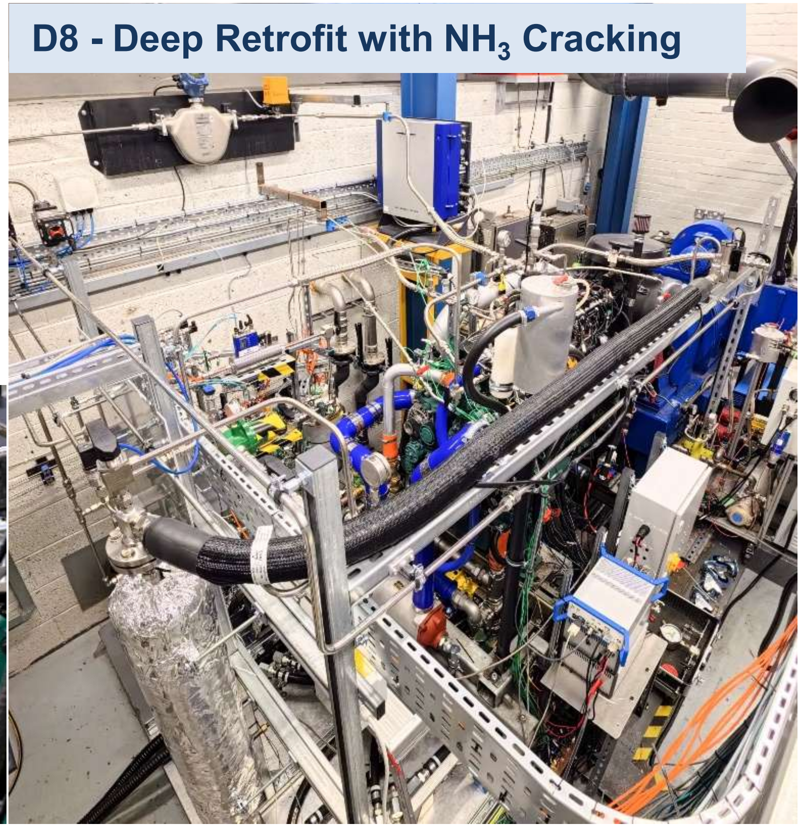
04 Hydrogen energy demand is reduced **by up to 70%** through high-compression-ratio operation, enabling more efficient **ammonia-cracker integration**.

The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by
UKRI Engineering and Physical Sciences Research Council

Ongoing work

MariNH3
Clean, green ammonia
engines for maritime

- Single-Cylinder (SCRE):
  - **N_2O mapping** across the operating range at different compression ratios
  - NH_3 DI injector fitted with installation of liquid supply in progress
- Volvo D8 Deep Retrofit:
  - **SCR–cracker** test with waste heat recovery integrated
  - Transient testing



The partnership
University of Nottingham UK | CHINA | MALAYSIA
UKRI Science and Technology Facilities Council
University of Birmingham
University of Brighton
Cardiff University Prifysgol Caerdydd
Funded by UKRI Engineering and Physical Sciences Research Council

Acknowledgements

MariNH3
Clean, green ammonia engines for maritime

University of Nottingham

- Prof Alasdair Cairns
- Prof Antonino La Rocca
- Jen Baldwin
- Benjamin Shaw
- Marcus Beal
- Dr Sikai Geng
- Dr Ajith Ambalakatte
- Alexander Birch
- Gagan Gopakumar Suja

Funding

MariNH3
Clean, green ammonia engines for maritime

REACT™
Retrofittable Emission-free Ammonia Combustion Technology

MAHLE Powertrain

- Anthony Harrington
- Jonathan Hall

MAHLE Powertrain

Industry Partners

clean air power™

H-POWER

JM Johnson Matthey

The partnership

University of Nottingham UK | CHINA | MALAYSIA

UKRI Science and Technology Facilities Council

University of Birmingham

University of Brighton

Cardiff University Prifysgol Caerdydd

Funded by UKRI Engineering and Physical Sciences Research Council

Thank you for listening

Any questions?

MariNH3

Clean, green ammonia engines for maritime

The partnership

University of Nottingham UK | CHINA | MALAYSIA

UKRI Science and Technology Facilities Council

UNIVERSITY OF BIRMINGHAM

University of Brighton

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

Funded by UKRI Engineering and Physical Sciences Research Council