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engines for maritime

Advancing Maritime Decarbonisation: Design and Optimisation of Ammonia-Fuelled Propulsion Systems

Dr Ebrahim Nadimi
Yan Zhang
Prof Dawei Wu
Department of Engineering, Durham University

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- Current state of ammonia-fuelled vessels
- 3D model of large-bore dual-fuel engine
- 1D model of ammonia-fuelled marine engine and propulsion
- Summary

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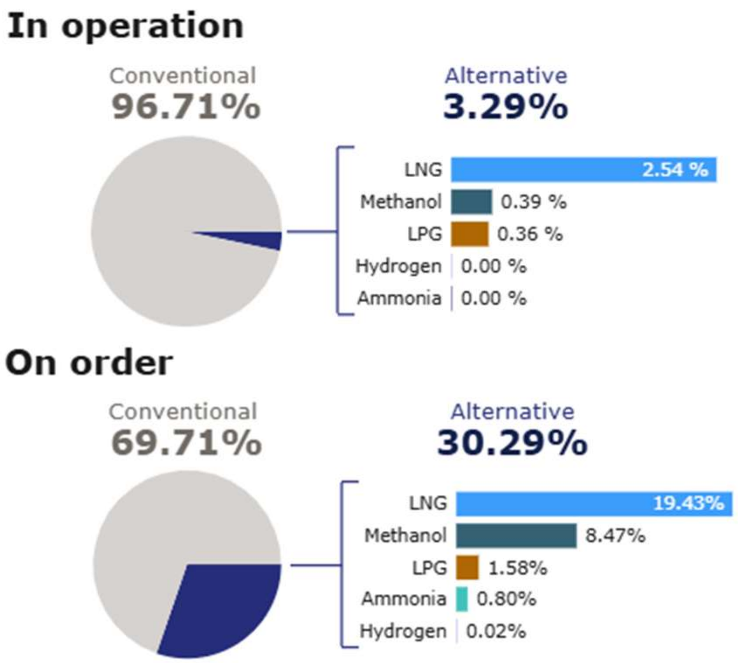
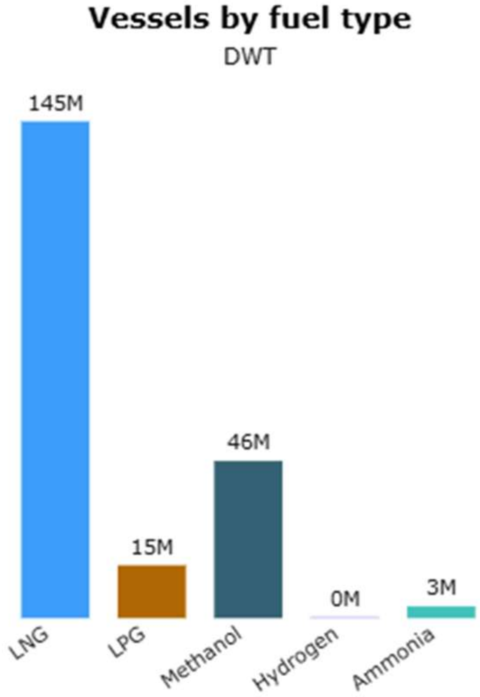
Current state of ammonia-fuelled vessels

- Despite a low current share in operating vessels, ammonia secured 0.80 % of all new fleet orders
- Around 3 million DWT of ammonia-fuelled vessels are currently on order





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Recent developments in ammonia marine engines

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Author / year	Engine / condition	Main parameters	Key findings
Xu et al., 2023	Wärtsilä DF32 marine engine; 6-cyl, 320 × 400 mm, 32.2 L/cyl, 750 rpm	Gaseous NH_3 port injection + diesel pilot; diesel energy 8.5–28%	Direct LNG→NH_3 replacement failed at very low diesel. Stable operation needed ~24–28% diesel. GHG ↓ ~70%, but NH_3 slip, NO and N_2O remained key issues.
Zhu et al., 2023	340 × 1600/ Large two-stroke marine engine	Low-pressure NH_3 gas; pilot timing; ASR	ASR ↑ delayed ignition. NO_x ↓ below ~ASR 40%, then ↑ due fuel-N. Clear NO_x–N_2O trade-off; advancing pilot reduced NH_3/N_2O.
Park et al., 2025	12.5 L single-cylinder marine DI NH_3 engine; 900 rpm	High-pressure NH_3 DI + diesel pilot timing/amount	Optimum pilot timing around BTDC 10 CAD / 3.7 ms advance. Reducing pilot energy by 4.1 pp caused power ↓ 5.9 pp and NH_3 ↑ 12.5 pp; N_2O followed poor combustion.
Bjørgen et al., 2024/2026	High-pressure NH_3–pilot dual-fuel combustion, marine-relevant	NH_3/pilot overlap; ambient T; OH* and NH_2* imaging	Partial pilot–NH_3 overlap gave lowest NH_3 and N_2O, highest efficiency, but NO_x ↑. Higher T improved ignition and reduced NH_3/N_2O but increased NO_x.
Yang et al., 2026	Direct-injection NH_3/diesel marine engine; 50% load, 900 rpm	NH_3/diesel timing; central vs side pilot; AEF 0.8	Optimised timing reduced NH_3/N_2O. Central 9-hole pilot + NH_3 advanced 5 CAD gave IMEP ↑4.8%, NH_3/N_2O ↓ by ~3×, but NO_x doubled.
Pedersen et al., 2025	NH_3/n-heptane DI CI engine, 1500 rpm	NH_3 injection timing; N_2O source tracking/ AES 42	N_2O accumulates near walls, NH_3-cooled zones, and late expansion oxidation. Early misdirected NH_3 increased N_2O up to 50%; simultaneous injection reduced N_2O by 37%.
Qian et al., 2024	130× 114/ 1500 rpm/ NH_3+diesel CI engine with premixed H_2	H_2 addition; diesel SOI; load; intake heating	H_2 increased pressure/HRR and ITE up to ~50%. NH_3 slip ↓, N_2O ↓ with early diesel, but NO_x ↑. Low load needed intake heating to 55 °C.

