UK National Clean Maritime Research Hub

# Clean Maritime Assembly 2026

Collaboration | Innovation | Transformation

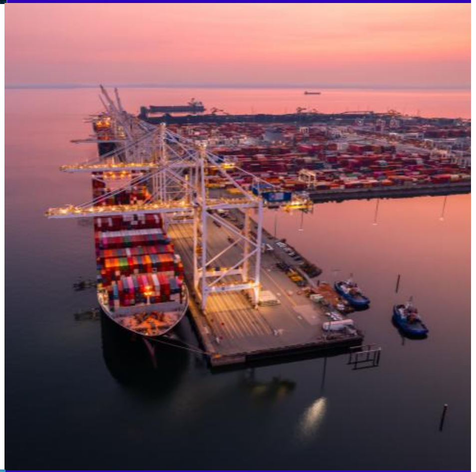
UKRI Engineering and Physical Sciences Research Council
Funded by UK Government

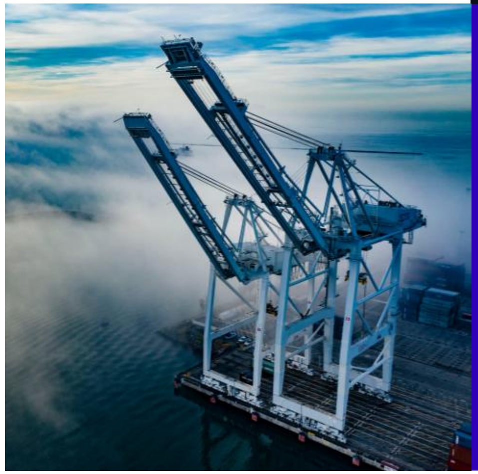
Academic Insights

# Session 1

# Economics, Technology & Systems Perspectives


- Dr Ioannis Moutzouris
- Prof Alice Larkin



FIRM-LEVEL EVIDENCE FROM GLOBAL SHIPPING

# Stepping Stone or **Stumbling Block**?

## How intermediate technologies shape the adoption of clean energy in the global shipping industry

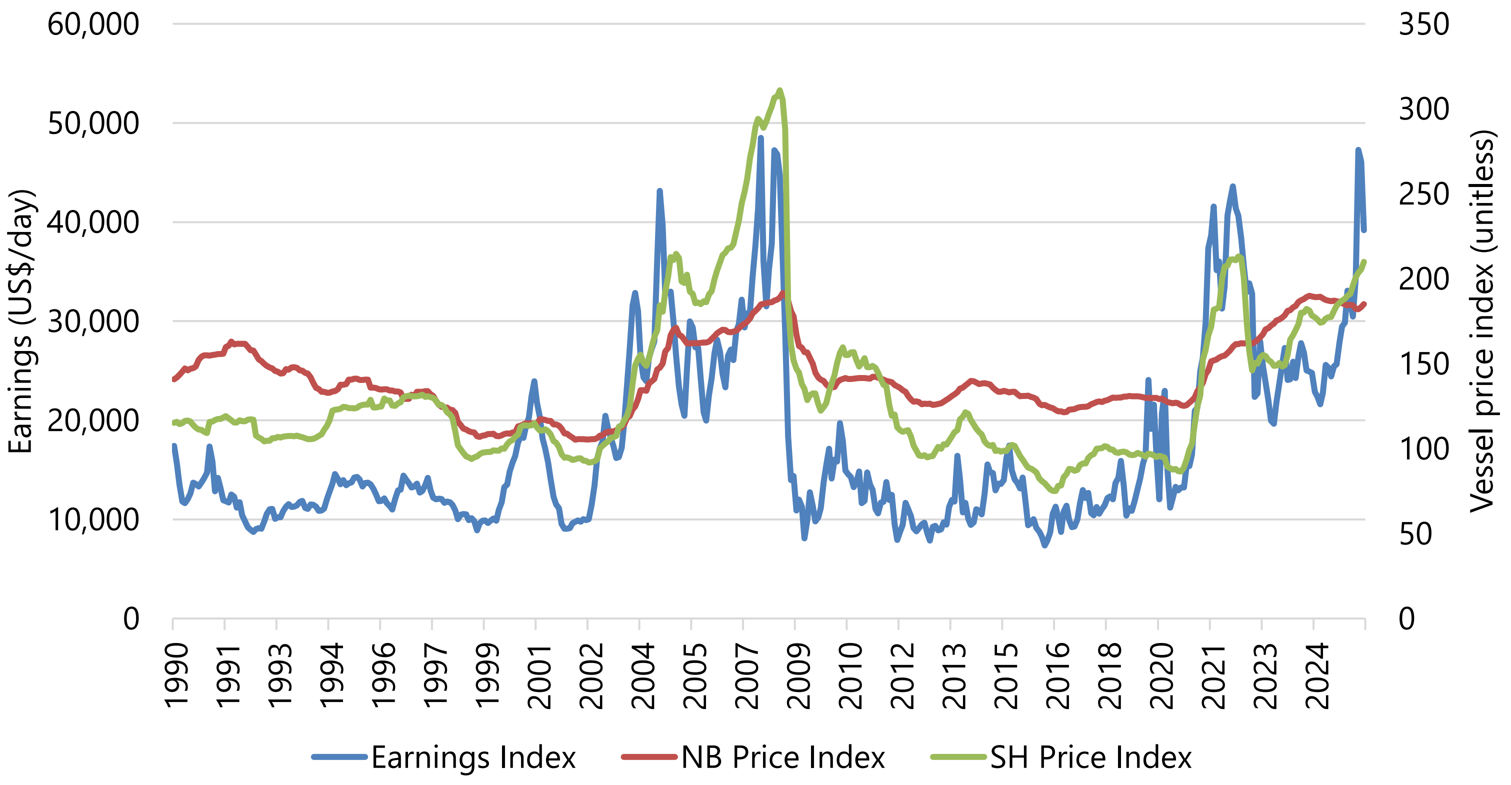
Yongyuan Huang[1, 2] Yao Shi[3] **Ioannis Moutzouris[3]**

1. SPRU, University of Sussex
2. University of Warwick
3. Bayes Business School, City St George's, University of London

Fact 1

# Shipping is a highly volatile and capital-intensive industry

- ❑ Traditionally, the primary investment risk in shipping had to do with freight rates volatility
- ❑ When is the right time to order/buy/sell/scrap a vessel?




Source: Data are from Clarksons' SIN (2026).

Fact 2

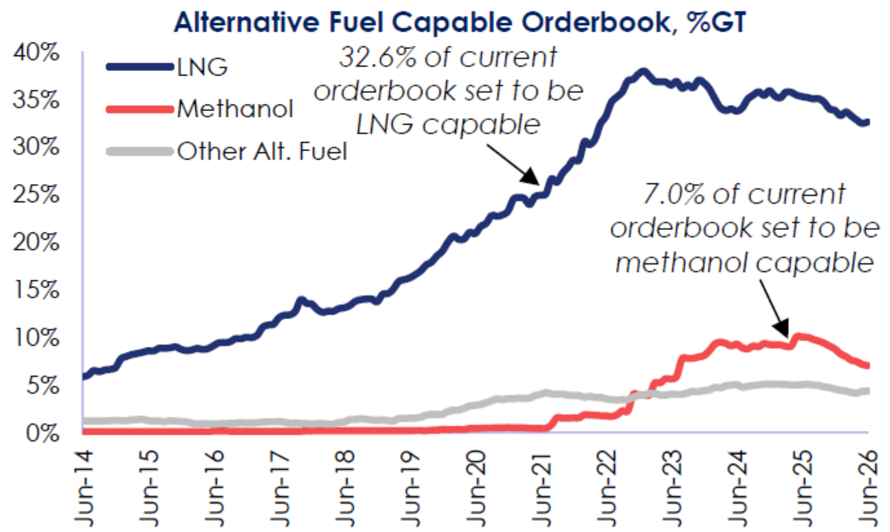
# Recently, also technological & regulatory uncertainty

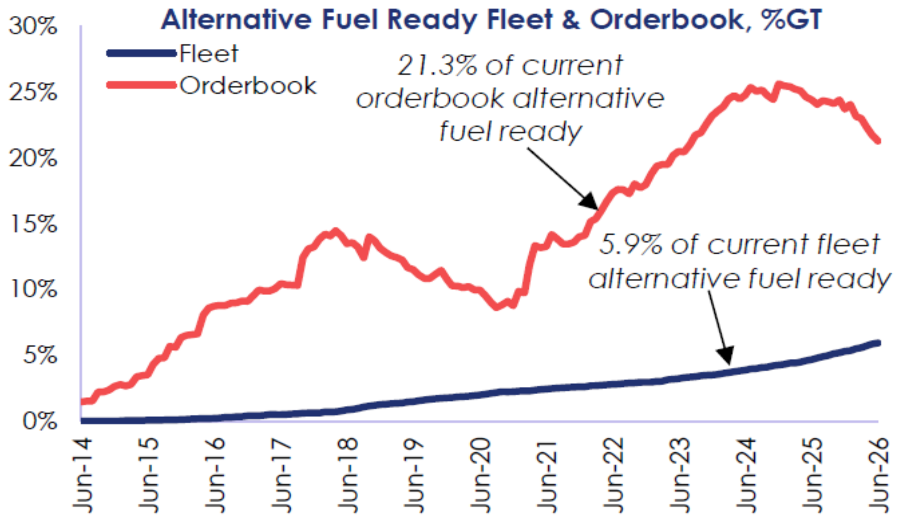
- ❑ Affordability, availability, and scalability of the fuel: What is the optimal fuel of the future?
- ❑ What are the required technological specifications for a newly ordered or purchased or retrofitted vessel to burn that fuel?
- ❑ Safety concerns related to alternative fuels?
- ❑ How will current and forthcoming regulations affect the industry?
  - ➢ These can vary among jurisdictions, e.g. EU ETS, FuelEU, UK ETS
- ❑ Economic measures such as GHG pricing

Fact 3

# Shipowner's investment trilemma

1. Investing in a cheaper but more polluting conventional fuel-engine ship
   - ➢ Still, more than half of the orders are for (solely) fuel oil vessels
2. Investing in a more expensive alternative fuel-engine ship
   - ➢ If yes, which fuel type(s)?
   - ➢ "Transitional" or "clean"?
   - ➢ The current fleet set to be alternative fuel capable is ca. 10% of the total fleet
   - ➢ Most new building orders are for LNG, which is a fossil fuel
3. Postponing the investment decision
   - ➢ Fleet is aging: Average tanker is 14.2 yo; dry bulker 13.1 yo; containers 14.5 yo



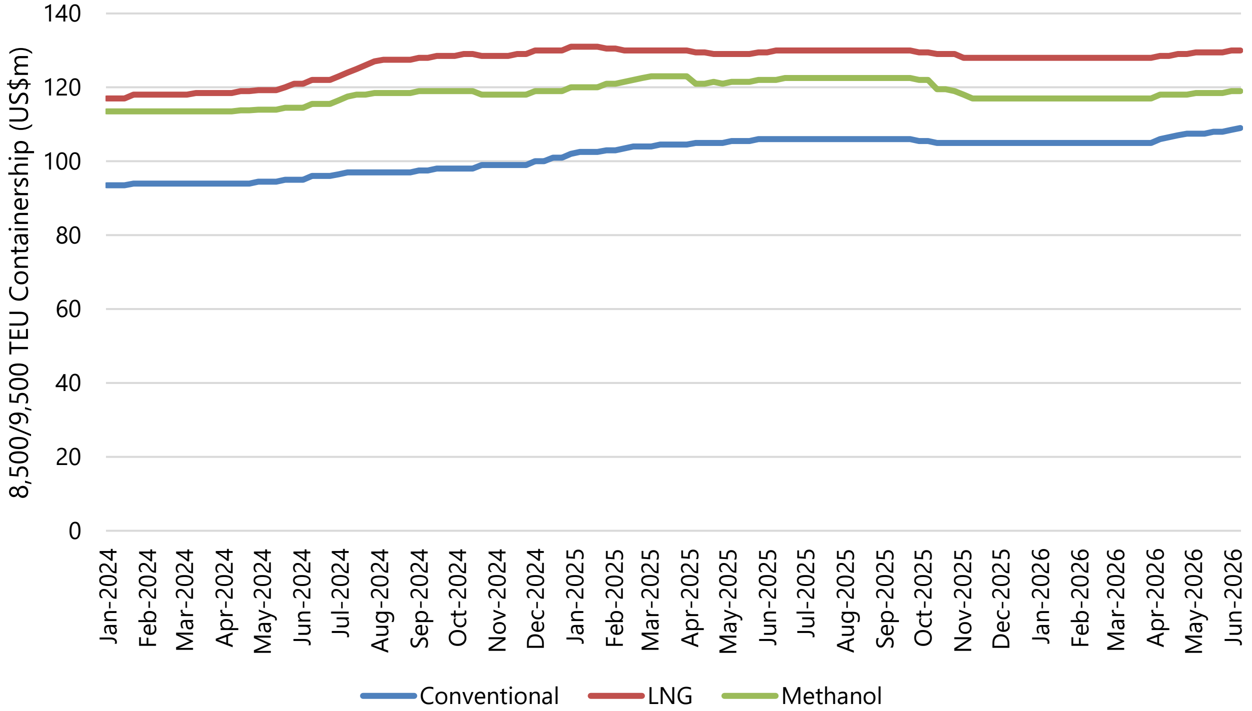




Source: Clarksons' SIN (2026).

Fact 4

# Alternative-fuel vessels require significant excess Capex

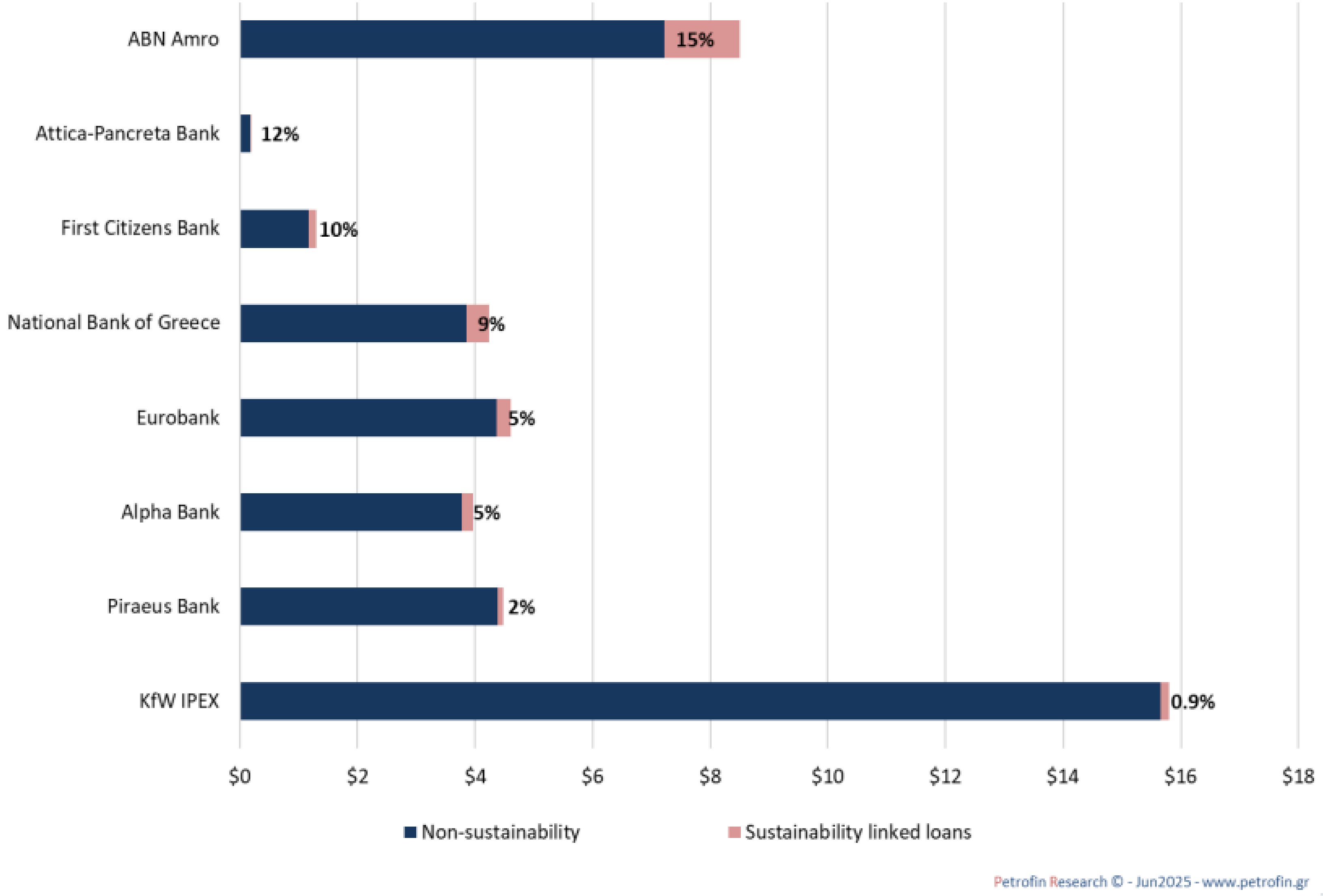
- The price of an LNG dual-fuel containership can be 12-25% more compared to an oil-fuelled one
- 9-17% more for a methanol dual-fuel one
- Overall, the smaller the vessel, the larger the Capex premium




Source: Data are from Clarksons' SIN (2026).

Fact 5

# Global shipping sustainability-linked portfolios (in 2024)

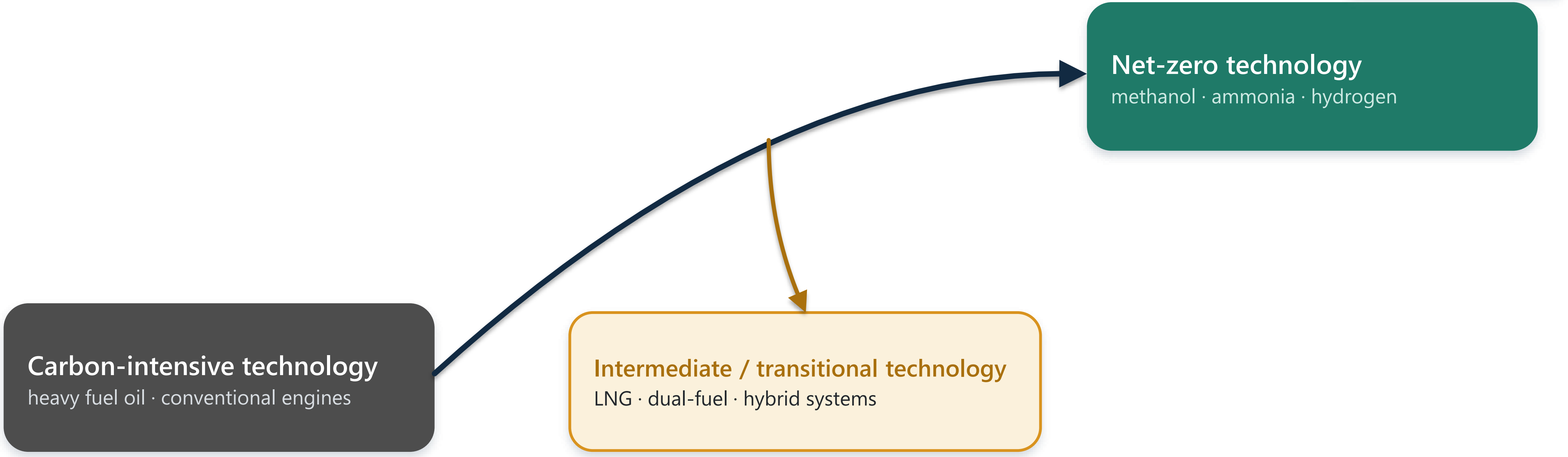


THE BIG PICTURE

# Decarbonisation journey

*The fleet must move from carbon-intensive to net-zero propulsion — but the* **middle of that journey** *is where the hard choices, and this paper, live.*

NET ZERO 2050




**Transitional technologies** are more feasible today and cut pollution sharply — **but they still emit.** Examples: LNG / natural gas, dual-fuel engines, hybrid-electric systems.

# Shipping can't agree — is gas a bridge, or a trap?


LNG: Greenwashing or Realism

Wendy Laursen, Contributing Writer
Wendy Laursen has more than 20 years of experience as a journalist....

November 13, 2025

The October delay a
continues to spark c
fuel choices, includi

Debate is expected
more complicated re
uncertainty created
force emissions redu
such as CII and reg

With the number of

© mark_gusev / Adobe Stock


The Problems with Liquefied Natural Gas

There is no time to waste on false climate solutions like LNG

Delaine McCullough
Shipping Emissions Policy Manager, Arctic Program

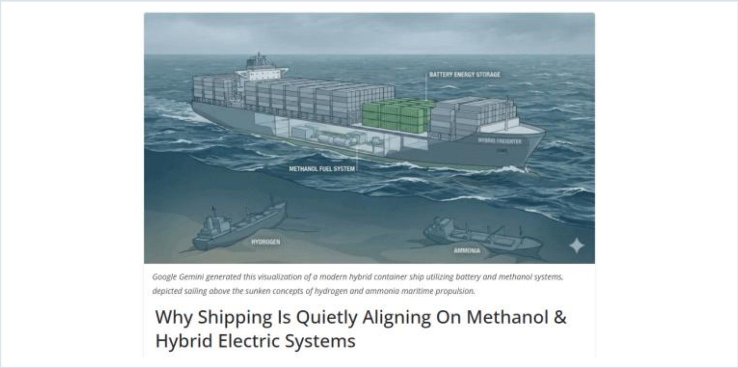
6 Minute Read


TAGS: DNV | Maersk Group | Wartsila

Shipping leaders disagree on future of LNG in shipping

*Maersk's head of decarbonisation said that a $100 per tonne of CO2 levy is probably the minimum level that shipping needs to make future fuels cost competitive*

12 May 2021 | ANALYSIS



Google Gemini generated this visualization of a modern hybrid container ship utilizing battery and methanol systems, depicted sailing above the sunken concepts of hydrogen and ammonia maritime propulsion.