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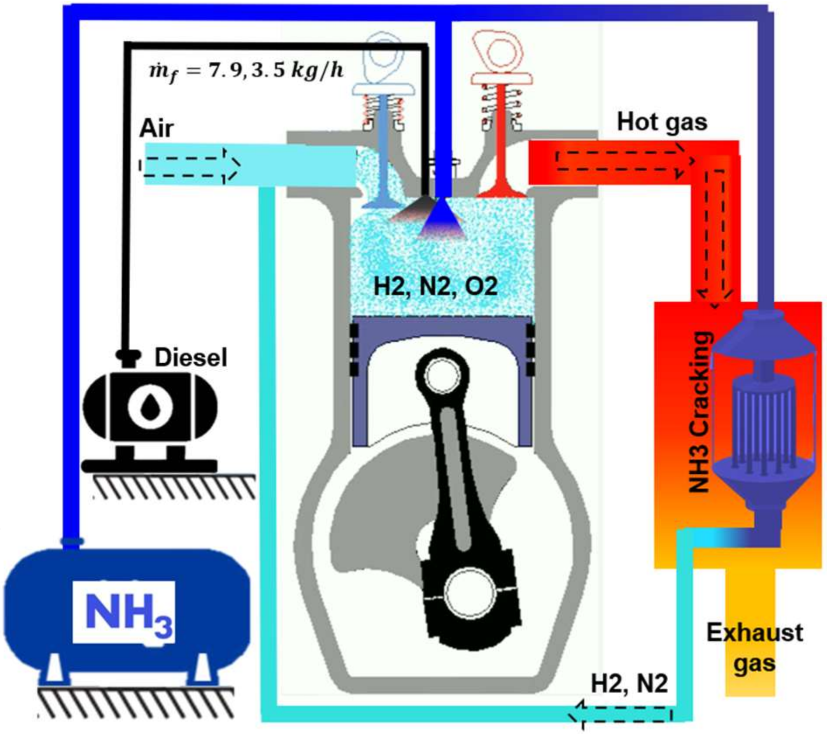
Dual fuel marine engine R&D

a) Retrofit pathways: retain pilot-diesel ignition and introduce ammonia:

- Ammonia port fuel injection in dual-fuel diesel engines ✓
- Direct ammonia injection with pilot diesel ignition ✓
- Partial ammonia cracking to generate H_2-rich reformate ✓
- Jet-ignition or pre-chamber concepts for enhanced combustion stability

b) Key modelling gaps and challenges for MW-scale engines:

- Limited experimental data/validated models are available for MW-scale, large-bore marine engines
- Identify NH_3 slip, NO_x and N_2O formation mechanisms and mitigation strategies
- Validated 1D models are required to transfer cylinder-level findings to multi-cylinder engine and ship-powertrain studies
- Use NSGA-II for powertrain component sizing optimisation and operating-strategy design optimisation



3D model of large-bore ammonia dual-fuel engine

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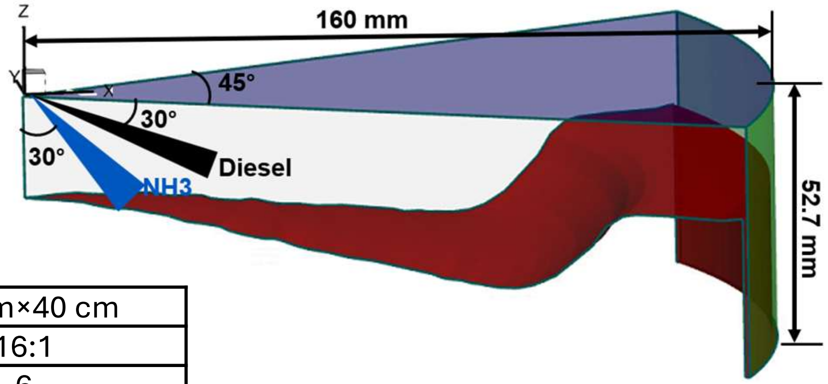
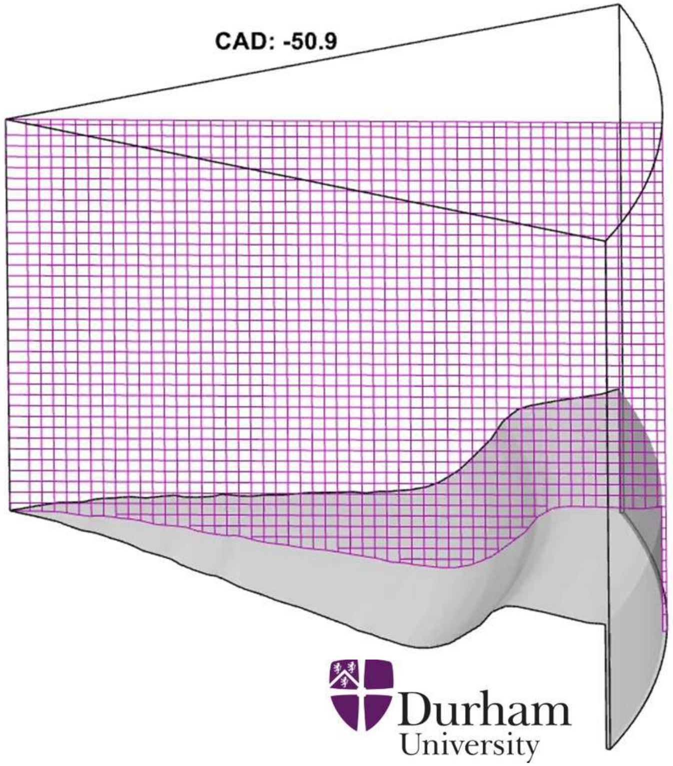
Ammonia dual-fuel marine engine model

- Wärtsilä DF32 Engine, 3.48 MW with H_2 enrichment
- 1/8 sector model with 8-hole diesel and ammonia injector representation.
- 1.15m cells/sector; base cell Δx = 2.7 mm; AMR near jets/walls
- Direct liquid ammonia injection when AES is 90% at fixed SOI diesel -25 CAD



Bore × Stroke	32 cm×40 cm
Compression Ratio	16:1
Number of cylinders	6
Displacement volume	32.2 L/cyl (192l)
Cylinder output power	580 kW/cyl
Engine speed	750 rpm
Intake valve close	-225 CA aTDC
Exhaust valve open	140 CA aTDC



Validation of the liquid-ammonia spray model

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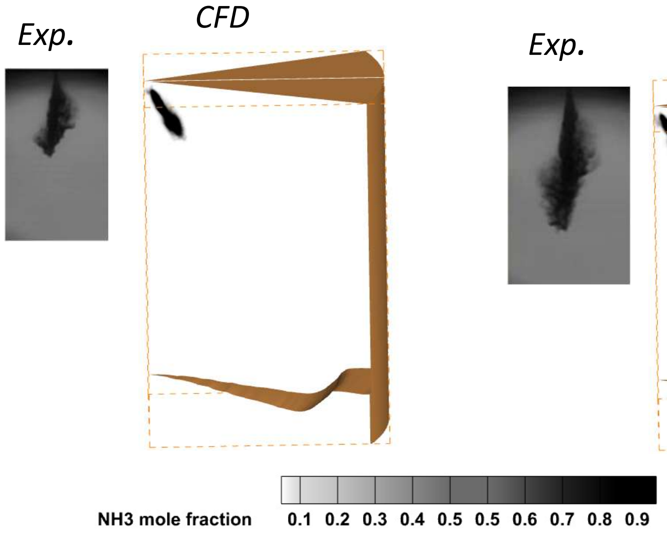
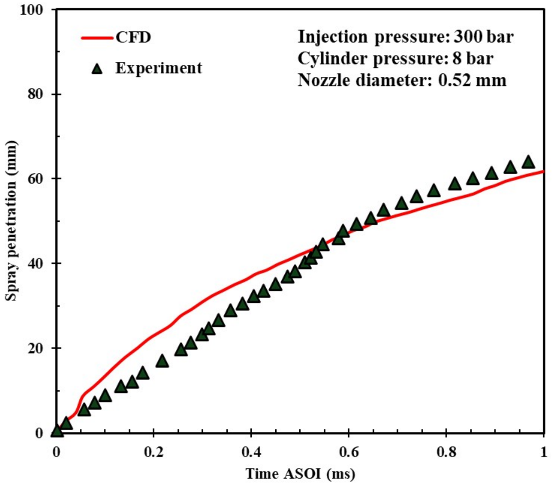
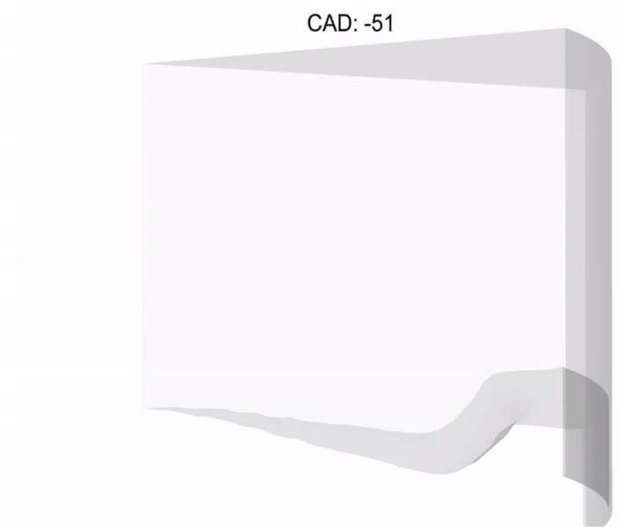
- Spray penetration was first validated under controlled conditions.
- The validated spray model was then used to analyse in-cylinder combustion and emissions formation

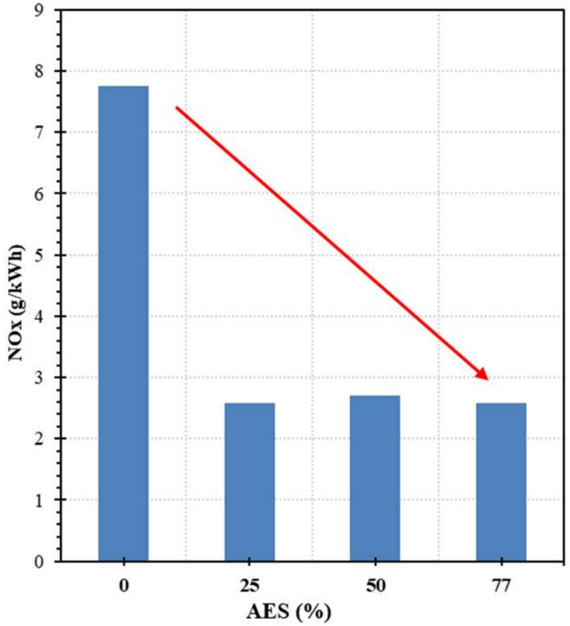


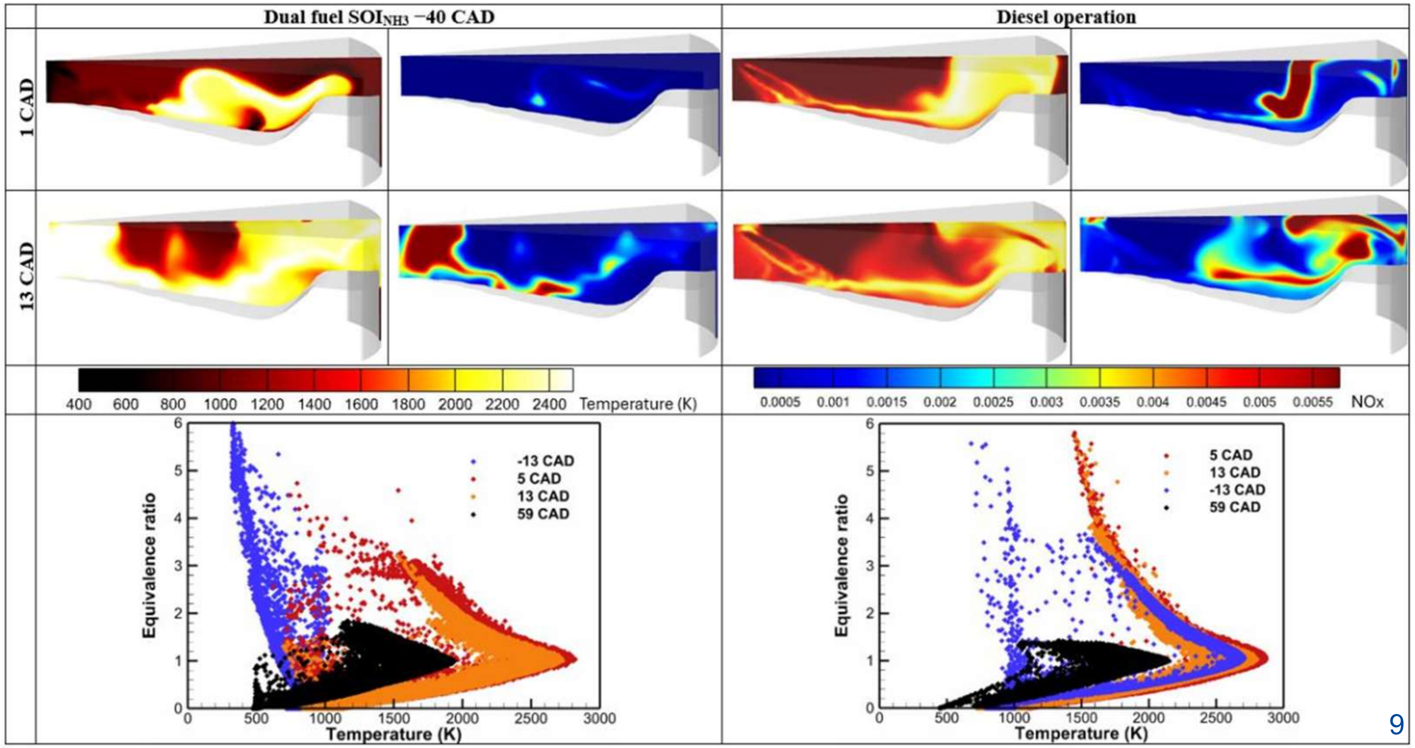




NOx formation dual-fuel marine engine model

- Ammonia reduced NOx emission from 7.76 g/kWh for pure diesel to 1.16 g/kWh for direct dual fuel injection
- Late injection of ammonia decreases NOx emissions due to decrease in local and peak cylinder temperature