Why Shipping Is Quietly Aligning On Methanol & Hybrid Electric Systems

## 37.9%

LNG-capable share of the global newbuild orderbook (end-2024; Clarksons 2025)

*Orderbook = vessels currently on order. LNG-capable is ≈ 6.3% of the in-service fleet but 37.9% of what is being built — the industry is doubling down on gas.*

**Money is pouring into gas —**
yet the industry's own leaders **publicly disagree** on whether LNG is a pragmatic **bridge** or a costly **dead end**.

Behind the headlines, a question at the heart of the green transition: do intermediate technologies bring the clean destination closer, or push it away?

WHY IT MATTERS & WHY SHIPPING

# High stakes, and the sharpest test of lock-in theory

**87%**

of world trade carried by sea

**2.0%**

of global GHG emissions

**2050**

net-zero target (IMO 2023)

Yet the fleet is still **overwhelmingly dirty.**

*This is the moment lock-in theories make their sharpest predictions.*

## THE STATE OF THE FLEET, END 2024

**< 8%** of ships can use any alternative fuel

**~ 50%** of new orders are still oil-fuelled

LNG dominates the alternatives: 6.3% of fleet, 37.9% of orderbook

Truly net-zero-capable ships: < 2% of fleet, < 15% of orders

Each newbuild:

**USD 80–400m**

20-year operating life

*Ships ordered today run into the 2040s.*

*Sources: UNCTAD (2021, 2023); Clarksons (2025); IMO (2023, 2024).*

THE CENTRAL DEBATE

# Two literatures, opposite predictions

Does prior **transition** adoption **crowd in** or **crowd out** a firm's later **clean** adoption?

*Lock-in explains the industry backlash; the gateway view says it need not be so.*

1 · LOCK-IN · the standard worry

## Transition fuels as a stumbling block

- Asset-specific sunk capital and refuelling infrastructure
- Path dependence diverts investment from radical options
- Path dependence / directed change *(Arthur 1989; Unruh 2000; Acemoglu 2012)*

VS

2 · GATEWAY · the optimistic counter-view

## Transition fuels as a stepping stone

- Build operating know-how, bunkering, supply chains
- Capability spillovers lower the cost of going clean later
- Innovation / multi-system transition view *(Mäkitie 2022; Andersen & Markard 2020)*

**The cautionary tale:** US shale gas first cut $CO_2$ by displacing coal, then slowed renewable innovation and delayed net zero.
*(Acemoglu et al. 2023; Gillingham & Huang 2019)*

# A first-order question, never tested where it is decided

To what extent does a firm's prior adoption of **transition (intermediate)** technology raise or lower its subsequent adoption of **clean** technology?

**The gap:** we have **competing theories** — but little **firm-level empirical evidence**, and **no causal evidence**, where the decision is made.

### 1 · Empirical evidence

The debate runs on anecdote and aggregate trends — almost no within-firm evidence at the level where fuel decisions are taken.

### 2 · Causal identification

Unobserved **green strategy** can drive both transition and clean adoption — correlation ≠ causation.

**Crowd in** = prior transition adoption **raises** later clean adoption; **crowd out** = it **lowers** it. We identify a ***within-firm causal effect***, not the raw correlation.

OUR FRAMEWORK

# When does a bridge become a trap? It depends on the firm

Path-dependence theory makes a strong prediction — once a firm adopts, history **binds**.

**HISTORY BINDS · the classic, pessimistic view**

- Early choices **self-reinforce** through **increasing returns**, **learning-by-doing** and **network / coordination effects** (plus adaptive expectations)
- → lock-in, crowd-out — a **trap**

*Arrow 1962 · Nelson & Winter 1982 · David 1985 · Katz & Shapiro 1985 · Arthur 1989 · Dosi 1982 · Unruh 2000*

?

# When does a bridge become a trap? It depends on the firm

… but a second tradition disagrees: the outcome is not destiny, it is **contingent** — history can also **help**.

### HISTORY BINDS · the classic, pessimistic view

- Early choices **self-reinforce** through **increasing returns**, **learning-by-doing** and **network / coordination effects** (plus adaptive expectations)
- → lock-in, crowd-out — a **trap**

*Arrow 1962 · Nelson & Winter 1982 · David 1985 · Katz & Shapiro 1985 · Arthur 1989 · Dosi 1982 · Unruh 2000*

VS

### HISTORY HELPS · the contingent view

- Prior related experience can build **redeployable capability** — absorptive capacity, dynamic capabilities
- → stepping stone, crowd-in — a **bridge**

*Cohen & Levinthal 1990 · Teece 1997 · Mäkitie 2022*

OUR FRAMEWORK

# When does a bridge become a trap? It depends on the firm

We resolve the tension by asking **where** path dependence is embedded in the firm's resources.

### HISTORY BINDS · the classic, pessimistic view

- Early choices **self-reinforce** through **increasing returns**, **learning-by-doing** and **network / coordination effects** (plus adaptive expectations)
- → lock-in, crowd-out — a **trap**

*Arrow 1962 · Dosi 1982 · Nelson & Winter 1982 · David 1985 · Katz & Shapiro 1985 · Arthur 1989 · Unruh 2000*

VS

### HISTORY HELPS · the contingent view

- Prior related experience can build **redeployable capability** — absorptive capacity, dynamic capabilities
- → stepping stone, crowd-in — a **bridge**

*Cohen & Levinthal 1990 · Teece 1997 · Mäkitie 2022*

Our answer: the sign of path dependence depends on **where** it is embedded — **transition embeddedness** (trap, −) vs **redeployment capacity** (bridge, +).

| ① Capital *(sunk costs)* | ② Routines *(learning)* | ③ Ecosystem *(coordination)* | ④ Governance *(expectations)* |
|---|---|---|---|

*Four resource domains, deduced from Arthur's (1989) four self-reinforcing mechanisms; Nelson & Winter (1982) bring them inside the firm.*

THE FRAMEWORK

# Where does path dependence lodge? Four firm resource domains

Path dependence can lodge in **four firm resource domains**. Each can **bind** (transition embeddedness, −) or — where resources stay **redeployable** — **help** (redeployment capacity, +).

### ① Capital & investment · *Arthur (1989): sunk costs*

Durable, specific, irreversible assets **raise switching costs** → lock-in.

*Williamson 1985 · Pindyck 1991 · Dixit & Pindyck 1994*

### ② Operational routines · *Arthur (1989): learning*

Prior related experience builds **absorptive capacity** — but can harden into **core rigidity**.

*Cohen & Levinthal 1990 · Leonard-Barton 1992 · Teece, Pisano & Shuen 1997*

### ③ Complementary ecosystem · *Arthur (1989): coordination*

Shipyards, operators, suppliers & infrastructure **co-evolve around the path** → carbon lock-in.

*Teece 1986 · Unruh 2000 · Geels 2002*

### ④ Governance boundary · *Arthur (1989): adaptive expectations*

Ownership & mandates **set the objective function** (e.g. fossil-mandate national oil companies).

*Hart, Shleifer & Vishny 1997 · Musacchio & Lazzarini 2014*

These four domains organise the boundary-condition analysis — each moderator is a **marker of one domain** (next: the moderator results).

DATA & MEASURES

# The first global firm–vessel panel of green adoption

**13,188**
shipping companies

**48,828**
unique vessels

**566,110**
vessel-year observations

**2011–2024**
annual panel

Sources: **Clarksons** — fleet, engine, builder, ownership (firm = vessel owner); **Veson / AIS** — 5.5m voyages 2014 for SECA exposure.

MAIN-ENGINE TECHNOLOGY, THREE CATEGORIES

**DIRTY**
Heavy fuel oil, marine gas oil

**TRANSITION**
LNG, LPG, et al.

**CLEAN**
Methanol, ammonia, hydrogen

*We study the change in* ***main-engine technology****, not fuel purchasing.*

**X — regressor**
Lagged DWT-weighted **transition fleet share** of the firm's owned fleet (incl. gas carriers).

**Y — outcome**
New-order **clean share** — methanol / ammonia / hydrogen (mono + dual). Also, binary & count.

EMPIRICAL MODEL

# Within-firm panel, and why OLS is not enough

X = firm's lagged **transition-fuel fleet share** — how transition-intensive its fleet already is.
Y = **clean share** of its new vessel orders — methanol / ammonia / hydrogen.

$$Y_{it} = \beta_1 X_{i,t-1} + \gamma' W_{i,t-1} + \alpha_i + \delta_t + \varepsilon_{it}$$

$\alpha_i$ firm FE · $\delta_t$ year FE · W lagged firm controls · SE clustered by firm · coefficient of interest $\beta_1$

## The problem · endogeneity

- Unobserved, time-varying **green strategy** lifts both transition and clean adoption → $\beta_1$ **biased upward**.
- Firm + year FE remove *fixed* greenness and common shocks.

## Why FE is not enough

- **Reverse causality**: a firm already planning to go clean may build transition capacity first.
- Any remaining **time-varying confounder** still contaminates OLS and FE.

→ we need an instrument: **predetermined**, and reaching clean adoption **only through transition fuels**.

IDENTIFICATION

# A predetermined regulatory instrument

THE INSTRUMENT Z **Z = 2014 SECA-exposed vessel count (log, excl. gas carriers) × Post-2018**

We combine **two predetermined facts** — a firm's historical **trading geography** and a historical **environmental regulation**, neither chosen with decarbonisation in mind.

**Firm's 2014 trade routes** → **Overlap with SECA zones** Baltic · N. Sea · N. America → **SECA exposure score** *= the instrument Z* → 2015 sulphur cap + **2018 IMO strategy** ⇒ pressure to switch → **LNG / transition** adoption (first stage)

Installing LNG is the leading way to comply with SECA low-sulphur limits — so more SECA-exposed firms are pushed harder toward LNG.

The instrument **switches on at 2018**, when the IMO Initial GHG Strategy (and the 2020 sulphur cap) turned compliance pressure into a fleet-renewal signal; before 2018 the exposure is dormant. Identification comes from **differential within-firm trajectories after 2018**.

### Relevance · a strong first stage

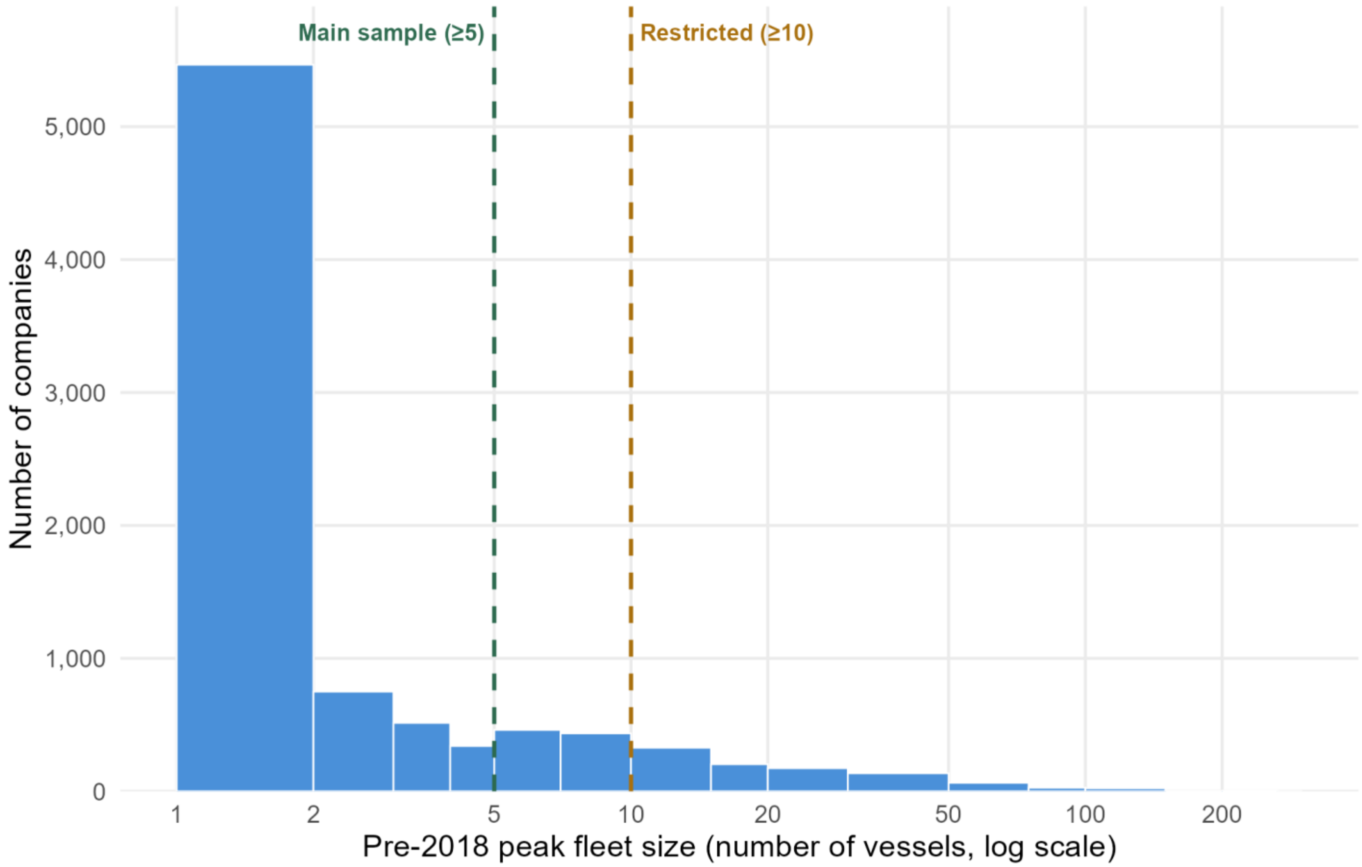
First-stage F (KP) = **86–264** ≫ Stock–Yogo 16.4; Wu–Hausman $p < 0.0001$.

### Exclusion · only through transition

SECA geography is **chemically unrelated** to methanol/ammonia/hydrogen → reaches clean only via transition. Robust across 4 SECA measures; bypass risk flagged openly.

SAMPLE

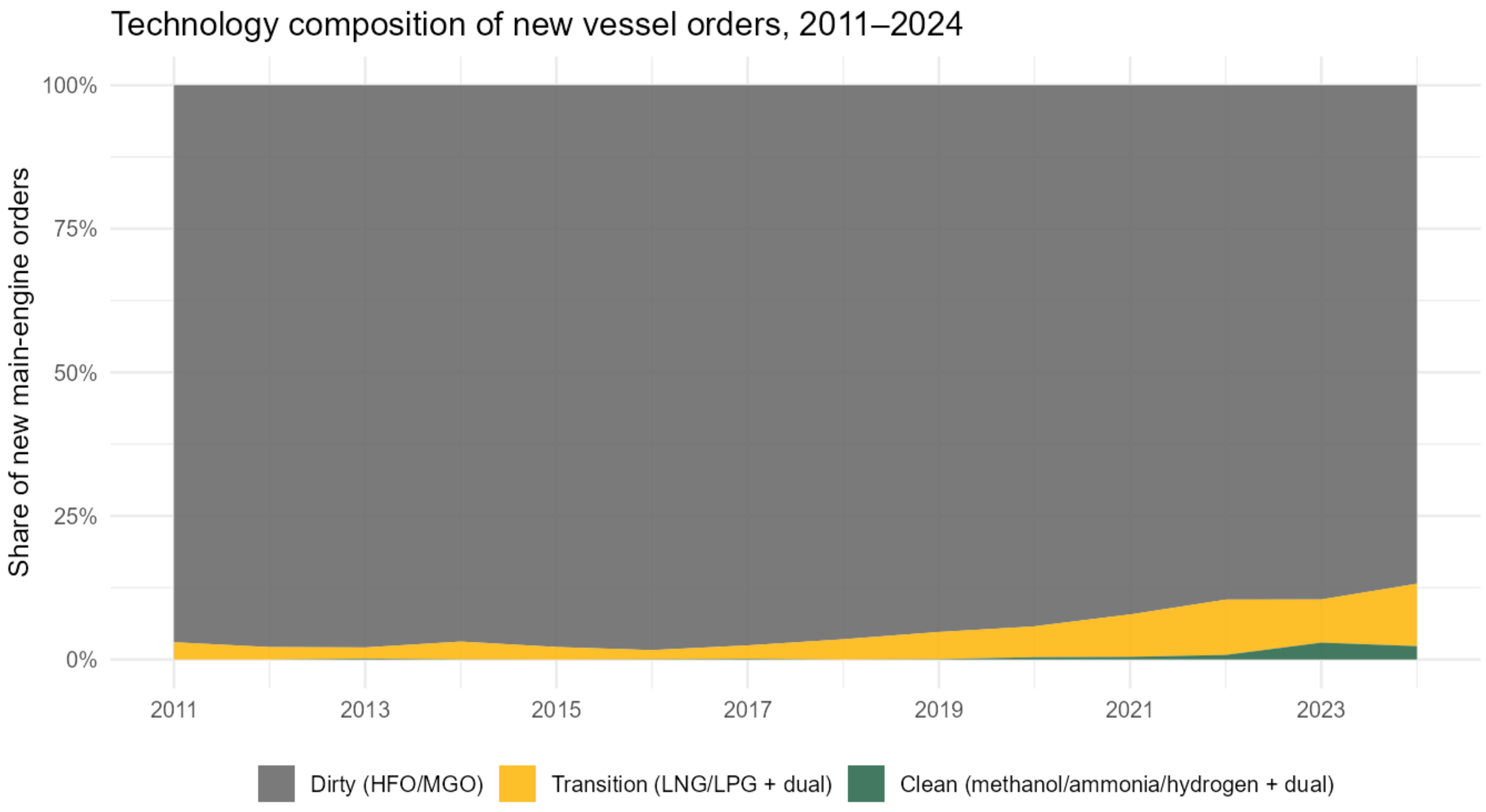
# Clean adoption is rare — our main sample is firms with ≥5 vessels




*Histogram of pre-2018 peak fleet size (log scale). Thresholds shown by dashed lines.*

- Only **1.25%** of firms ever run a clean engine.
- Median firm owns **2 vessels**; 75% own fewer than 5.
- **Three nested samples by pre-2018 peak fleet:**
- Main ≥5: **2,101 firms** (N = 20,491)
- Restricted ≥10: **1,051 firms**
- Full: **10,559 firms**
- *Nesting doubles as a robustness check.*

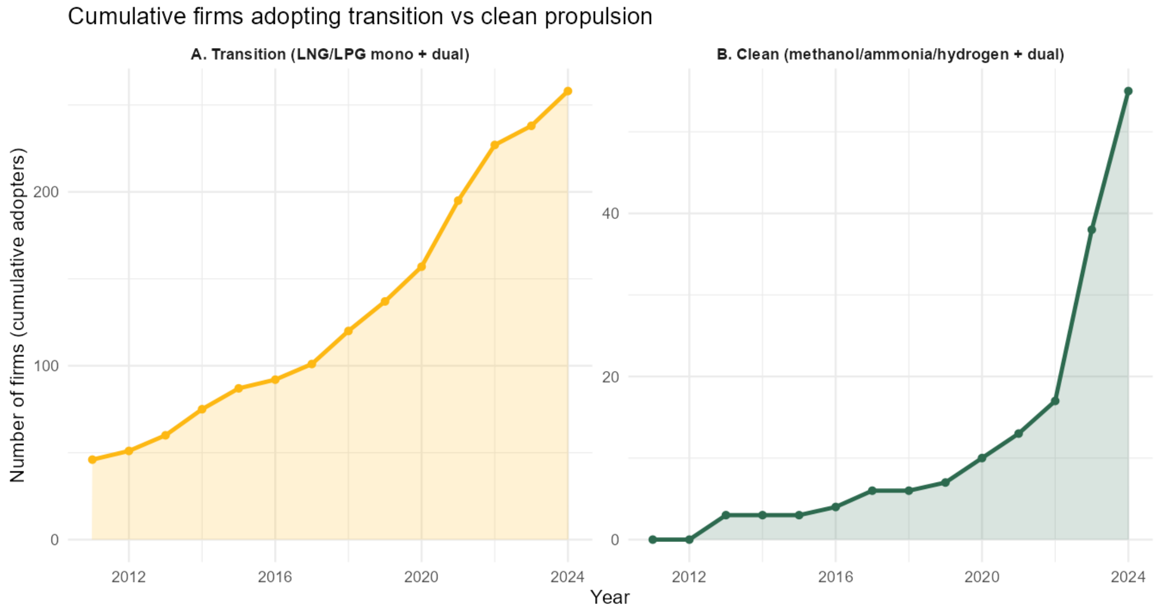
# New-order engine mix is still overwhelmingly dirty

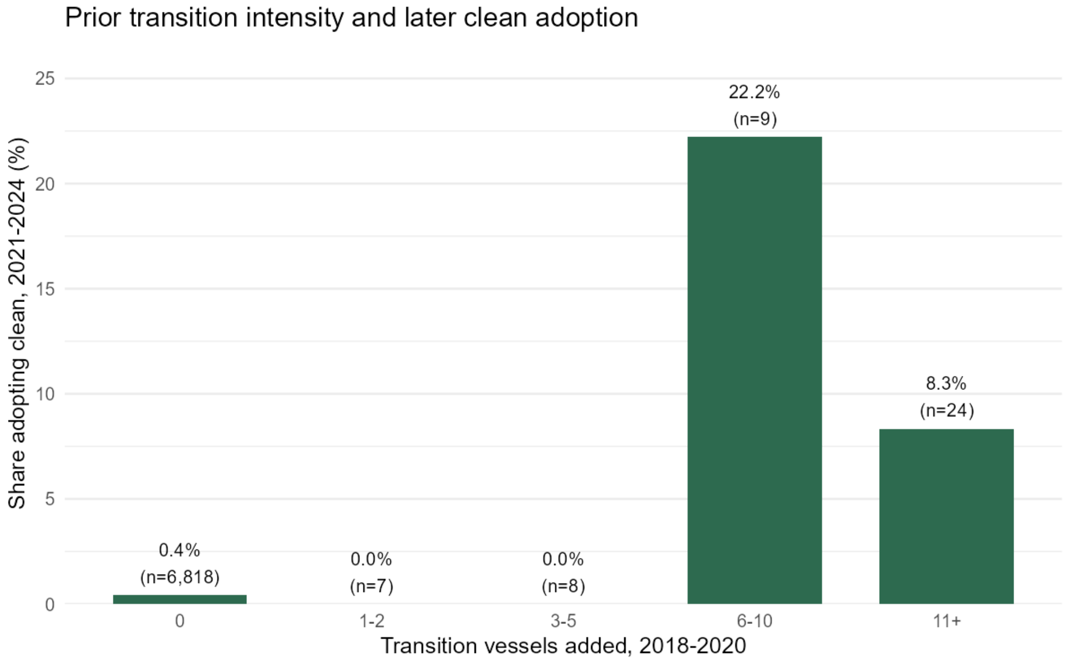



- Dirty share falls only **97.0% → 86.8%**
- Transition climbs **3.0% → 10.9%**, mostly after 2018
- Genuine clean stays **below 3%**
- Sharp break around the **2018 IMO strategy**
- *→ we set 2018 as treatment onset*

*New annual vessel orders by main-engine technology (counts, not tonnage).*

# Two routes to clean — and transition adopters lead




**By 2024:** Transition **258** firms · Clean **55** firms (mostly post-2022). Of 48 firms with any prior transition, **8.33%** went clean vs **0.43%** with none (≈ **20×**). Suggestive, not causal — adopters may be greener to begin with.