NOx formation dual-fuel marine engine model

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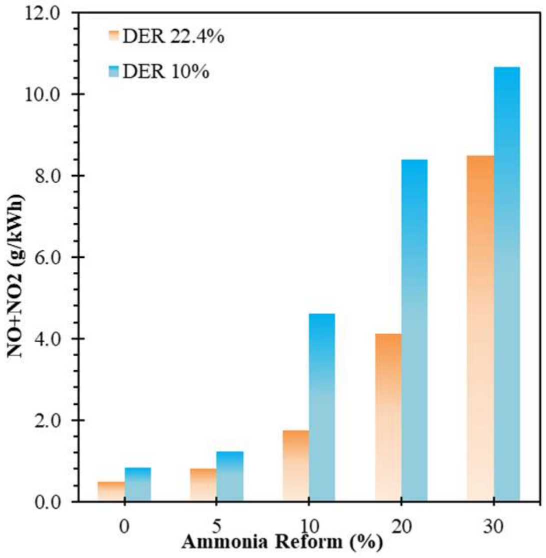
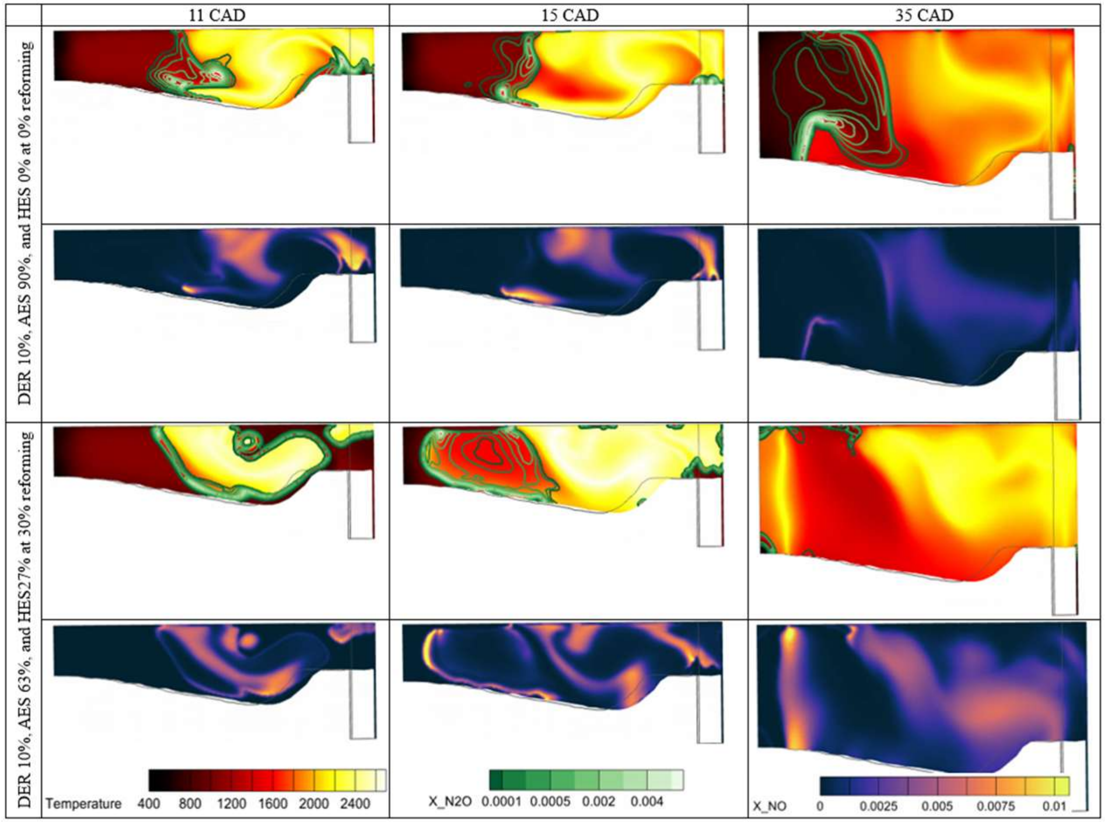
- At 30% reforming, NO_x increases from 0.83 to 10.67 g/kWh for DER 10%.
- H_2 enrichment improves flame propagation, expands the high-temperature region and increases the H/O/OH radical pool.





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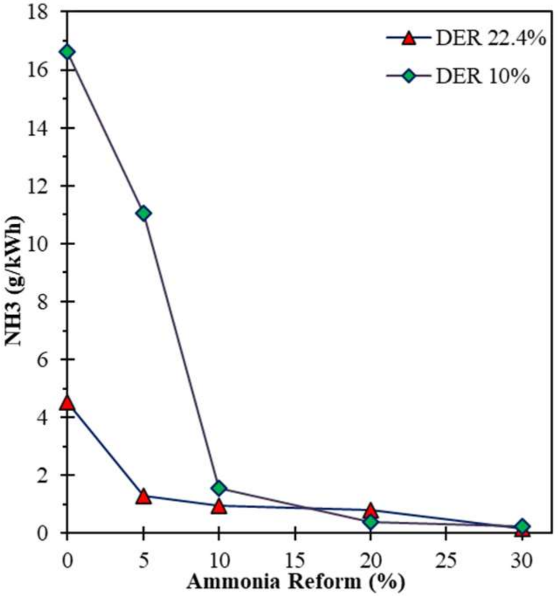
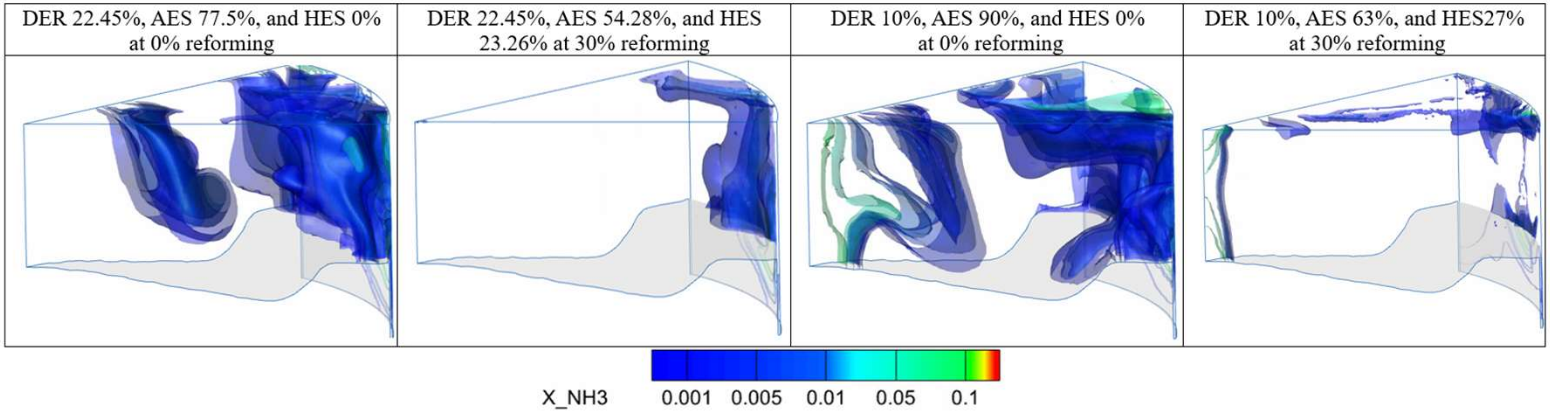
NH_3 in dual-fuel marine engine with H_2

- Lower diesel energy increases NH_3 slip: 4.52 → 16.63 g/kWh when DER decreases from 22.4% to 10%.
- Ammonia reforming sharply reduces NH_3 slip to 0.18–0.24 g/kWh at 30% reforming.
- H_2-rich reformate improves flame propagation and increases the H/OH radical pool, accelerating NH_3 oxidation.
- Residual NH_3-rich regions contract markedly, enabling near-zero NH_3 slip, even at AES 90%.





N_2O in ammonia dual-fuel marine engine model

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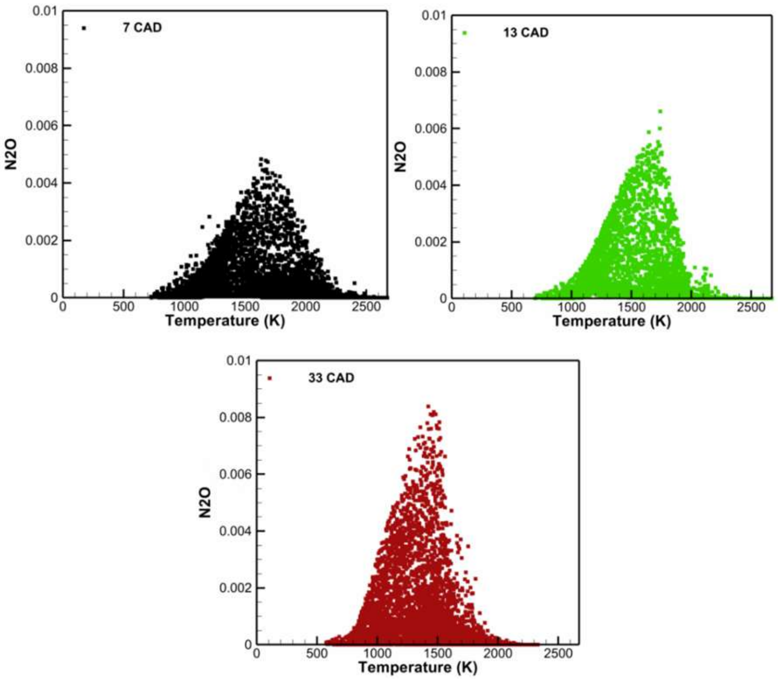
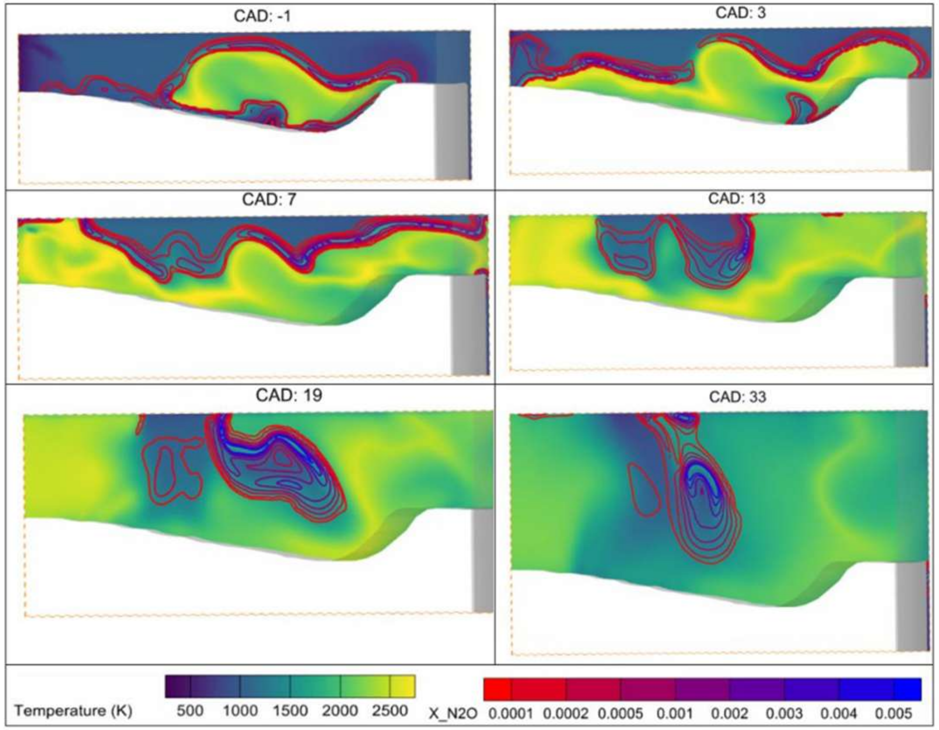
- N_2O mainly forms at 1000–1600 K, not in the hottest flame regions.
- At AES = 77%, N_2O first appears near the flame front and NH_3-rich pockets.
- At 19-33 CAD, residual NH3 and NO can continue forming N2O during expansion.
- Better NH_3–pilot overlap reduces N_2O formation.





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N_2O in dual-fuel marine engine with H_2

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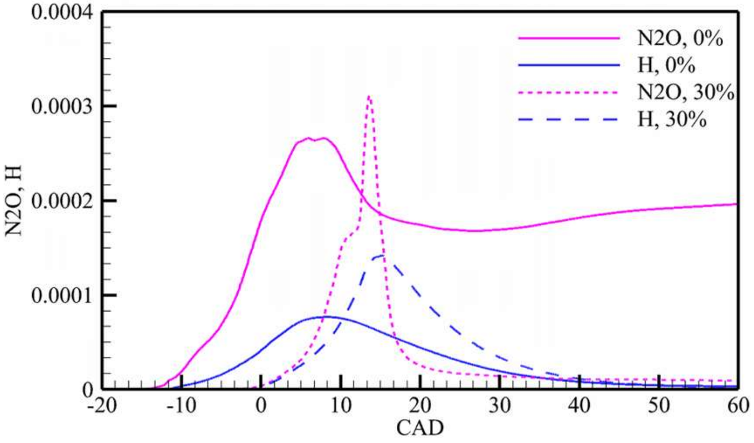
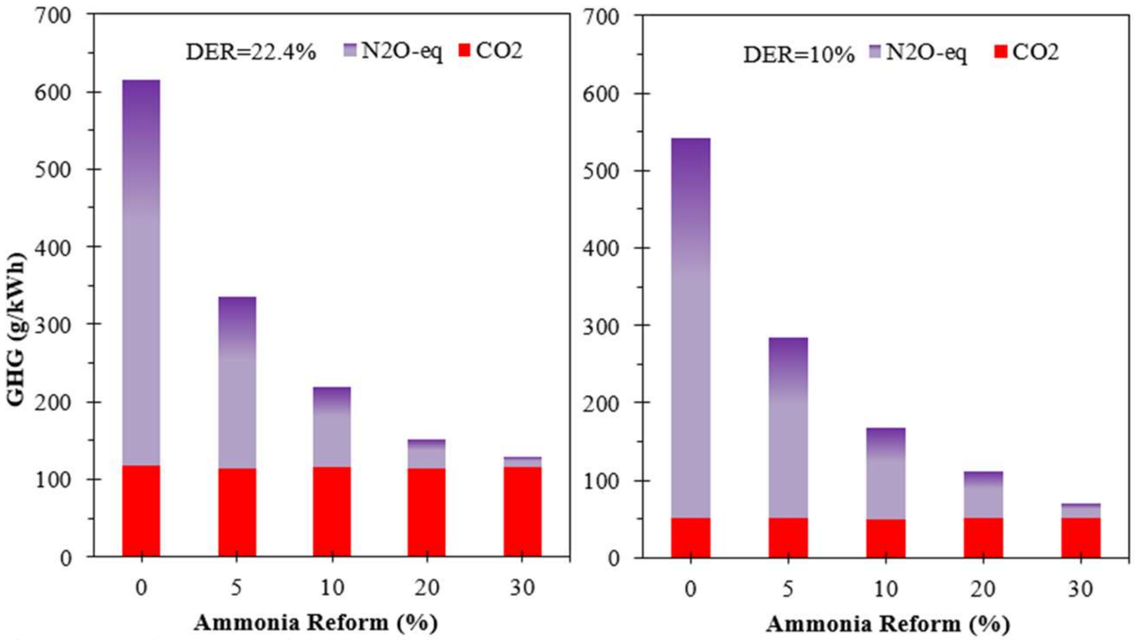
- H_2 from ammonia reforming increases the H/OH radical pool, accelerating NH_3 consumption and N_2O decomposition.
- For AES90 without reforming, weak H-radical availability allows N_2O to survive during expansion.
- Total GHG decreased from 542.6 to 70.2 g/kWh for AES90, an 87.1% reduction.