*Left: cumulative firms on each pathway, 2011–2024. Right: firms grouped by transition vessels added 2018–2020; bar = share adopting clean 2021–2024 (clean = methanol/ammonia/hydrogen, mono + dual).*

MAIN RESULT

# Transition experience crowds in later clean adoption — modestly

| | Clean share | Clean share | Clean 0/1 | # clean |
|---|---|---|---|---|
| Transition fleet share (t−1) | **0.003** | **0.73*** ** | **1.37** ** | **7.45** ** |
| | *(0.013)* | *(0.26)* | *(0.54)* | *(3.25)* |
| **Estimator** | OLS | 2SLS | 2SLS | 2SLS |
| **Lagged controls** | ✓ | ✓ | ✓ | ✓ |
| **Firm FE** | ✓ | ✓ | ✓ | ✓ |
| **Year FE** | ✓ | ✓ | ✓ | ✓ |
| **First-stage F (KP)** | — | 86 | 86 | 86 |
| **Mean of Y** | 0.0012 | 0.0012 | 0.0024 | 0.0098 |
| **N (firm-years)** | 20,491 | 20,491 | 20,491 | 20,491 |
| **# Firms** | 2,101 | 2,101 | 2,101 | 2,101 |

## IV ≫ OLS

OLS ≈ 0: shared greenness would bias the other way, so it is not the story

- **Robust** across binary, count and share outcomes, and four SECA measures.
- Holds at the **country level** too.

### A modest gateway.

For the marginal firms the instrument moves, transition fuels **open the door** to clean propulsion.

*Main sample: 2,101 firms, 20,491 firm-years. Estimation window 2014–2024, anchored to the 2014 SECA instrument. Firm + year FE, firm-clustered SE. Clean = methanol/ammonia/hydrogen. *** p<0.01, ** p<0.05.*

BOUNDARY CONDITIONS

# When the bridge bends — four resource domains

Recall the four domains — average gateway $\beta_1 = +0.73^{***}$, but it bends by **where** the transition path is embedded.

*Each cell = interaction coefficient X×M on the clean share. Controls ✓ · Firm & Year FE ✓ · min first-stage F 44 · N 20,491 · 2,101 firms.*

| | TRANSITION EMBEDDEDNESS → trap (−) | REDEPLOYMENT CAPACITY → bridge (+) |
|---|---|---|
| ① **Capital & investment**<br>*Arthur: sunk costs* | Path depth −2.81*** · young fleet −1.13* · newbuild contract −0.95* | Fleet renewal +0.31* · fleet operating experience +0.26* |
| ② **Operational routines**<br>*Arthur: learning* | Transition operating commitment −1.38* | Group backing +0.15* · operating scale +0.13** |
| ③ **Complementary ecosystem**<br>*Arthur: coordination* | Transition-specialised yard −1.51*<br>Transition-specialised operator −1.37*** | *clean ecosystem too thin pre-2017 — not yet a stable bridge* |
| ④ **Governance boundary**<br>*Arthur: adaptive expectations* | Fossil-mandate governance (NOC) −0.71*** | *no positive counterpart — green mandate is rare in shipping* |

Trap mechanisms span **all four domains**; bridges concentrate where capital and organisation stay **redeployable** — the firm-level micro-foundation of carbon lock-in.

CONCLUSION

# A conditional gateway

Whether a transition fuel **bridges or traps is not a property of LNG** — it depends on the **firm**: how deeply its capital, routines, ecosystem and governance are embedded in the transition path.

### What we find

- Prior transition modestly raises later clean adoption (firm & country level)
- But it reverses where the firm is deeply path-embedded — and holds where resources stay redeployable
- Lock-in is a bounded condition, not the average

### What it means for policy

- Don't ban LNG outright — the gateway is real
- Back leap-frog pioneers (clean bunkering, fuel-neutral standards)
- Target switching-cost relief at deeply path-embedded firms

**A caveat on external validity.** Identification comes from firms whose SECA trading geography quasi-forced them toward LNG. The estimate is a **local average treatment effect for these compliers** — not (yet) the average effect across all firms.

**The lesson travels to autos, aviation and steel: an intermediate technology pays off only where the firm's underlying resources stay redeployable.**

# Thank you

## Stepping Stone or Stumbling Block?

How intermediate technologies shape the adoption of clean-energy adoption in the global shipping industry

Yongyuan Huang · Yao Shi · **Ioannis Moutzouris**

SPRU, University of Sussex · University of Warwick · Bayes Business School

Tyndall°Centre for Climate Change Research

MANCHESTER 1824 The University of Manchester

# Opportunities & Challenges Across the Shipping System


**Alice Larkin, Professor of Climate Science & Energy Policy**

Tyndall Centre, School of Engineering, University of Manchester

**Simon Bullock, Paolo Della-Moglie & James Mason**


# Outline

Climate change context in 2026

Options for near-term interventions

- Energy system shifts
- Operational opportunities
- Wind assist propulsion

Conclusions

# 2026 Context

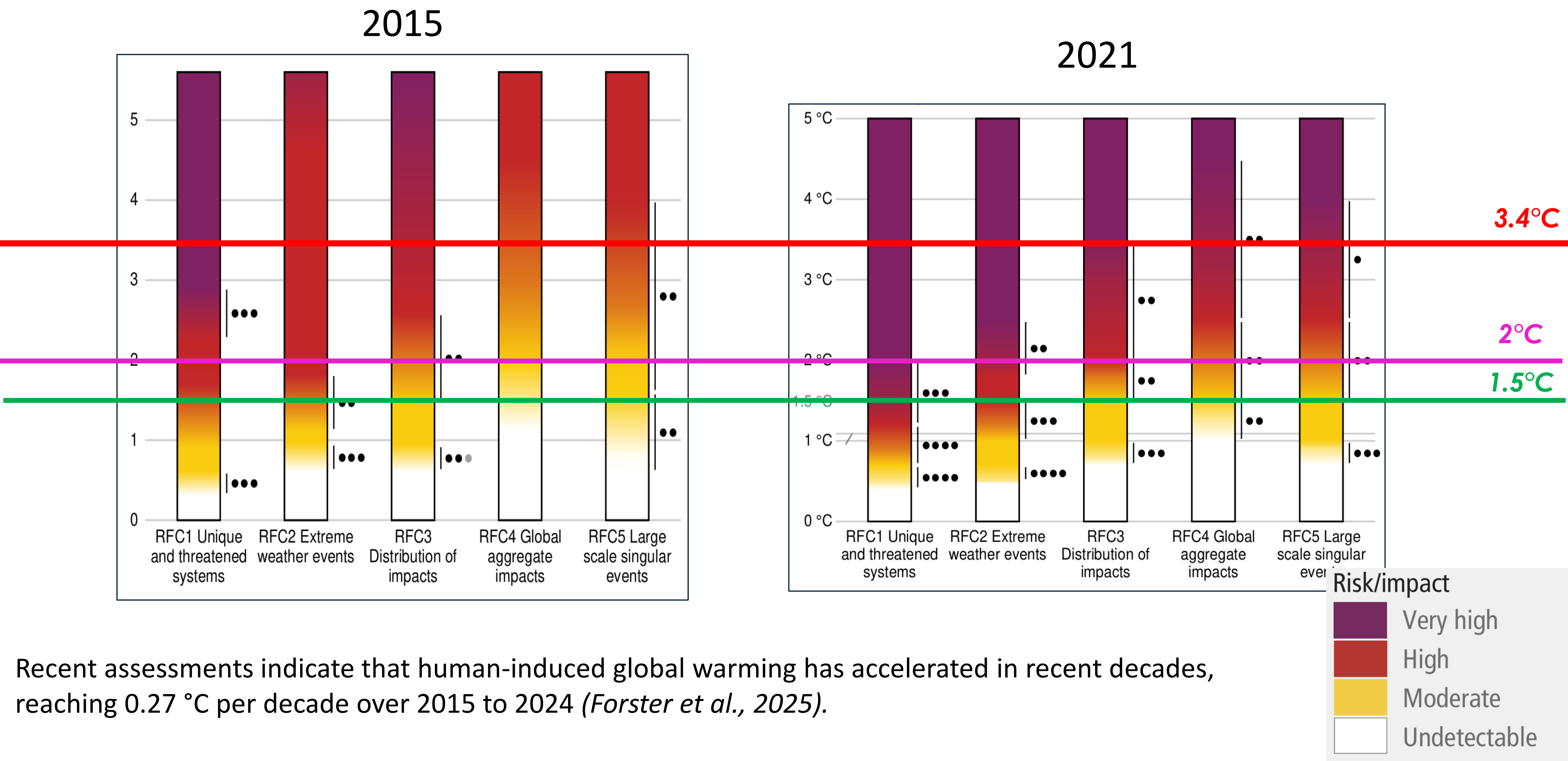
# Paris Agreement – starting point for ‘**net zero**’

… hold the increase in global average temperature to **well below 2°C** above pre-industrial levels & pursue efforts to limit the temperature increase to **1.5°C**

…rapid reductions in accordance with **best science**

…on the basis of **equity**, and efforts to eradicate poverty.

# Climate impacts are happening sooner




Recent assessments indicate that human-induced global warming has accelerated in recent decades, reaching 0.27 °C per decade over 2015 to 2024 *(Forster et al., 2025).*

# Carbon budget constraints

| Approximate global warming relative to 1850–1900 until temperature limit *(°C)**(1) | Additional global warming relative to 2010–2019 until temperature limit *(°C)* | Estimated remaining carbon budgets from the beginning of 2020 *(GtCO₂)* — *Likelihood of limiting global warming to temperature limit*(2)* | | | | | Variations in reductions in non-$CO_2$ emissions*(3) |
|---|---|---|---|---|---|---|---|
| | | *17%* | *33%* | *50%* | *67%* | *83%* | |
| 1.5 | 0.43 | 900 | 650 | 500 | 400 | 300 | Higher or lower reductions in accompanying non-$CO_2$ emissions can increase or decrease the values on the left by 220 $GtCO_2$ or more |
| 1.7 | 0.63 | 1450 | 1050 | 850 | 700 | 550 | |
| 2.0 | 0.93 | 2300 | 1700 | 1350 | 1150 | 900 | |

# Global carbon budget constraints

**Latest assessment (Friedlingstein et al., 2026)…**

50% chance of keeping warming to 1.5°C carbon budget was 170 $GtCO_2$ as of January 2026

Emissions in 2025 = 42$GtCO_2$

Remaining 50% 1.5°C budget - ***equivalent to 4 years*** at 2025 levels

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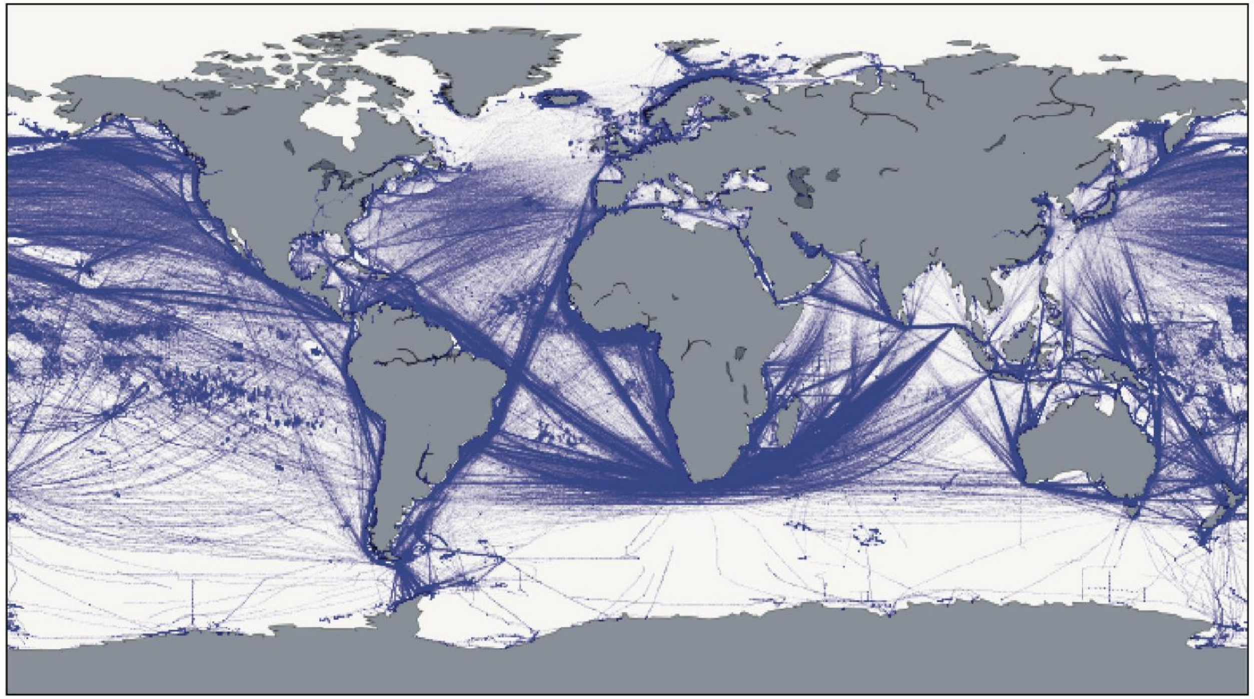
# How quickly can shipping cut emissions?

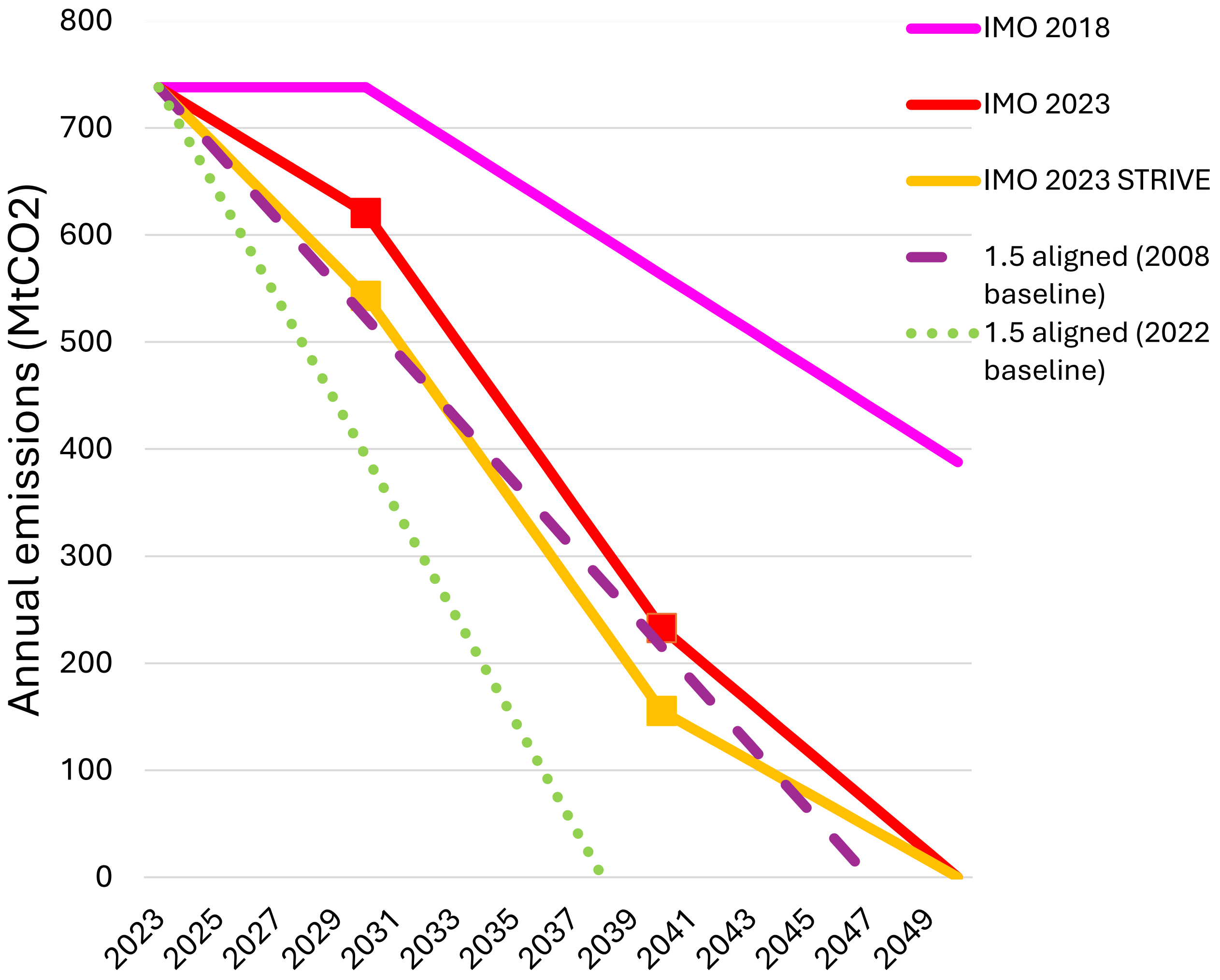
# How quickly can emissions be cut?