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1D model of ammonia-fuelled marine engine

(Design and Optimisation of Propulsion Systems)

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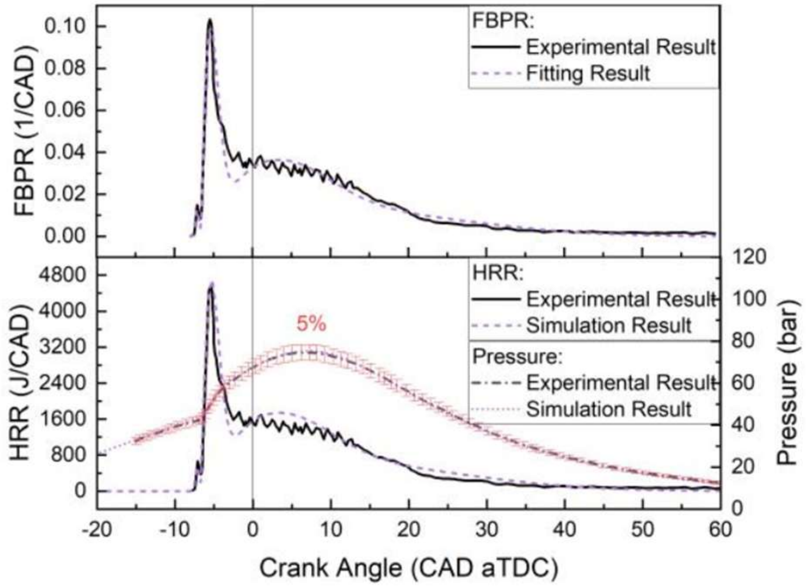
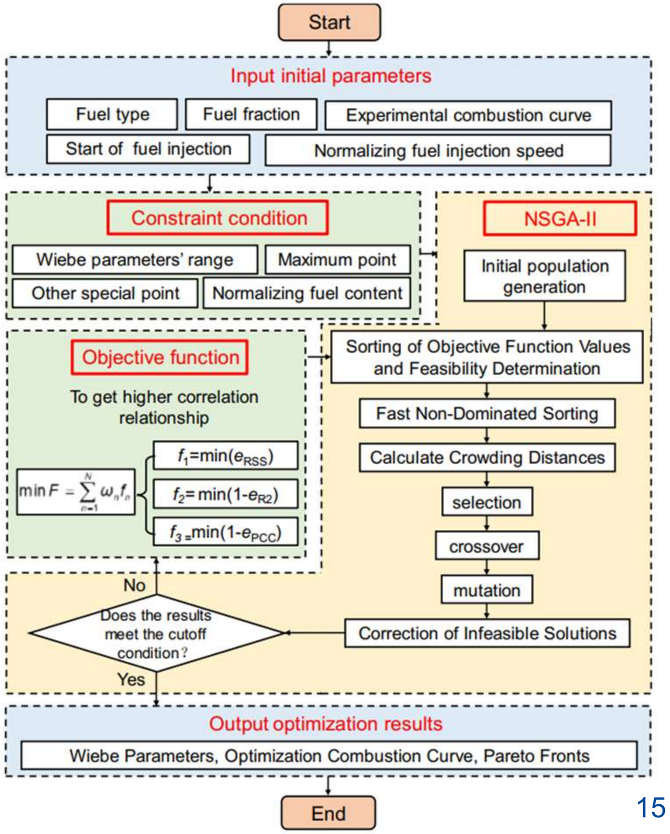
0D/1D ammonia–diesel marine engine model

- GT-Power 1D model was developed for the six-cylinder Wärtsilä 32 marine engine (3.48 MW).
- Multi-Wiebe combustion model captures the premixed, main/diffusion and tail heat-release phases.
- NSGA-II optimisation calibrates the Wiebe parameters against experimental pressure and HRR data
- 1D model enables rapid engine-performance prediction and ship powertrain optimisation




Start

Input initial parameters

Fuel type
Fuel fraction
Experimental combustion curve
Start of fuel injection
Normalizing fuel injection speed

Constraint condition

Wiebe parameters' range
Maximum point
Other special point
Normalizing fuel content

NSGA-II

Initial population generation

Objective function

To get higher correlation relationship

$\min F = \sum_{n=1}^{N} \omega_n f_n$

$f_1 = \min(e_{RSS})$
$f_2 = \min(1 - e_{R2})$
$f_3 = \min(1 - e_{PCC})$

Sorting of Objective Function Values and Feasibility Determination
Fast Non-Dominated Sorting
Calculate Crowding Distances
selection
crossover
mutation
Correction of Infeasible Solutions

Does the results meet the cutoff condition?
No
Yes

Output optimization results

Wiebe Parameters, Optimization Combustion Curve, Pareto Fronts

End

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Design and optimisation of ammonia-fuelled propulsion systems