Framed by carbon budgets – mindful of *timeframe* for change

Physical sciences underpinning but with a whole systems approach

# Analysing IMO targets



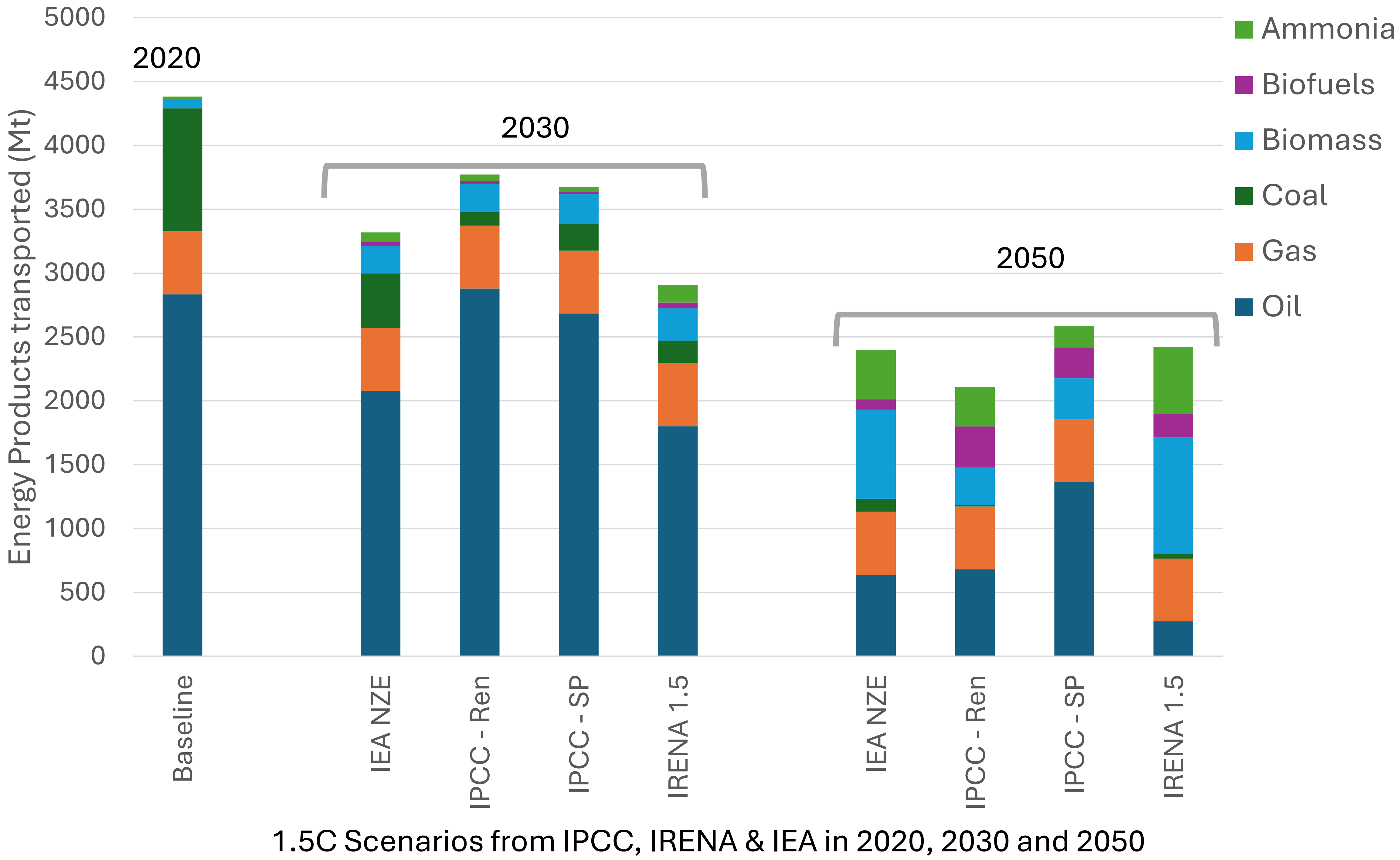

Analysed compatibility of IMO targets with Paris Agreement (Bullock et al., 2023)

https://www.tandfonline.com/doi/full/10.1080/14693062.2023.2293081

With 4 years left of 1.5°C budget, increasingly mis-aligned.

Interrogating consistency between CII and IMO targets

# Implications of energy system change


Energy Products transported (Mt)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
2020
2030
2050
Ammonia
Biofuels
Biomass
Coal
Gas
Oil
Baseline
IEA NZE
IPCC - Ren
IPCC - SP
IRENA 1.5
IEA NZE
IPCC - Ren
IPCC - SP
IRENA 1.5
1.5C Scenarios from IPCC, IRENA & IEA in 2020, 2030 and 2050

# Implications of 1.5°C for shipping...

- Shipping of energy products falls
- Growth in $H_2$ & bioenergy outweighed by falls in coal & oil
- 90-100% fall in coal shipments by 2050
- 50-90% fall in oil shipments by 2050
- Gas consumption falls but greater proportion transported
- $H_2$ (as ammonia) as high as gas today??
- Bioenergy - as high as coal today??

# Interventions that cut energy consumption

# Arrival Optimisation & Weather Routing

## Why are they important?

Operational (rather than technological) solutions, acting on ***how*** the ships are sailed

Features

- No new technology is needed
- Low cost implementation & scalability
- Benefits can grow with deployment in symbiosis with technological solutions

How do they work?

Optimise sailing speed to reduce port congestion.

- Lower fuel consumption
- Lower waiting time at anchorage
- Lower emissions

***Fuel consumption proportional to sailing speed***

***Slow steaming = less fuel***

# Arrival Optimisation & Weather Routing

## Benefits

**Case study: port of Tarragona (Spain)**

| Arrival optimisation | + | Ship weather routing | = | Arrival optimisation & Ship weather routing |
|---|---|---|---|---|
| **5-10% fuel savings on average** | | **1-20% fuel savings, on average, highly sensitive to weather conditions** | | **19% fuel savings on average, several voyages above 40%** |

Modelling arrival optimisation and weather routing, over 2 years of port operations…

- **Fuel savings: 15,000 tonnes**
- **$CO_2$ emission reductions: 47,000 tonnes**

***Just from one port!***

# Arrival Optimisation & Weather Routing

## Obstacles & limitations

Weather routing:

- usually offered by a third-party provider
- savings are very volatile

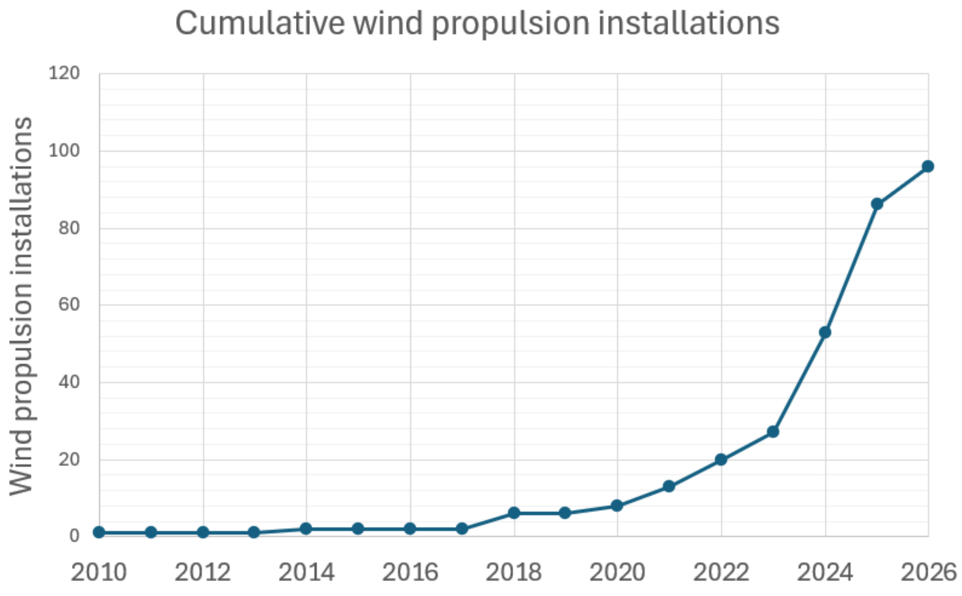
Arrival optimisation:

- vessel-to-vessel and vessel-to-port coordination
- decentralised IT infrastructure
- current operations perceived as a form of “fair competition”

# Wind propulsion

## Why is it important?

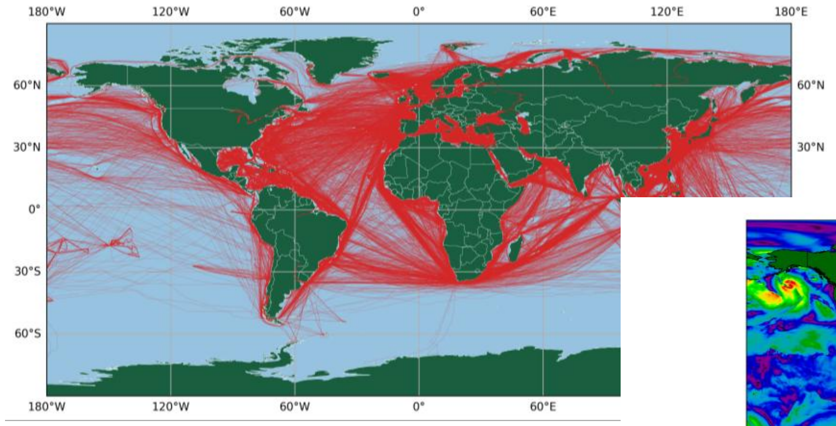
Alternative fuels likely to be more costly than fossil fuels for foreseeable future

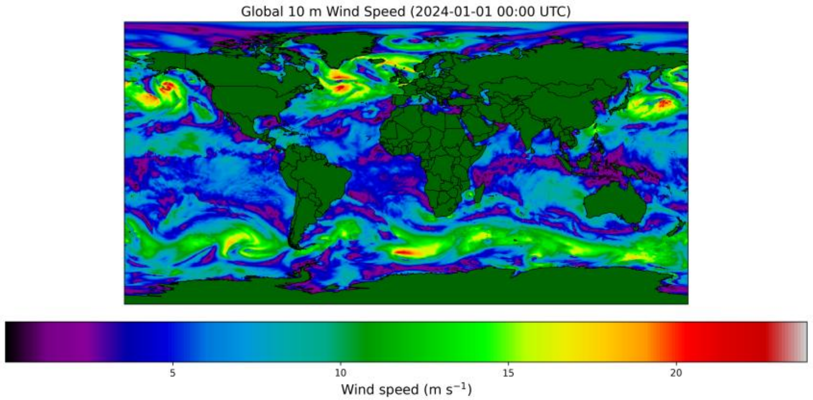




Source: International Windship Association (IWSA).

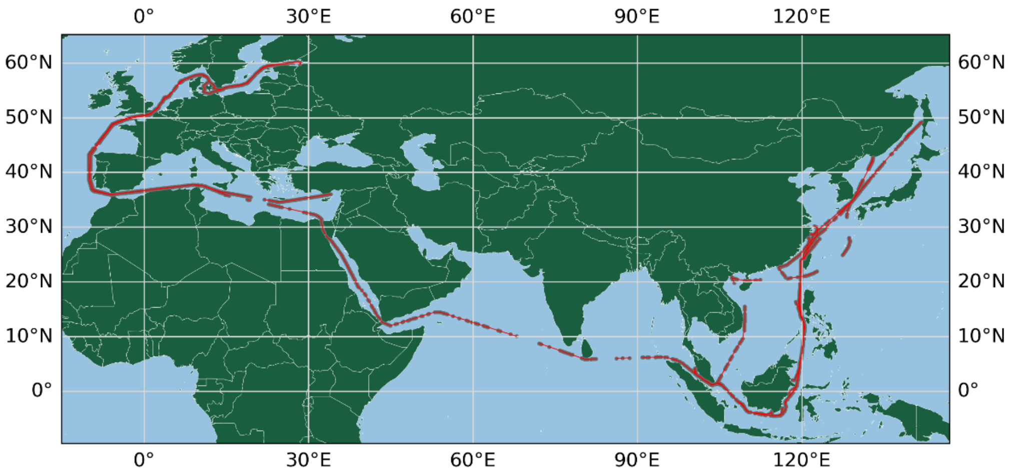
# Wind propulsion

Quantifying $CO_2$ savings from **wind propulsion** using billions of km of historical operational ship tracks and real weather data…




The Tyndall Centre's ship routing software




… modelled using the Tyndall Centre's ship routing software, running thousands of simulations on a high-performance computer.

# Wind propulsion

Top performing bulk carriers and tankers provide majority of wind propulsion emissions savings…

| % of wind ships | Emission savings | Total ships |
|---|---|---|
| Top 16% of ships | provide 50% of emissions savings | 5,569 |
| Top 33% of ships | provide 75% of emissions savings | 11,416 |
| Top 52% of ships | provide 90% of emissions savings | 17,863 |

6-9% cut, wind-propulsion alone using ~2 billion km of real voyage data.

Potential for more: combining route optimisation & weather routing.

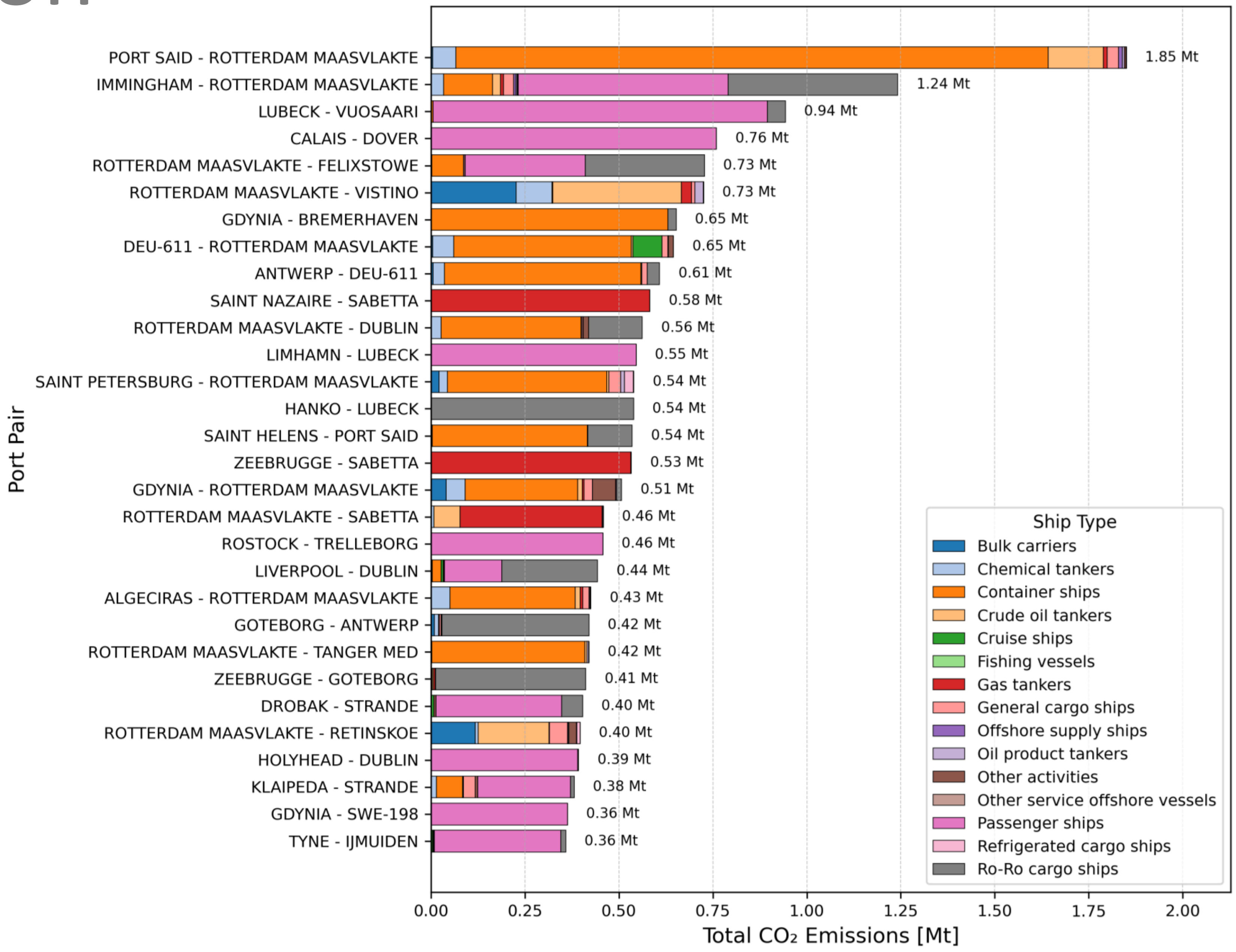
**Global Fleet Under Wind**: Mason, Della-Moglie et al., 2026, https://seas-at-risk.org/wp-content/uploads/2024/09/A-global-Fleet-Under-Wind_Seas_At_Risk-1.pdf

# Wind propulsion

Exploring where adoption should target

Not every ship needs to adopt wind propulsion to get most of the decarbonisation benefit for the fleet

Some routes offer much greater benefit potential



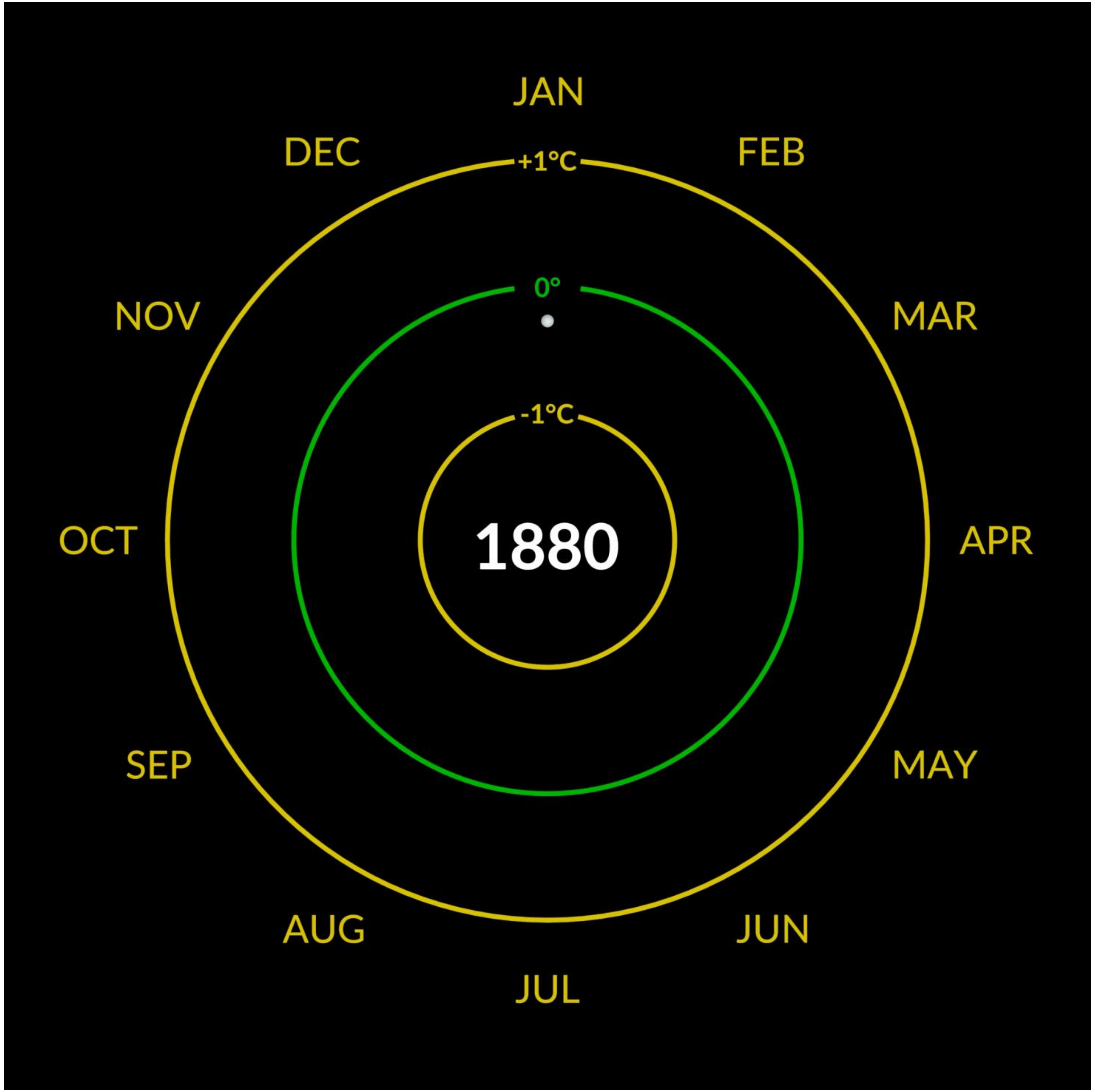
# Conclusion

Timescale to avoid the climate impacts that bring consequences for security, trade, mass human & biodiversity loss is short

Remaining 50% 1.5°C budget - ***equivalent to 4 years*** at 2025 levels

Whole system approach highlights opportunities for large cuts in $CO_2$ from shipping across: demand, operations, technology.

Analysis targeting key routes and ship types, and shifts in energy-system trade, may illustrate more realisable alternative fuel pathways.