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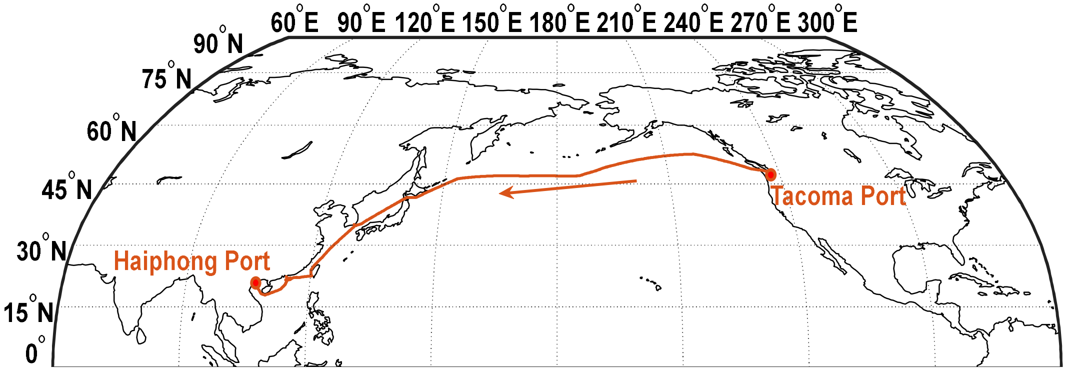
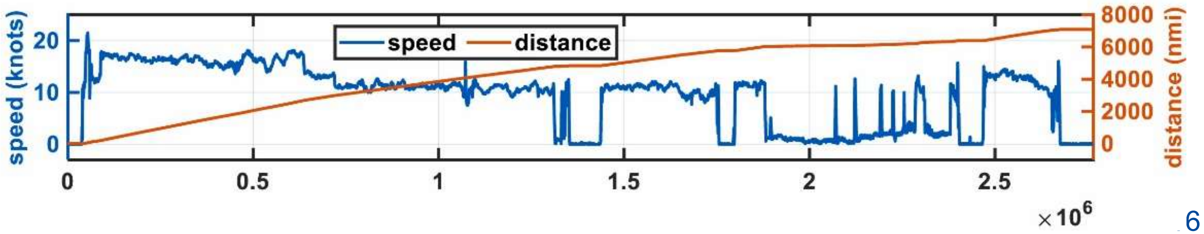
- 32-day sailing route from Tacoma Port, USA to Haiphong Port, Vietnam.
- Total sailing distance of around 8000 nautical miles.
- Vessel speed profile was used to drive the dynamic powertrain model.

Main parameters for the container ship.	Value
Length (m)	330
Breadth (m)	48
Depth (m)	27
Design draught (m)	13
70 %DWT for containerships (tonnes)	92,785
Propeller diameter (mm)	9,700
Number of blades	5
Number of Propeller set	1

- Large variation in propulsion demand makes engine oversizing and part-load operation.





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Model and optimisation framework

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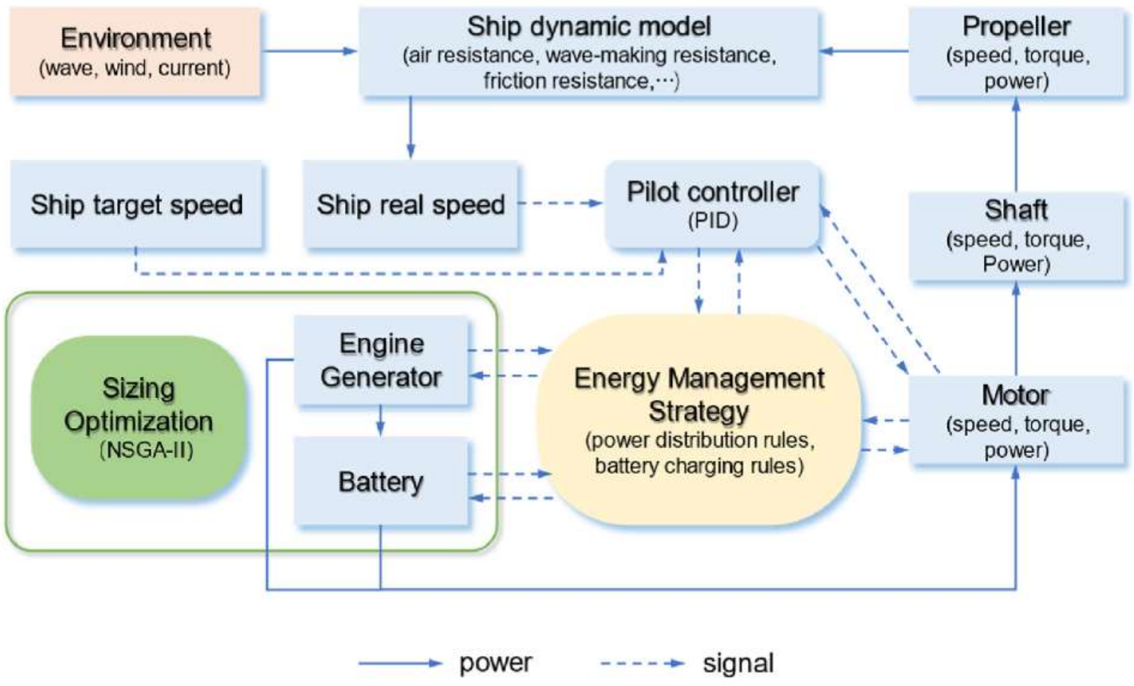


Integrated physics-based powertrain model

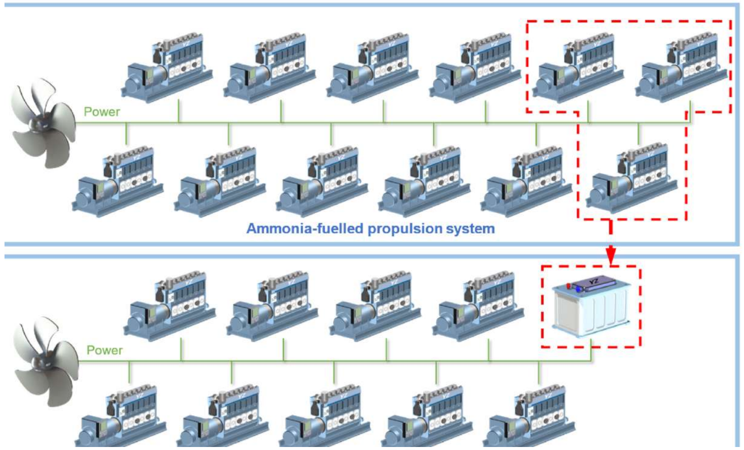
- Ammonia engines, battery pack, motor, shaft and propeller are coupled with ship-resistance and speed-control models.
- NSGA-II is used for multi-objective sizing with CAPEX, OPEX and EEXI as objectives.
- Rule-based EMS allocates engine and battery power under dynamic operating conditions.

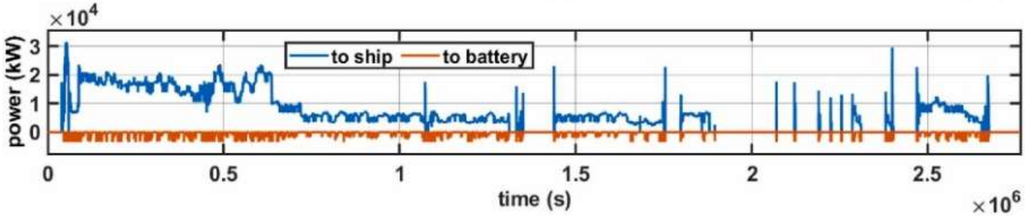
EMS logic

- Operate ammonia engines above 50% load when possible.
- Maintain battery SOC within 20–90%.
- At SOC >80%, battery can stop charging and supply propulsion demand.