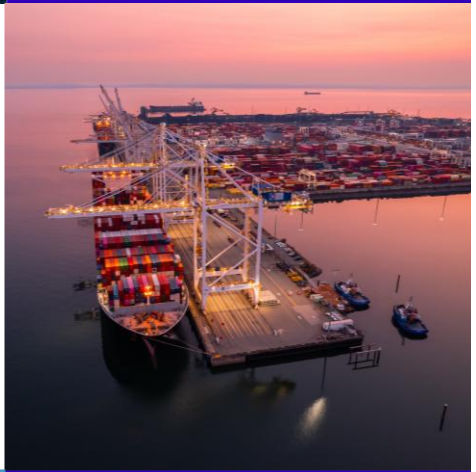

JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
+1°C
0°
-1°C
1880

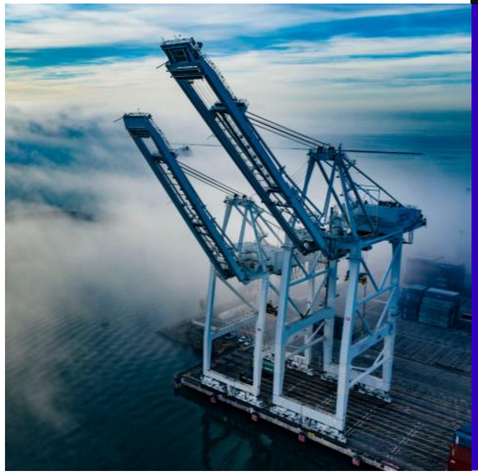
Academic Insights

# Session 2

# Engineering Future Vessels: Safety, Efficiency & Innovation

- Dr Sergii Kashkarov
- Prof Pietro Tricoli & Prof Thanos Tsolakis
- Prof Zhiqiang Hu





**UK-MaRes Hub: Clean Maritime Assembly 2026**
24-25 June, Durham University, Durham, UK

# Hydrogen storage safety under fuelling, release, ventilation and fire conditions

WP 1.3. Marine fuel storage, safety operation and handling

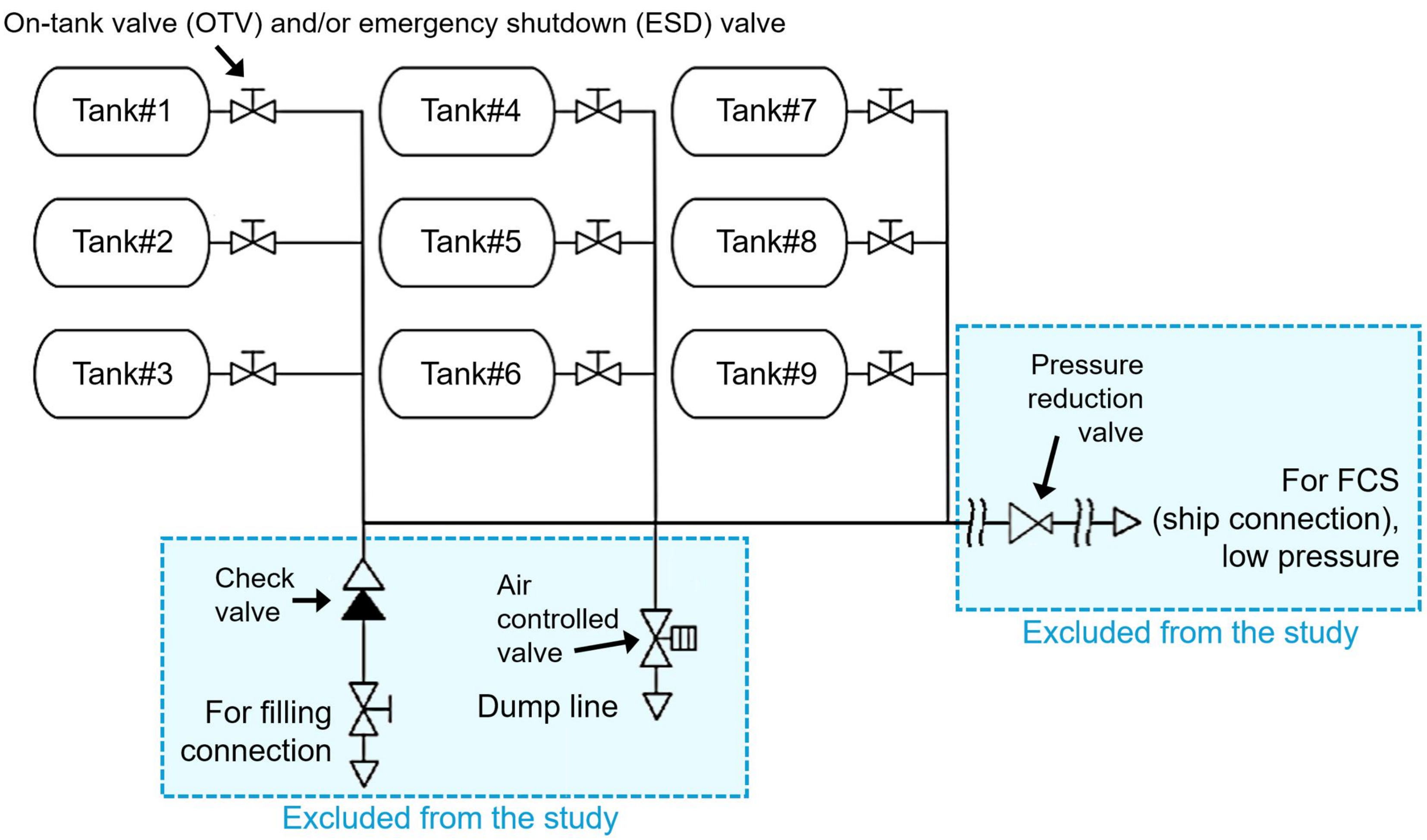
S. Kashkarov, H. Xie, D. Makarov, V. Molkov

**Hydrogen Safety Engineering and Research Centre (HySAFER)**
**ulster.ac.uk**

# Hydrogen release and ventilation behaviour in a marine storage room

# Problem formulation

## System of tanks in the maritime storage room

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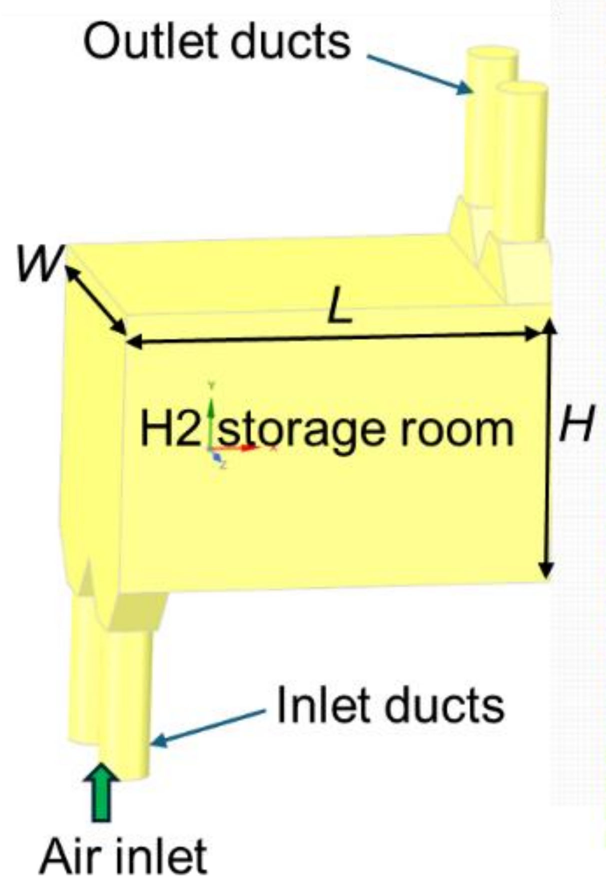
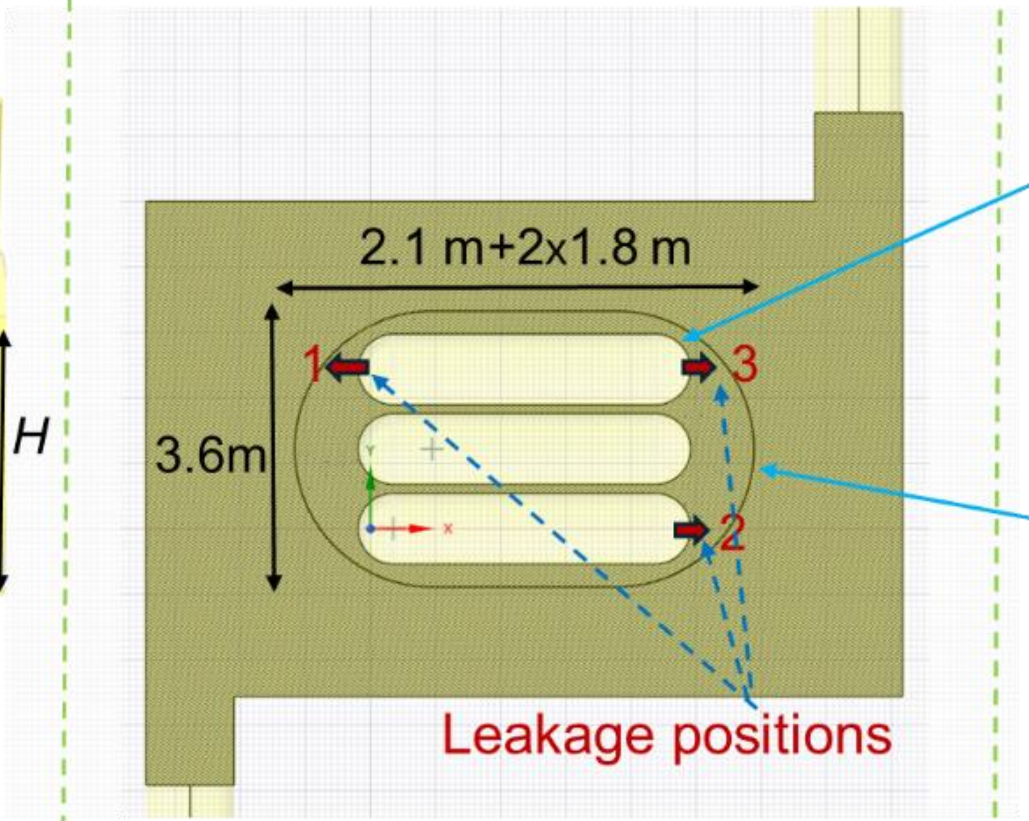
# Problem formulation

## System of tanks, ventilation and the diffusion shell

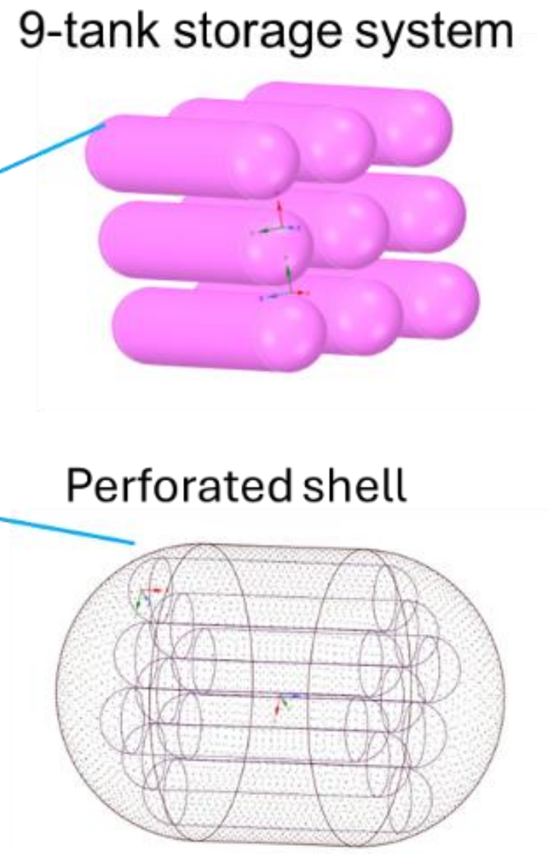
**Side view**




**Cross-sectional view**

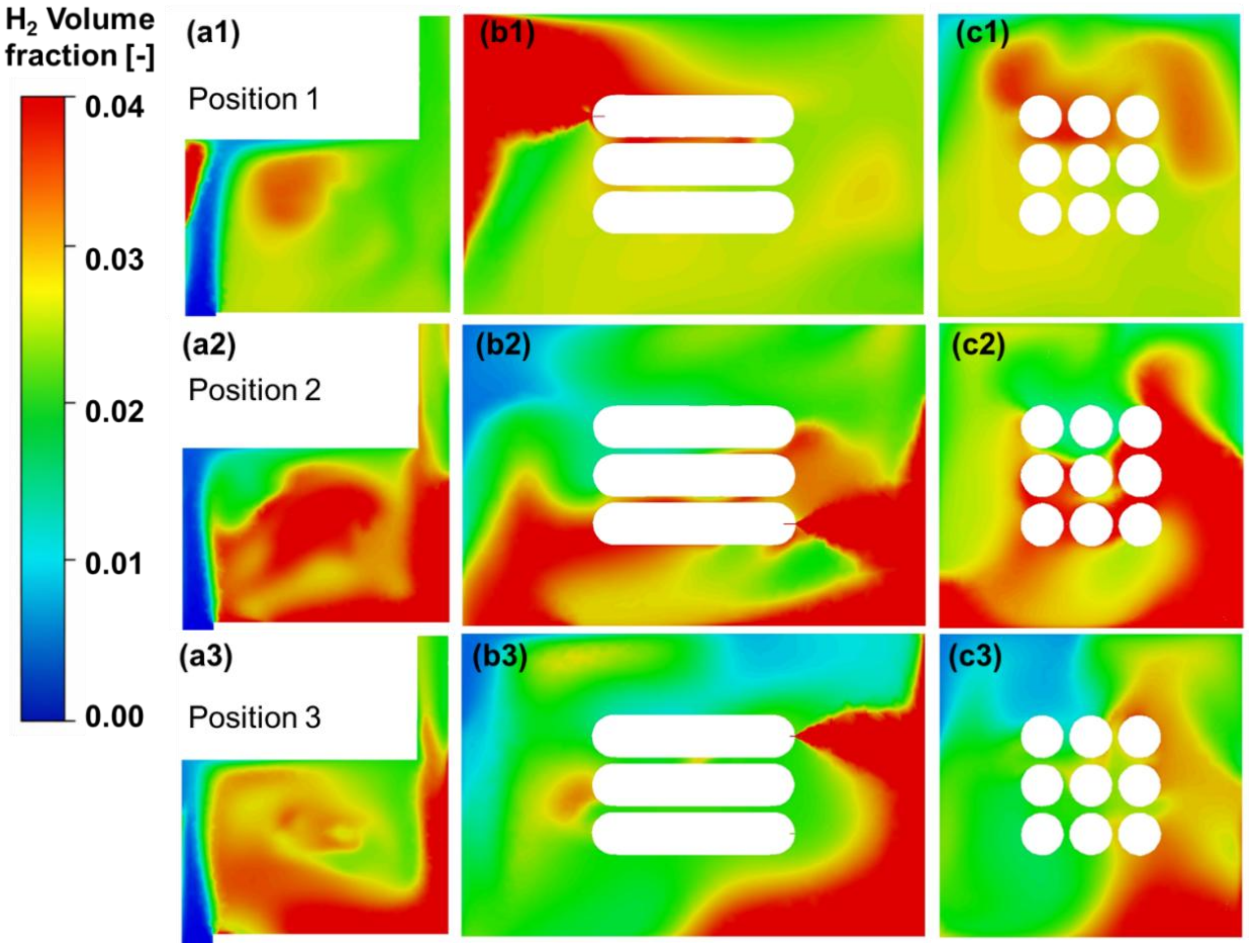



**Internal parts**

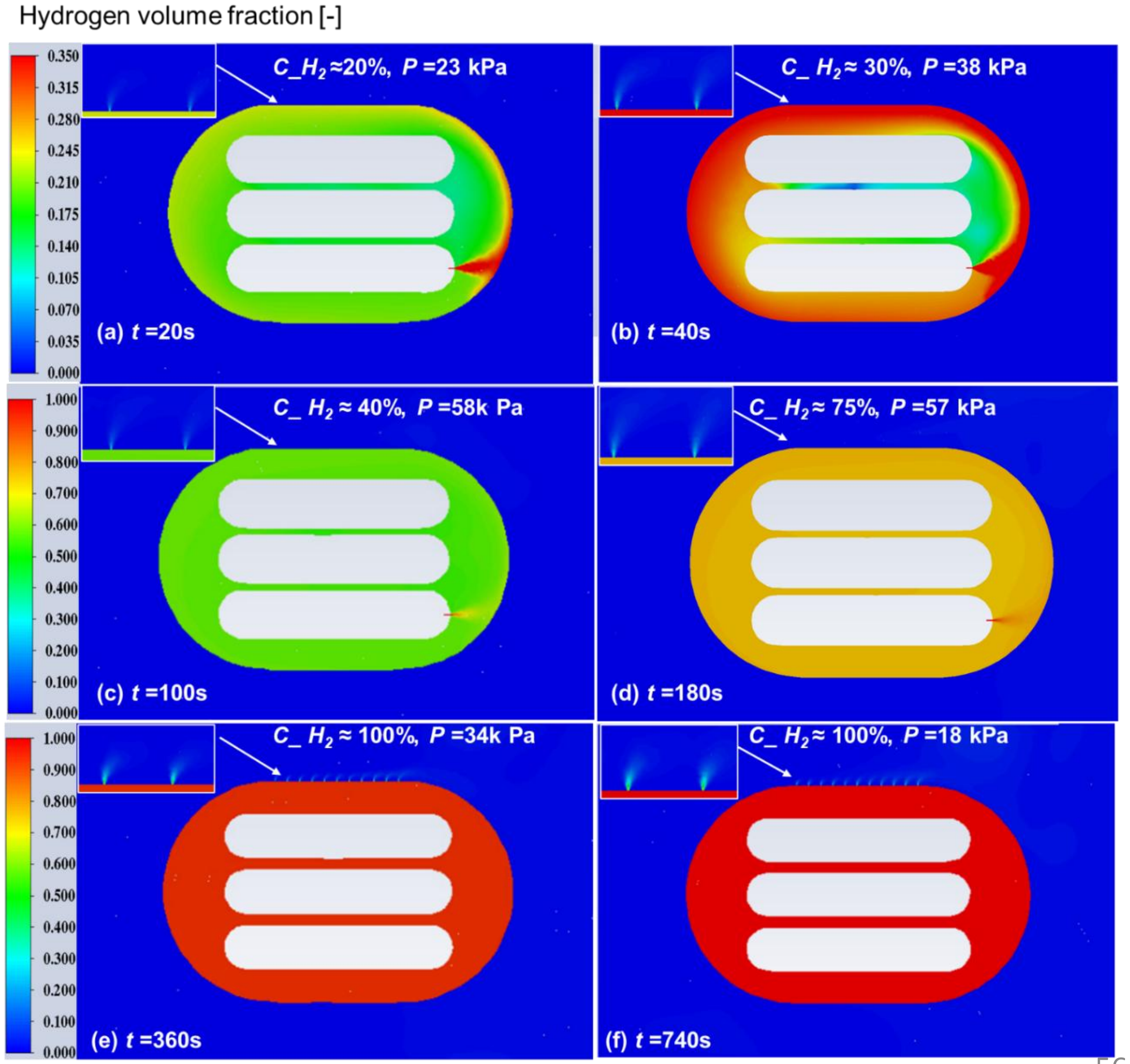


# Effect of the diffusion shell on H2 dispersion

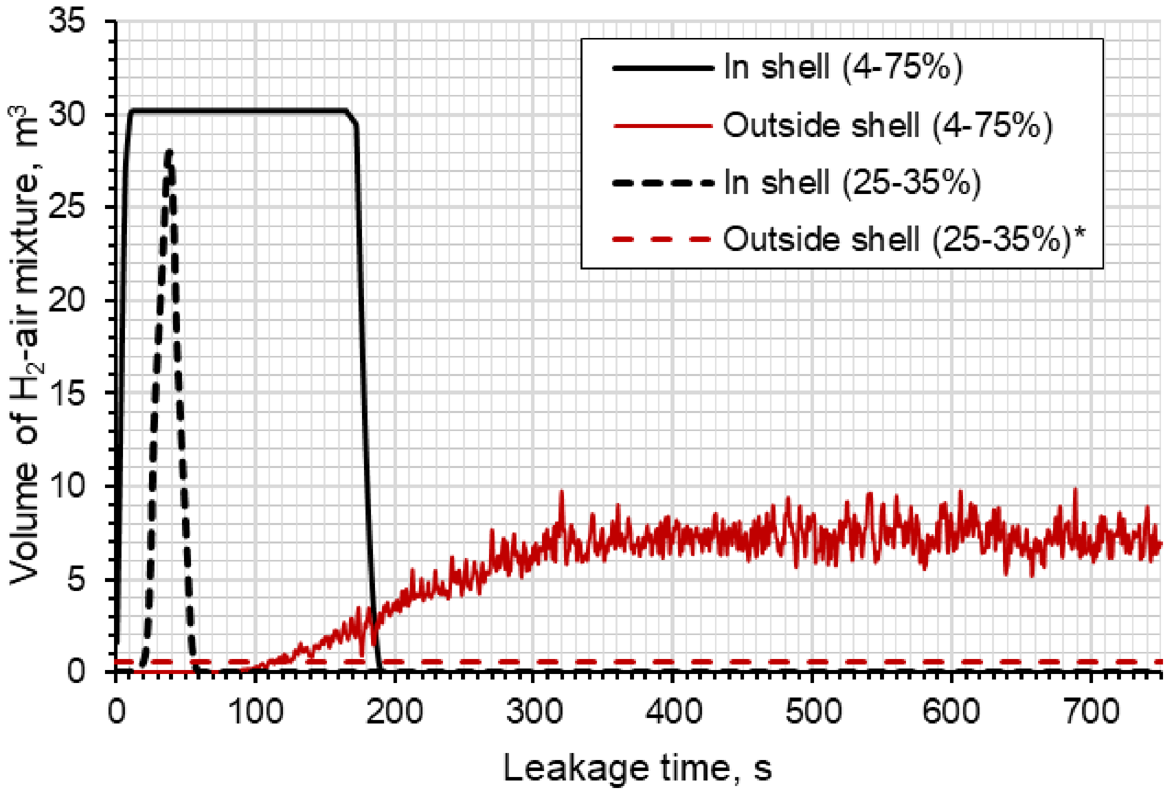
## No shell

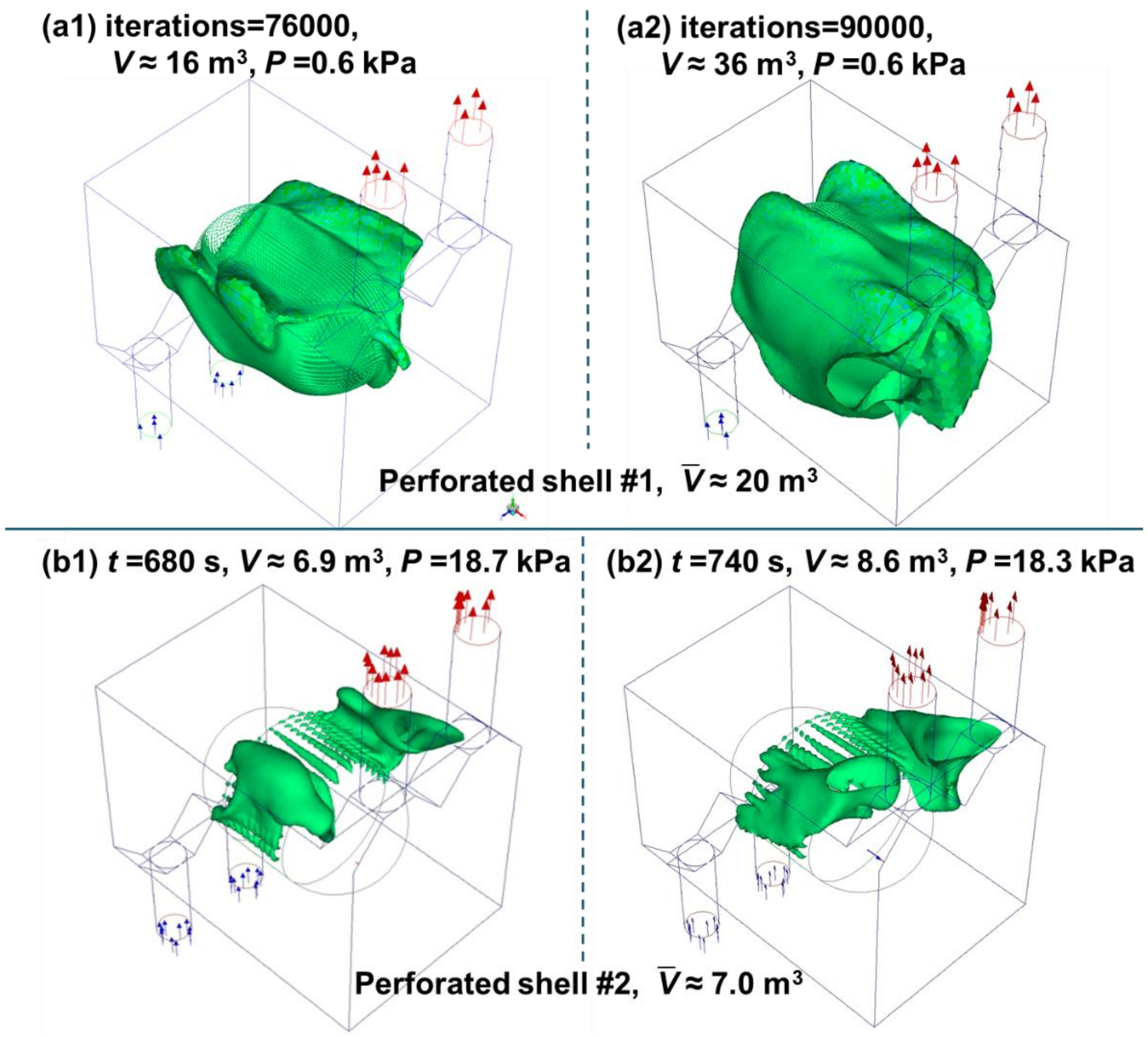



## With shell



# Effect of the diffusion shell on H2 dispersion

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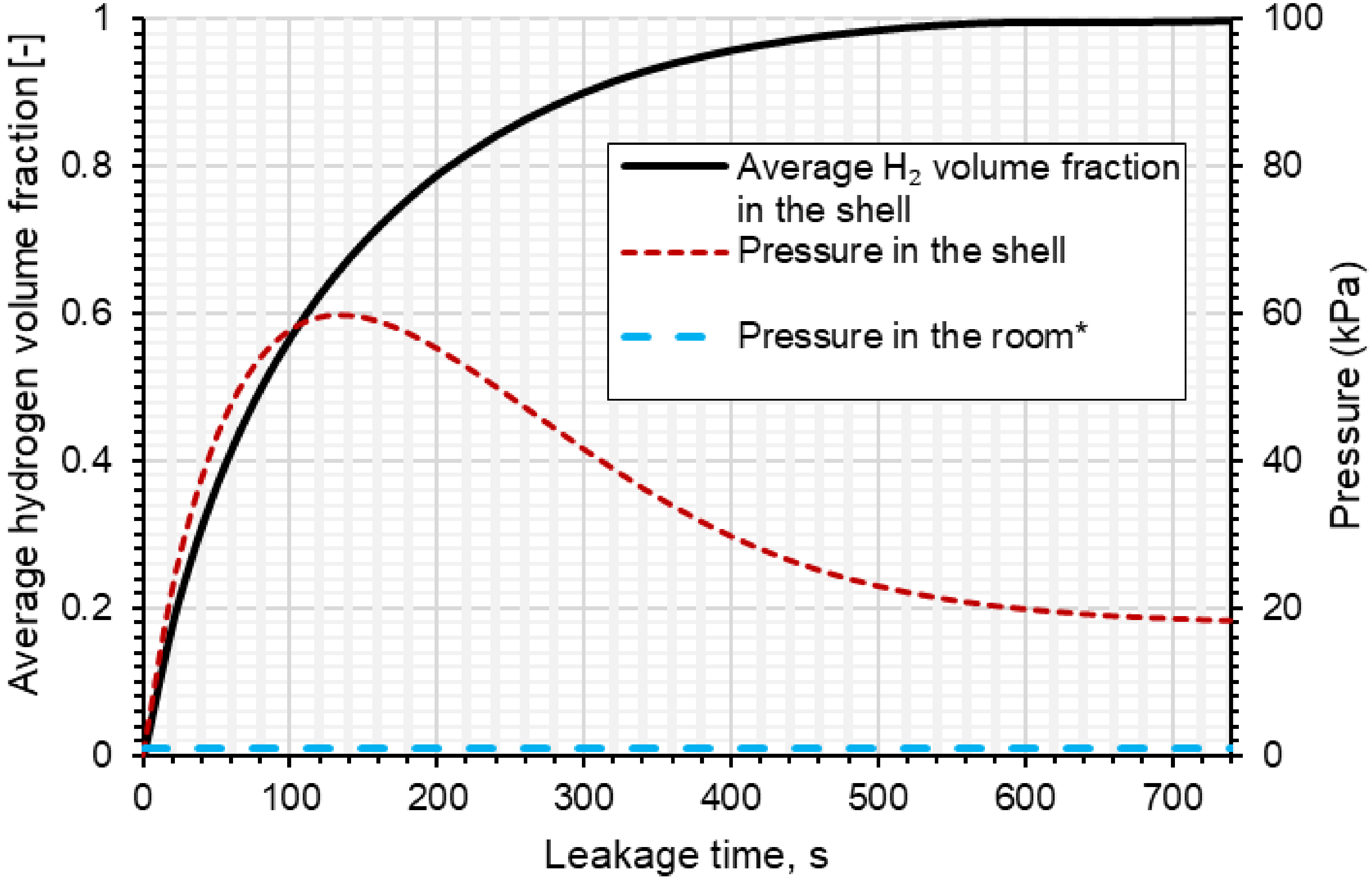
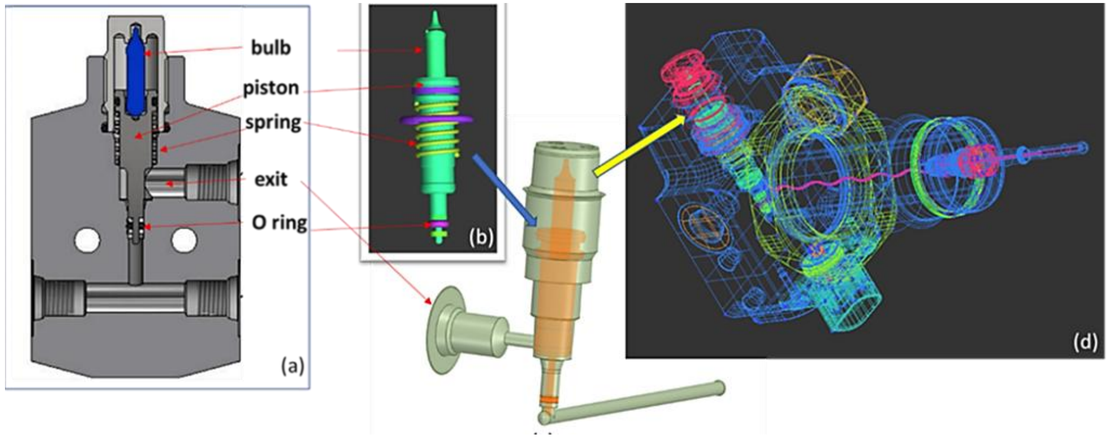
# Effect of the diffusion shell on H2 dispersion

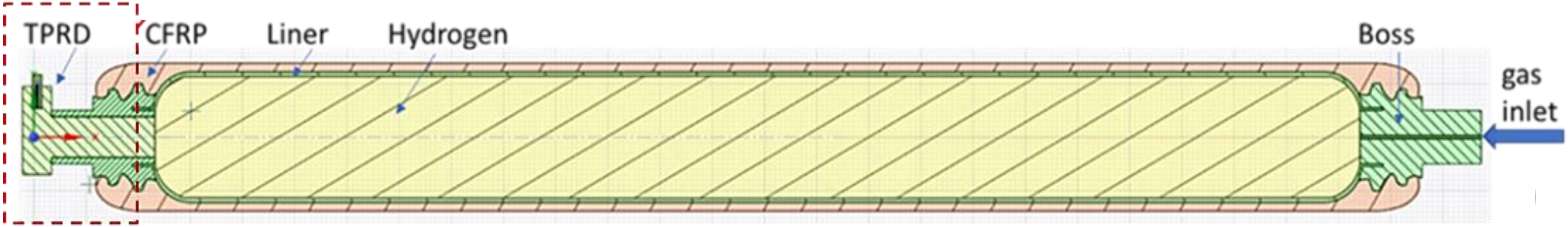


# Thermal behaviour of hydrogen tank with TPRD during fast fuelling

# Tank & TPRD geometry

- 12 L Type IV tank, NWP = **70 MPa**
- 1300×140 mm, L/D = **9**
- Nozzle D = **3.5** mm
- TPRD: glass bulb type, activates at **~110 ℃**

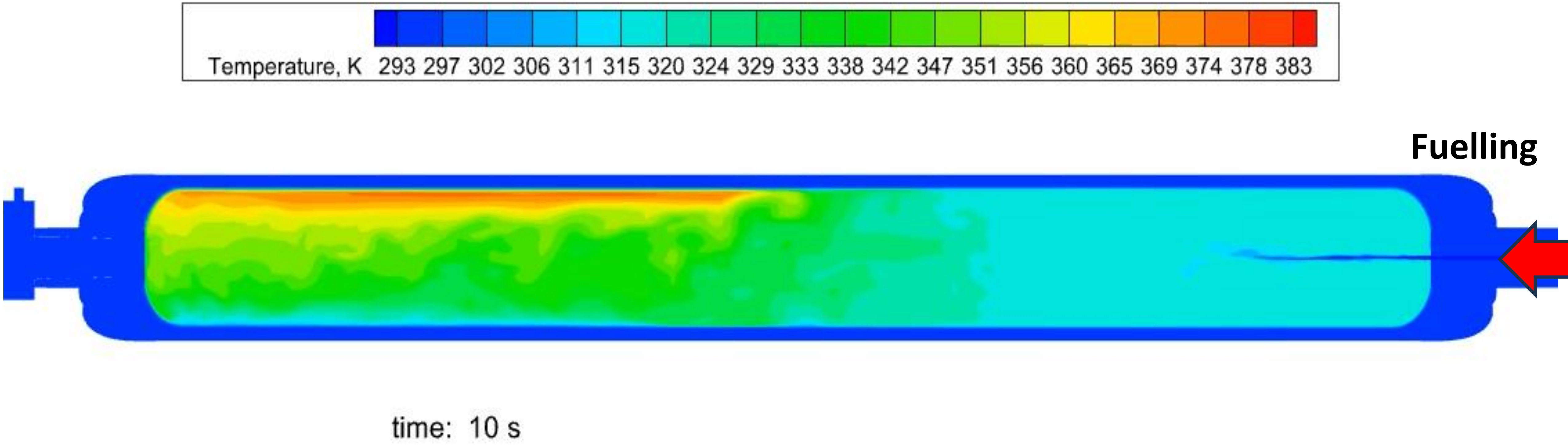



*Reference: Shentsov V, Kashkarov S, Xie H, Molkov V, Brennan S, Kazemi M. Deliverable D3.4 – Report on innovative engineering solutions for TPRD. Storage of hydrogen: alternative pressure enclosure development (SH2APED) Project. European Commission; 2024.*

# Simulation results

## 3-min fuelling of horizontal tanks (2→70 MPa)

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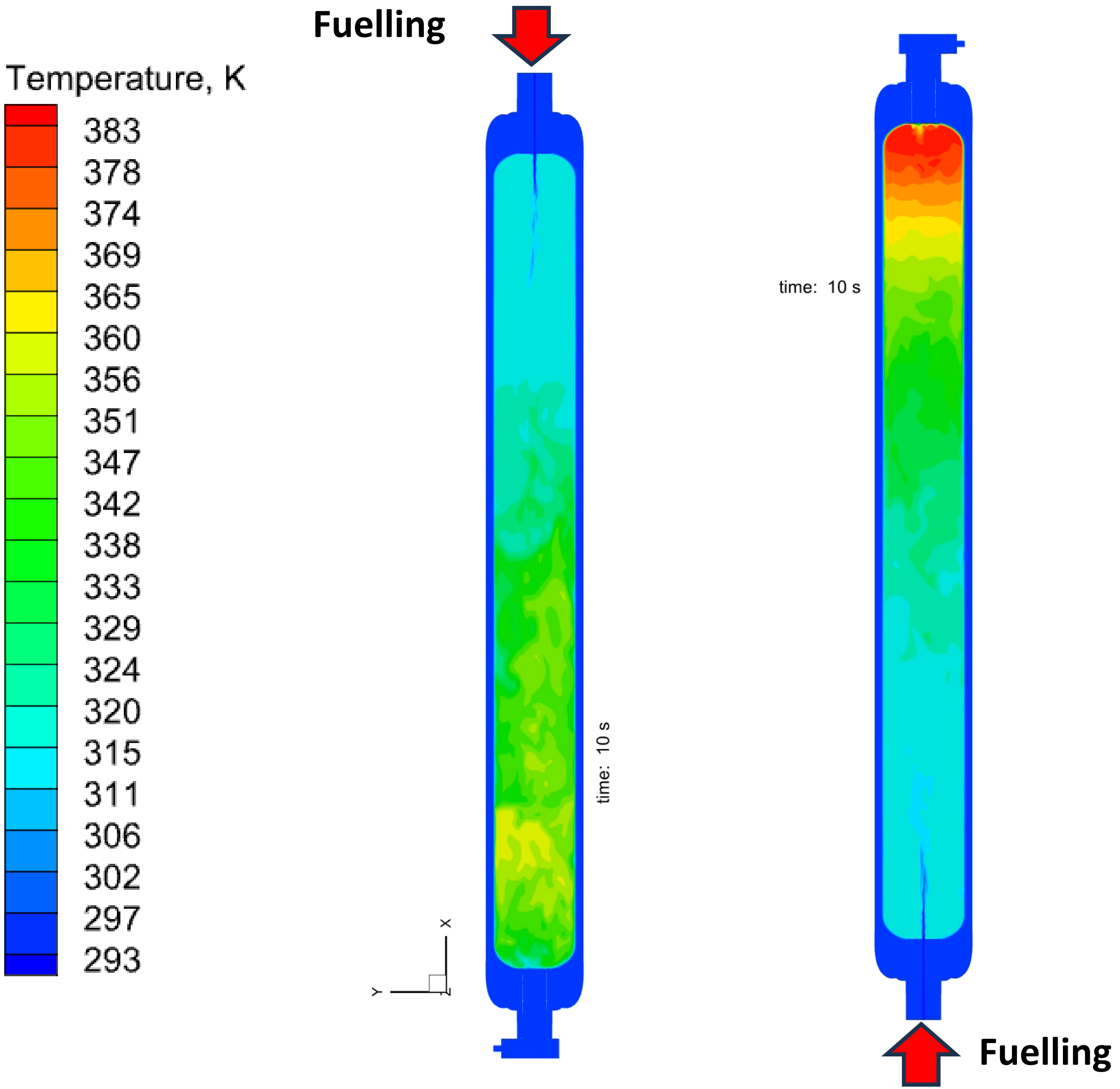
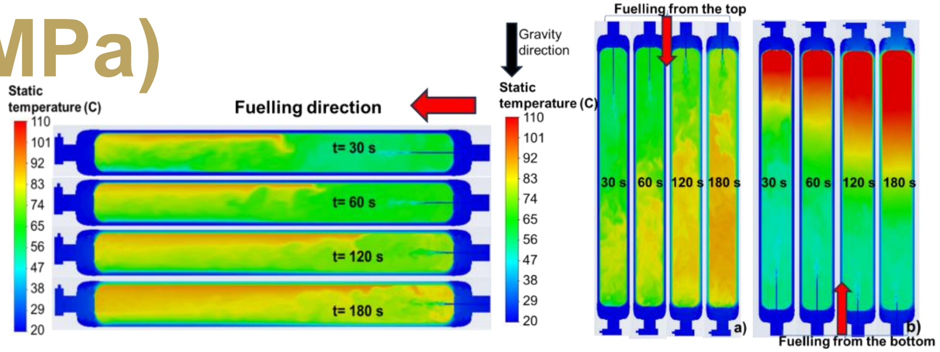

Fuelling
Temperature, K
383
378
374
369
365
360
356
351
347
342
338
333
329
324
320
315
311
306
302
297
293
time: 10 s
time: 10 s
Fuelling

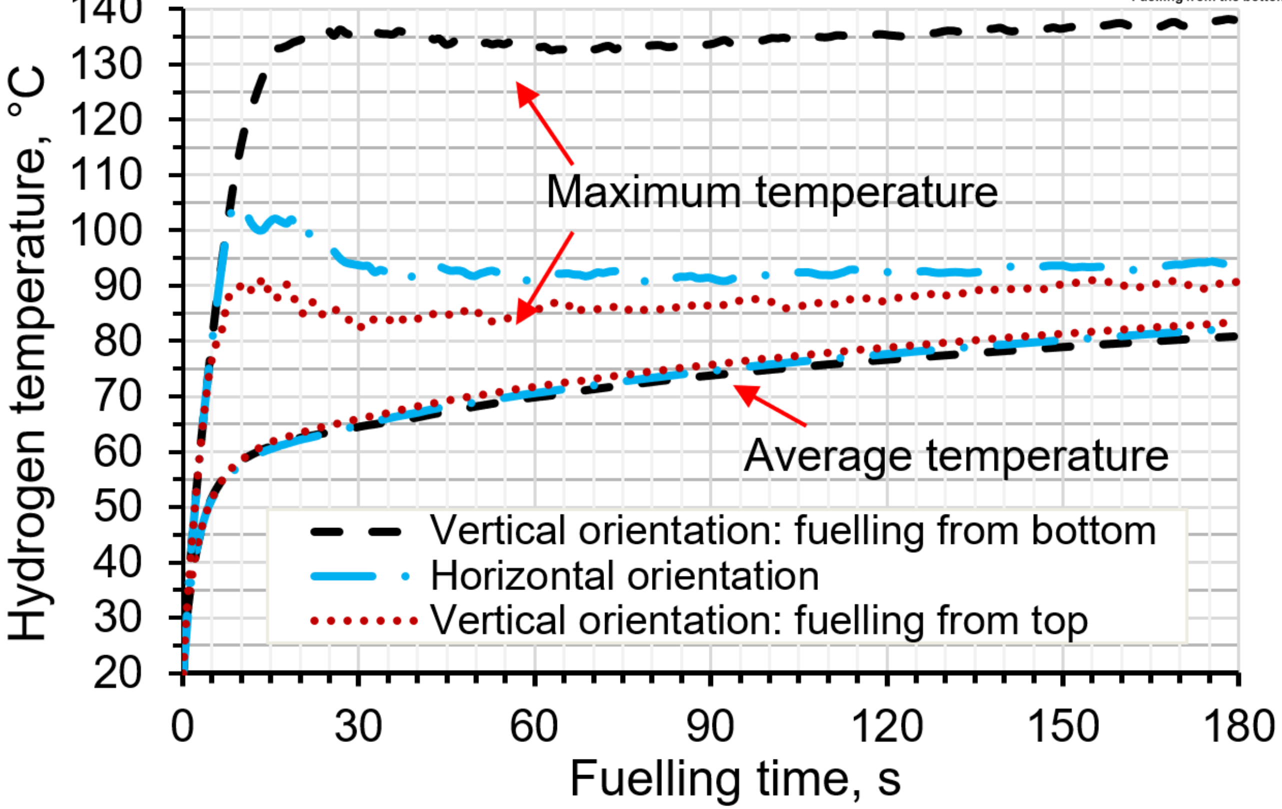
# Simulation results

## 3-min fuelling of vertical tanks (2→70 MPa)




Compared with horizontal fuelling,

- **Bottom-up fuelling** increases non-uniformity, with maximum hydrogen temperature ~**138℃**
- **Top-down fuelling** reduces non-uniformity by ~40%, with maximum hydrogen temperature ~**91℃**