Optimal system sizing

- Hybrid solution removes 3 ammonia gensets compared with the ammonia-only configuration.
- The selected 4.23 MWh battery mainly supports peak shaving and low-load operation.
- Retaining 9 engines provides practical redundancy for maintenance and navigation robustness.





Powertrain system	A. conventional	B. NH$_3$ engine	C. NH$_3$ hybrid
engine type	2-stroke HFO engine	4-stroke ammonia genset	4-stroke ammonia genset
engine number	1	12	9
cylinder number	8	72	54
engine rated power (kW)	42,420	41,760	31,320
battery cell number	-	-	40,300
battery capacity (kWh)	-	-	4,230.49

−25%
Rated engine power vs ammonia-only case

185 MWh
Energy supplied from battery to propulsion

4.23 MWh
Battery capacity in optimal hybrid sizing

Single-route environmental and economic analysis

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- NH_3 hybrid reduces CO_2 by 79.5% compared with the baseline.
- EEXI decreases from 3.94 to 0.80 $gCO_2/(t \cdot nmi)$.
- Hybrid system reduces OPEX by ~$19.5k per route compared with NH_3-only.
- However, ammonia systems remain more expensive than HFO because of high fuel cost.

	A. conventional	B. NH3 engine	C. NH3 hybrid
equipment volume (m^3)	1,980.00	1,518.53	1,154.91
equipment weight (t)	2,025.00	684.00	553.30
CO_2 emissions (kg)	2,594,424.44	535,443.30	531,646.02
CO_2 tax ($)	985,883.29	203,468.45	202,025.49
fuel consumption (kg)	809,240.31	243,861.19	243,856.00
	-	2,194,750.74	2,194,704.00
CAPEX ($)	39,373.66	58,973.55	64,092.19
OPEX ($)	1,628,539.86	2,435,967.20	2,416,489.55
EEXI ($gCO_2/(t*nmi)$)	3.9453	0.8142	0.8085

79.5%

CO_2 reduction for NH_3 hybrid vs conventional

0.80 $gCO_2/(t \cdot nmi)$

Lowest EEXI among the three architectures

$$\text{EEXI} = \frac{\text{Engine Power (kW)} \times \text{Specific Fuel Consumption (g/kWh)} \times CO_2 \text{ Conversion}}{\text{Capacity (DWT)} \times \text{Ship Speed (knots)}}$$

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Lifecycle environmental and economic analysis

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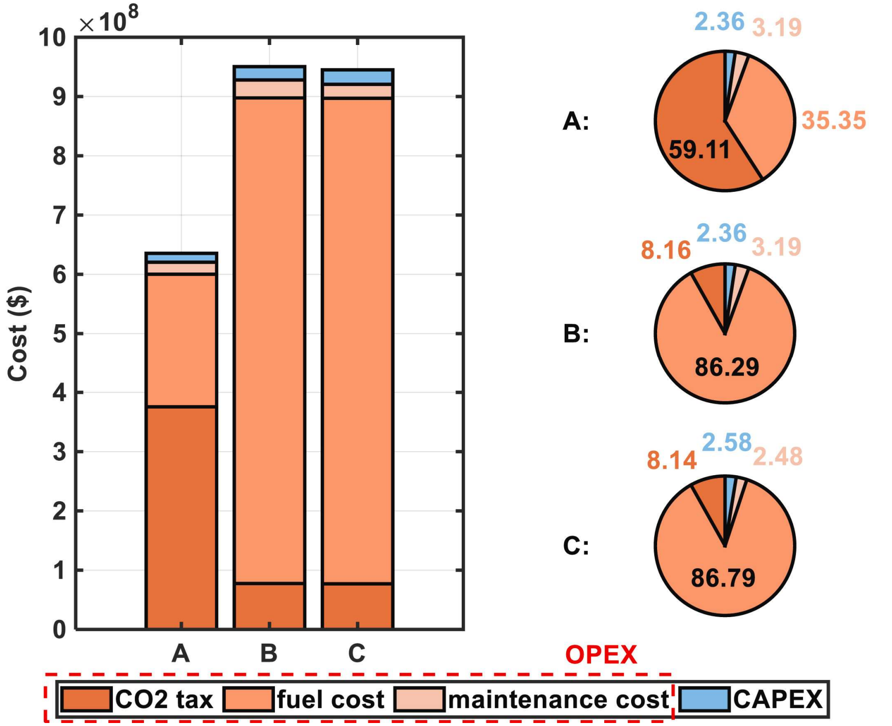
- Conventional powertrain has the lowest lifecycle cost: approx. $635 million.
- Ammonia-only system is highest: approx. $950 million.
- Hybrid ammonia system is slightly lower than the ammonia-only by about $5 million.
- For ammonia systems, fuel cost exceeds 86% of lifecycle expenditure.
- For the conventional system, CO_2 taxation dominates at 59.11% of lifecycle cost.
- The decarbonisation case is technically strong, but economic feasibility depends on ammonia price reduction and stronger carbon-cost pressure.



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- Developed and validated 3D CFD and 0D/1D models for ammonia–diesel dual-fuel marine engines.
- Direct liquid-ammonia injection and optimised injection timing reduced NO_x emissions by approximately 85%.
- On-board ammonia reforming produces H_2-rich reformate, improving flame propagation and reducing NH_3 slip and N_2O emissions.
- At AES 90%, 30% reforming reduced NH_3 slip by 98.6%, and decreased total GHG emissions by 87.1%.
- A ship-level powertrain model was developed and optimised for ammonia-only and ammonia–battery hybrid propulsion systems.
- The NH_3-hybrid system reduces route-level CO_2 emissions by 79.5% and decreases EEXI from 3.94 to 0.80 $gCO_2/(t\cdot nmi)$

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2. Debnath, Victor et al. ‘’Methanol Spray Characterisation with Different Fuel blend under Flash Boiling Conditions’’ **Fuel** (**2026**), 140370.
3. Nadimi, Ebrahim et al. ‘’ Experimental study of liquid ammonia injection timing in rapeseed methyl ester dual injection engine ‘’ **Energy** (**2025**), 335, 137919.
4. Zhang, Yan, et al. "Advancing maritime decarbonisation: Design and optimisation of ammonia-fuelled propulsion systems.“ **Journal of Cleaner Production** 535 (**2025**): 147145.
5. Zhang, Yan, et al. "Genetic algorithm-assisted multi-objective optimization for developing a Multi-Wiebe Combustion model in ammonia-diesel dual fuel engines “ **Energy**, (**2025**) 325, 136181.
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7. Zhang Y, Yu J, Zhao N, et al. Particle swarm optimization for a hybrid freight train powered by hydrogen or ammonia solid oxide fuel cells. **International Journal of Hydrogen Energy**, **(2024)**, 72: 626-641.
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9. Li M, Ngwaka U, Korbekandi R M, et al. A closed-loop linear engine generator using inert gases: A performance and exergy study. **Energy**, **(2023),** 281: 128278.

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