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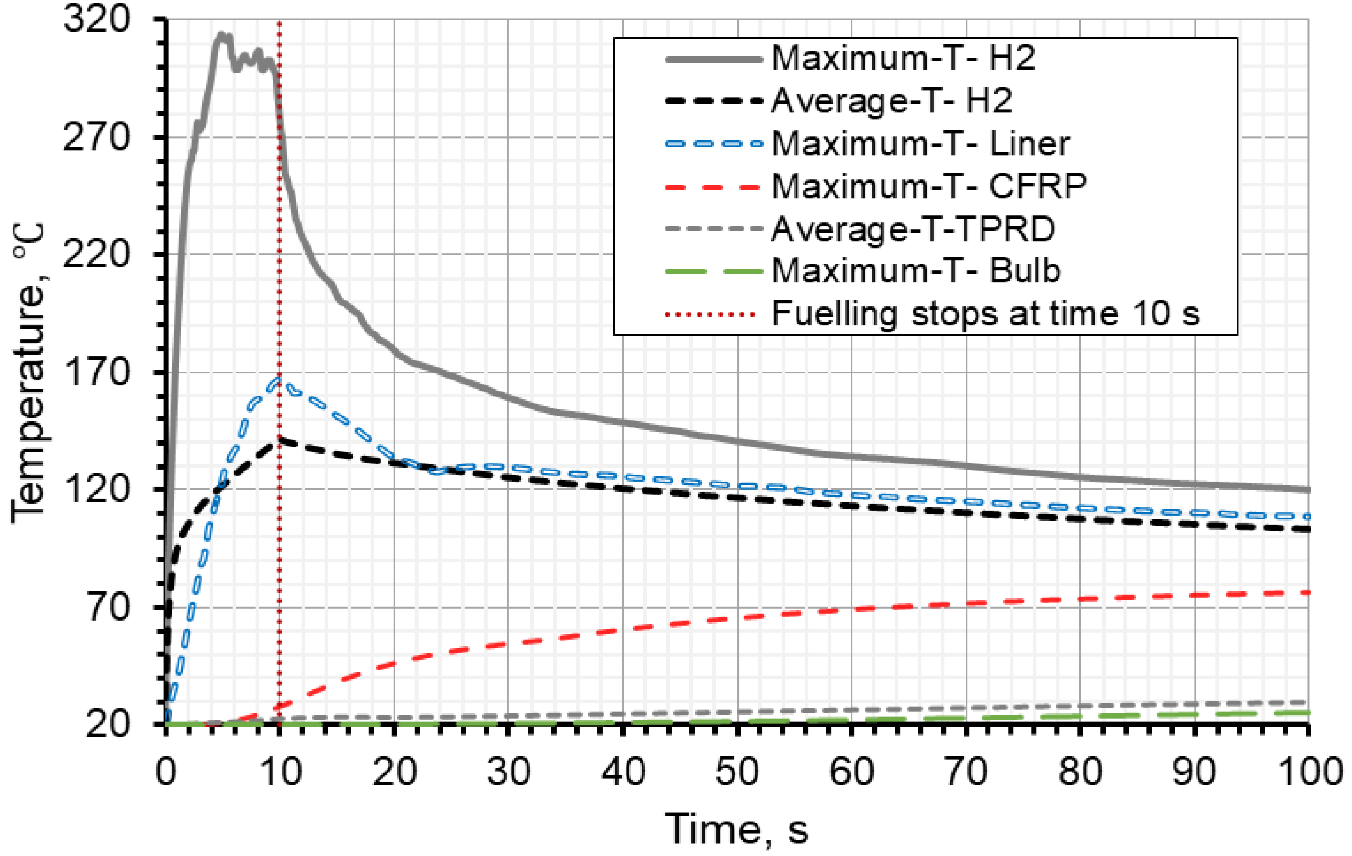
# Simulation results

## Extreme fuelling scenario of horizontal tanks ~ 10MPa/s

10 s fuelling at flow rate of 50 g/s for one tank ~10MPa/s, i.e., 450g/s for 9-tank system (Harris 2012)

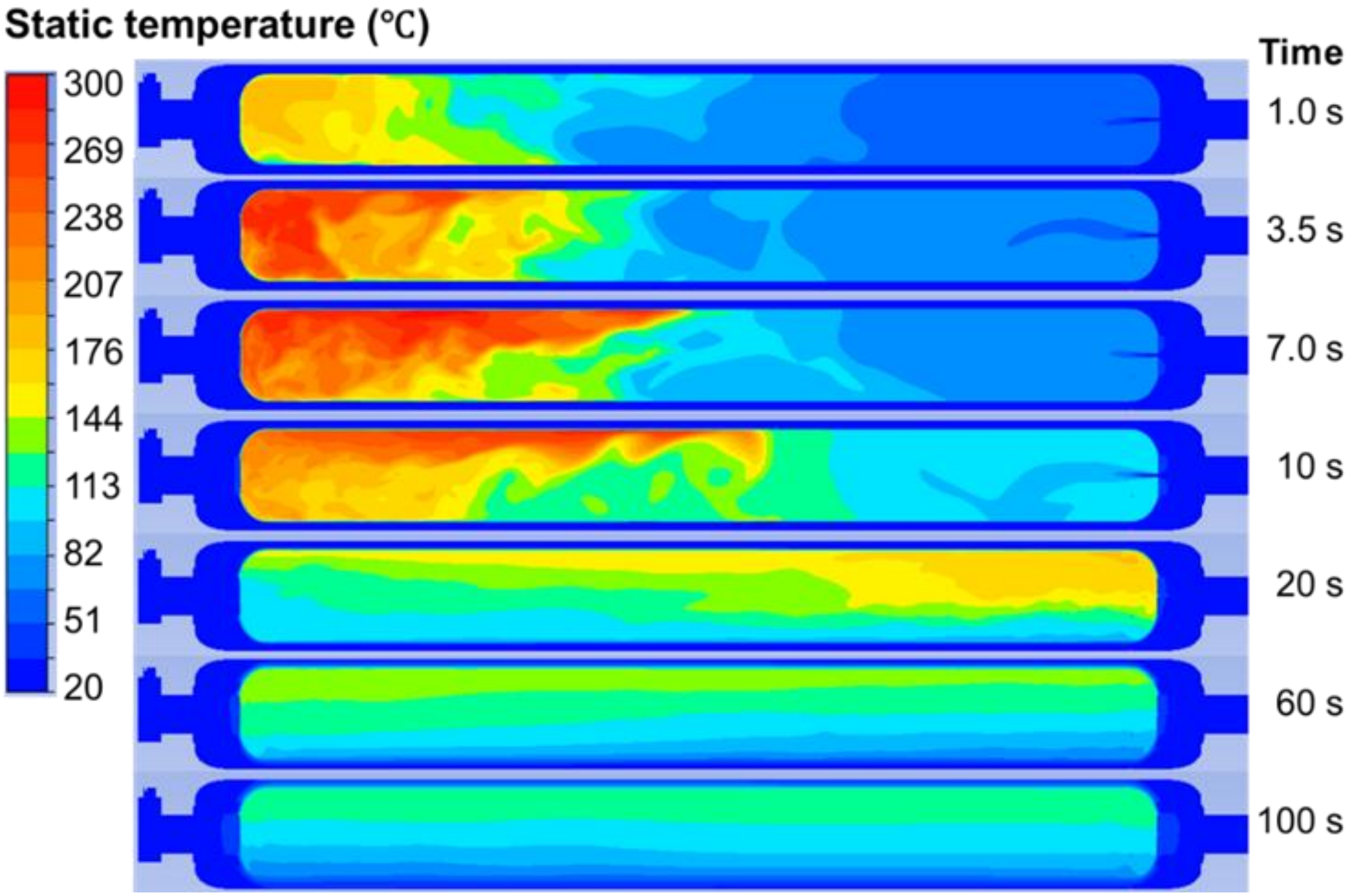



**Maximum $H_2$ temperature > 300 ℃! Maximum liner temperature> 160 ℃!**

*Reference: Harris AP, San Marchi CW. Investigation of the hydrogen release incident at the AC Transit Emeryville Facility. Sandia National Laboratories (SNL), Albuquerque, NM, and Livermore, CA; 2012.*

# Simulation results

## Extreme fuelling scenario of horizontal tanks ~ 10MPa/s

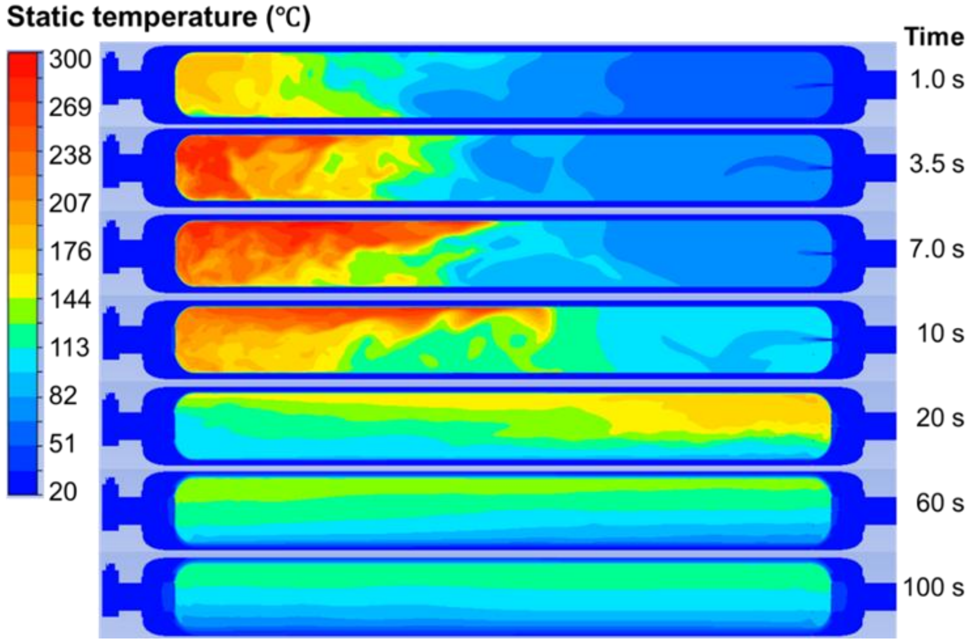


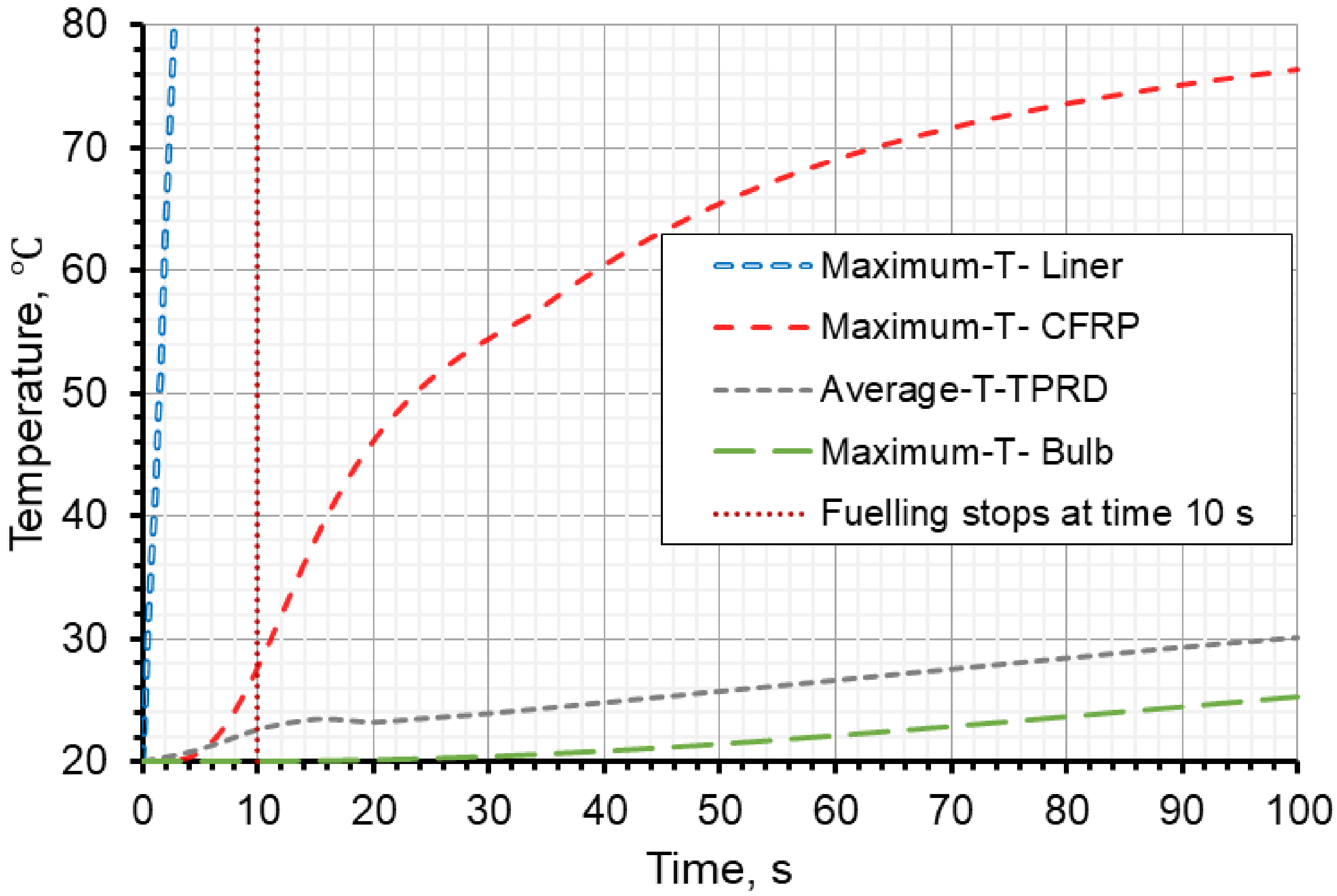

**Maximum $H_2$ temperature > 300 ℃! Maximum liner temperature> 160 ℃!**

# Simulation results

## Extreme fuelling scenario of horizontal tanks ~ 10MPa/s

- $T_{bulb} < T_{TPRD}$, **activation unlikely during extremely fast fuelling**
- Reveals safety gap: **liner may "fail" before TPRD triggers**



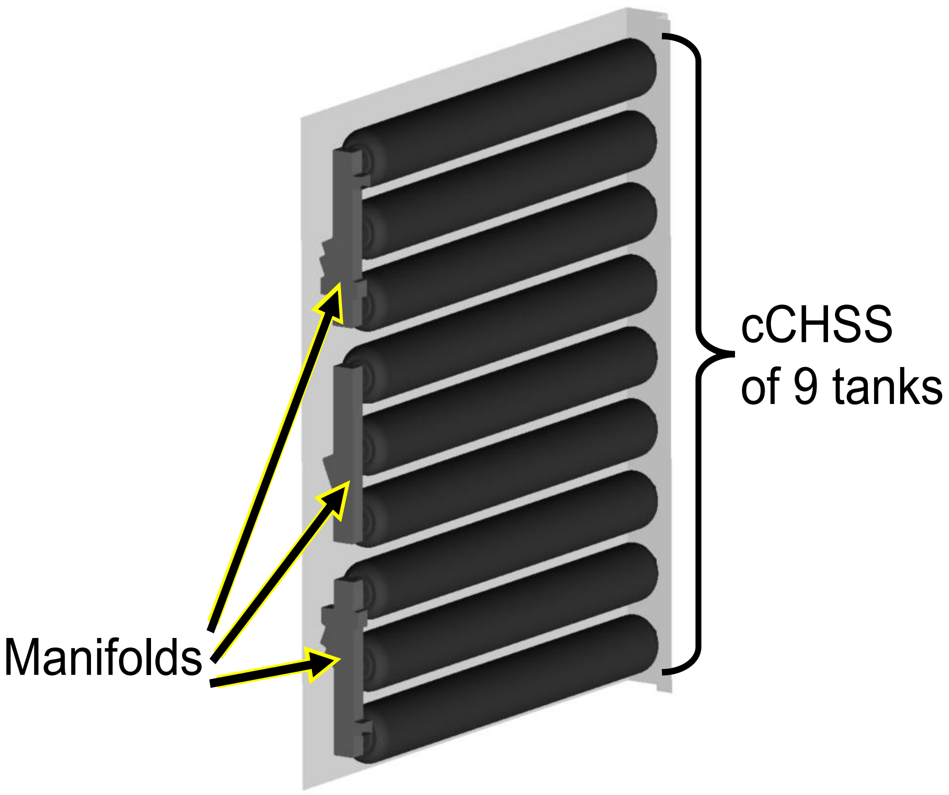



# Fire resistance of conformable self-venting hydrogen tanks

# Hydrogen initial conditions & cCHSS parameters

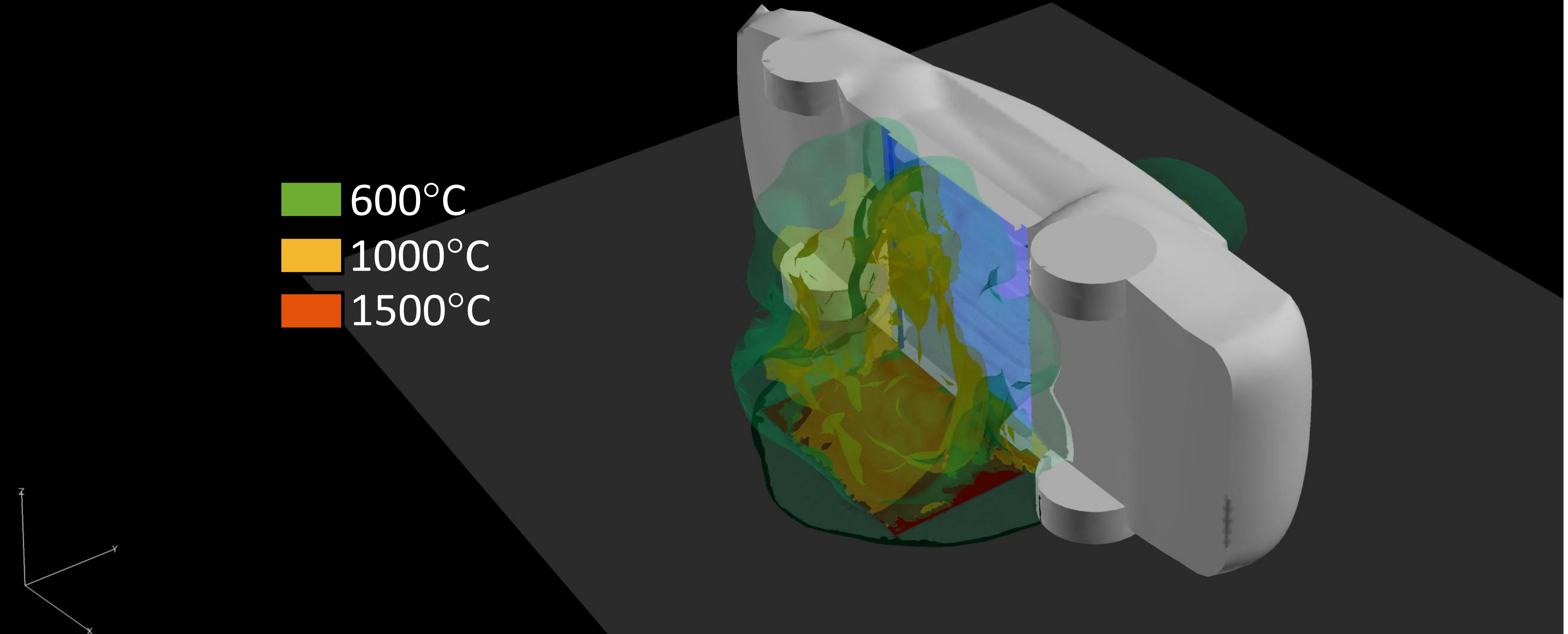
| H2 parameters | Per 1 tank | Per cCHSS (9 tanks) |
|---|---|---|
| $P$ | 70 MPa | |
| $V$ | 12 L | 108 L |
| $T$ | 20°C | |
| $\rho$ | 40.06 kg/m$^3$ | 40.06 kg/m$^3$ |
| $m$ | 0.48 kg | 4.32 kg |

Geometry of the cCHSS



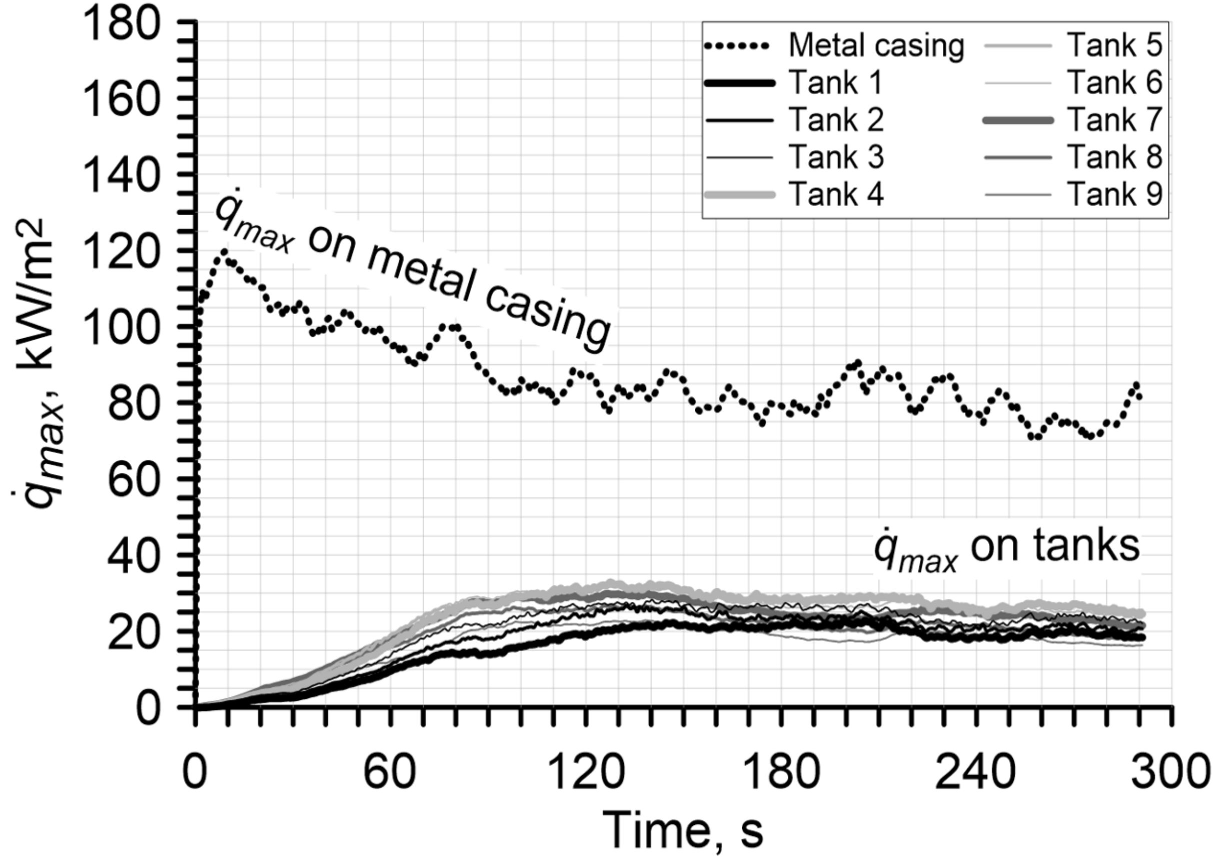

**L/D ratio of these conformable tanks is ~9.*

# 3D CFD simulation of under-vehicle fire (HRR/A=1 MW/m$^2$)

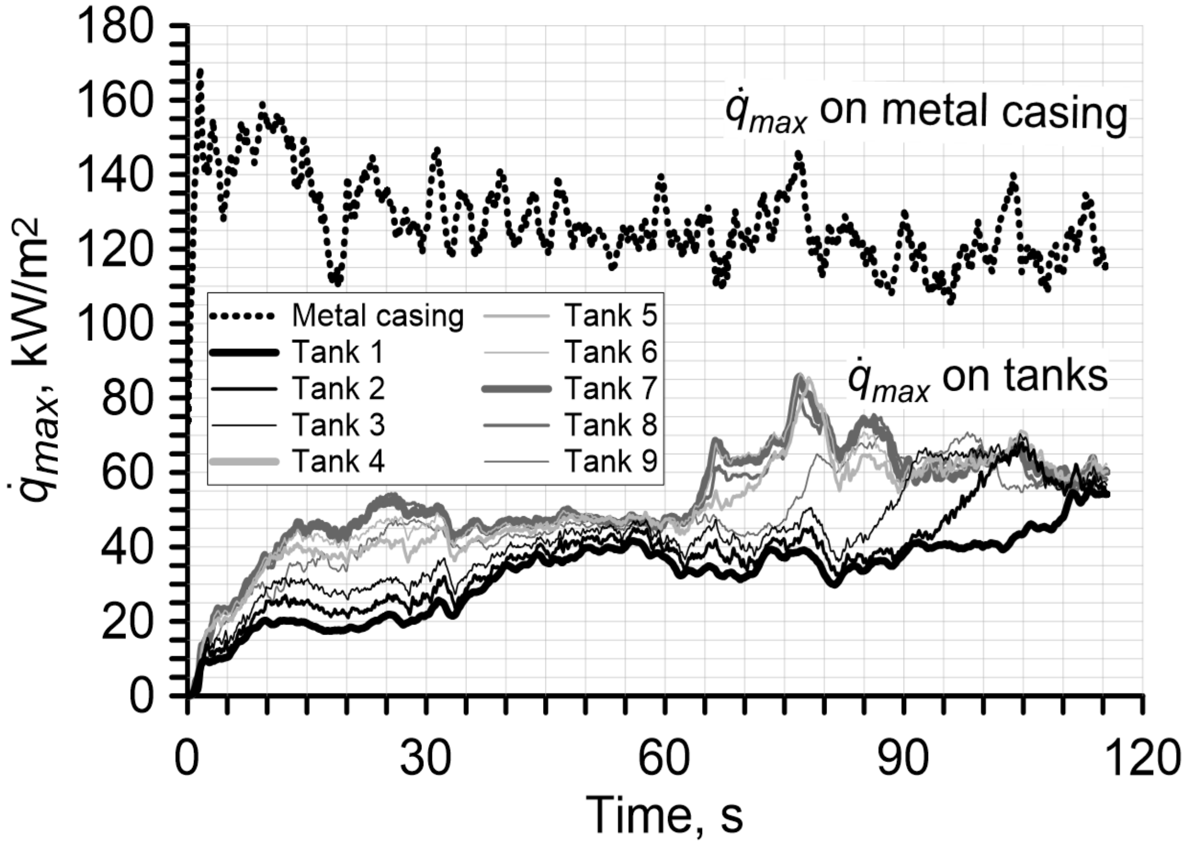


# Maximum $\dot{q}$ to the metal casing and the tanks

**No contact between the metal casing and a composite tank (<u>with air gap</u>)**



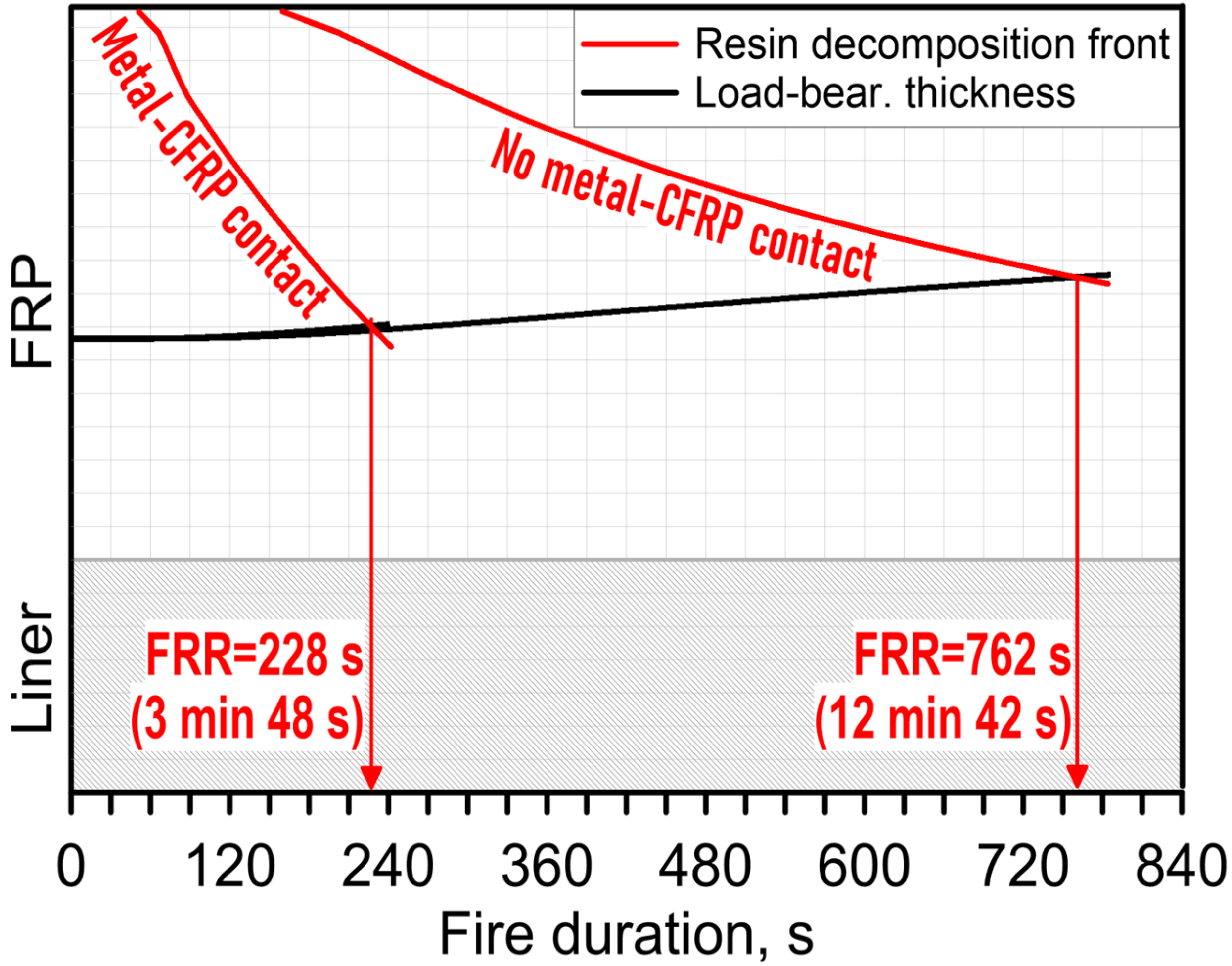

**The metal casing is in contact with a tank (<u>no gap</u>)**

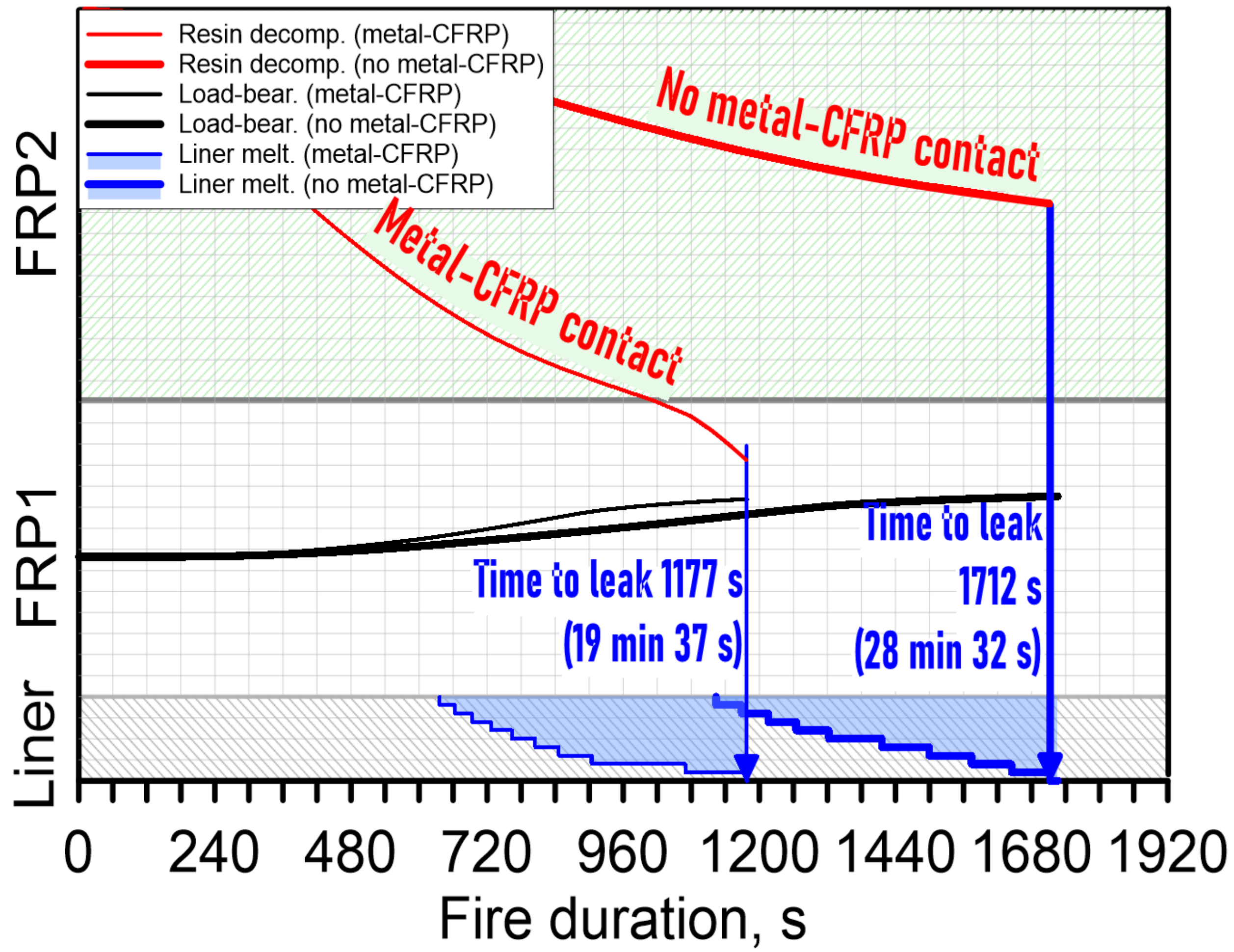



**In case of direct metal-composite contact, conduction dominates at the interface between these solid bodies, resulting in minimal thermal resistance. Hence $\dot{q}$ to the metal and tanks are higher.**

# Single tank protected by metal casing in a fire

## Standard tank vs self-venting tank (both with metal casing)



# Conclusions

- Fast filling of long horizontal tanks (L/D = 9) creates strong temperature non-uniformities, so tank geometry, orientation and fuelling direction are critical for thermal safety.
- Top-to-bottom fuelling reduces temperature gradients by about 40%, while bottom-to-top fuelling can trap hot gas and produce local temperatures up to 138°C.
- In extreme fuelling failure conditions (10 MPa/s), hydrogen can exceed 300°C and the liner can reach about 165°C, while the TPRD may not activate fast enough.
- μLNB self-venting tanks showed explosion-free fire performance, with microleakage after liner melting in 19-29 min, supporting safer alternatives to TPRD-equipped CHSSs.
- Together, these findings support safer hydrogen storage, fuelling and ventilation design for maritime alternative-fuel systems and future clean maritime infrastructure.

# Thank you!

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Faculty of Computing, Engineering & the Built Environment

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- **Hydrogen Safety Technologies**

Distance learning PgCertPD Hydrogen Safety

These short courses are designed to provide you with the knowledge and understanding of hydrogen safety engineering and technologies, developing your ability to deal with complex safety problems. The programmes are ideal for anyone involved in the safety of hydrogen systems and infrastructure, including its production, storage, transportation and use, and the safety training of personnel. Upon completion, opportunities for further doctoral study exist.

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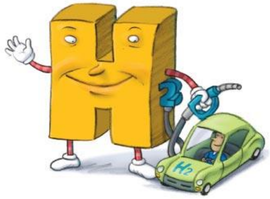


UK National Clean Maritime Research Hub

# DC Electrification and Hybrid Battery-Supercapacitor Storage for Maritime Electrical Power Systems

Professor Pietro Tricoli

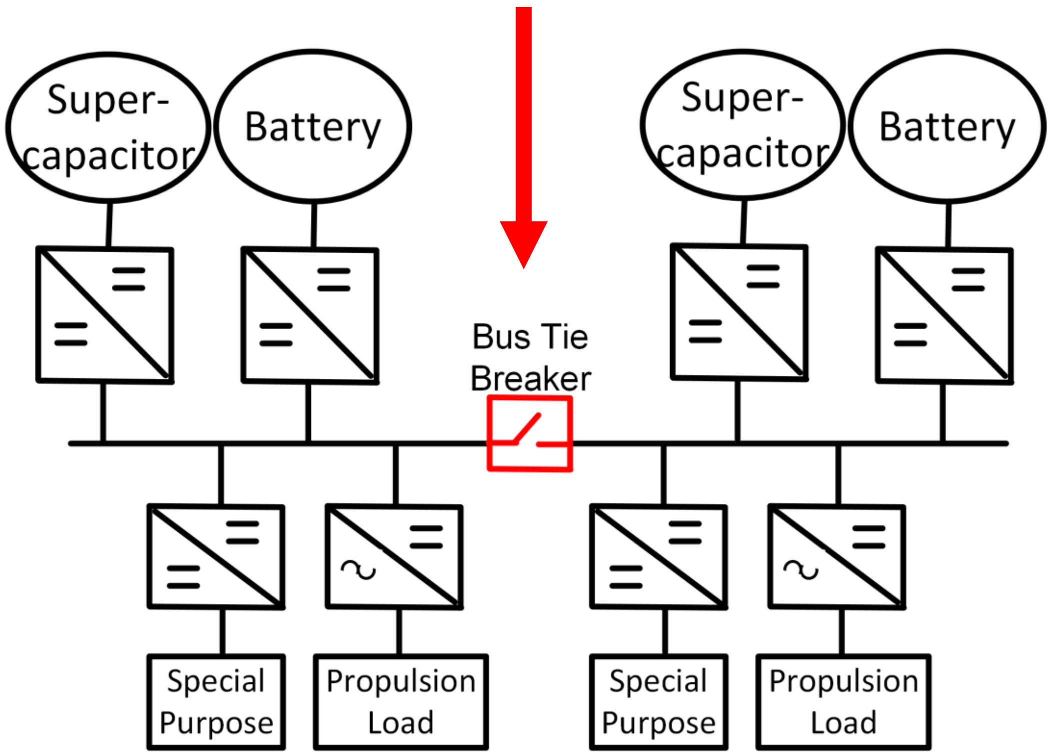
University of Birmingham
Department of Electronic, Electrical, and Systems Engineering, Edgbaston, B15 2TT, UK

# *Introduction*

- Maritime emissions in the EU accounts for 13% of all transport mode
- The EU has a target of reducing GHG emissions by a minimum of 55% by 2030.
- There are plans to introduce emissions-controlled zones, so operators will have to introduce new zero-emissions technologies
- The EU maritime industry is innovating in numerous aspects of vessels' propulsion, and it is widely recognised that substantial CO2 savings can be achieved by integrating some forms of electrifications with batteries charged by shore power (possibly from renewable power sources).
- It is also clear that there are some forms of shipping that will be very hard to decarbonise, but lessons learnt in the applications where decarbonisation is more feasible will steer the demand and will introduce technology improvement that will identify the correct solutions.

# *Marine DC Protection: Solid-State Circuit Breakers*

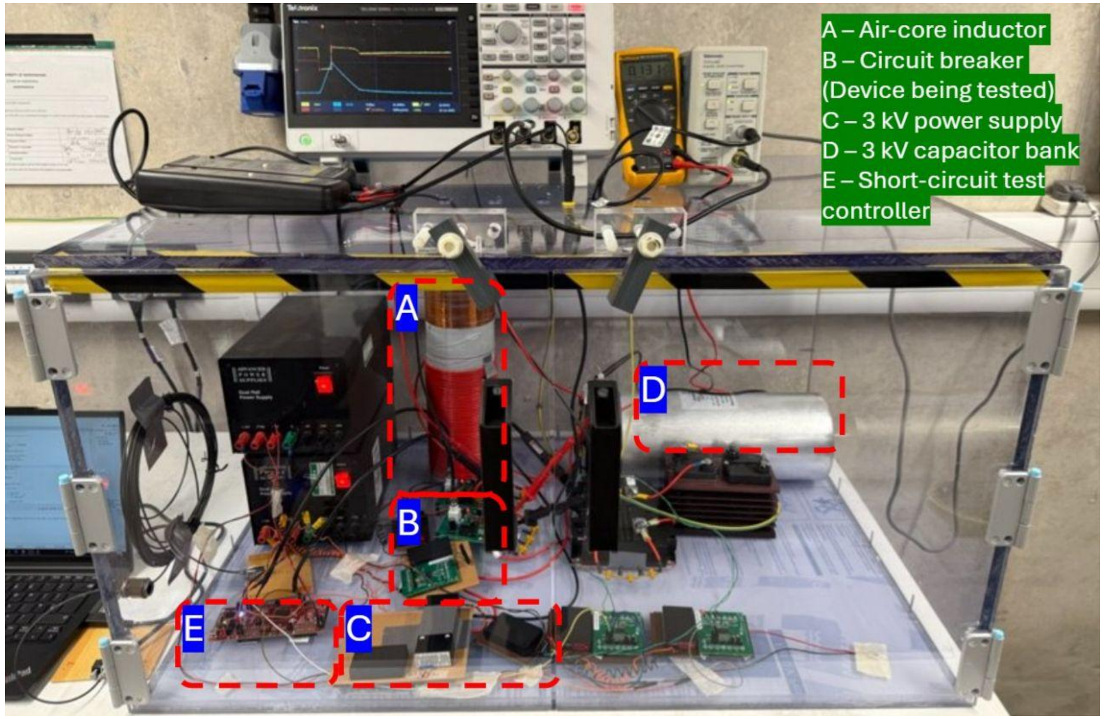
- Mechanical circuit breakers usually clears the faults in the range of milliseconds, too slow for fault interruption.
- How can a fast, reliable 3 kV solid-state DC breaker be designed to safely protect marine power systems?




M. Meraj, P. Weston, P. Tricoli, J. K. Banda, A. Holdyk, S. D'Arco, V. Stratigaki, P. Bonte, and M. Deruyck, "Fault analysis and protection scheme for marine DC power distribution networks", in Proc. of 2026 IEEE Transp. Electrific. Conf. & Expo + IEEE Elect. Aircraft Technol. Symp., Novi, MI, USA, 10-12 Jun. 2026

# 3 kV Solid State Circuit Breaker Test Rig

- Defined the system architecture and SSCB performance requirements (Tripping in microseconds).
- Designed SSCB topology using SiC devices and bespoke inductor.
- Built lab test rig for controlled 3 kV evaluation.
- Implemented fast fault-detection and control algorithms(with $i$^2 $t$ characteristics).
- Validated performance short circuit and working on overload tests.



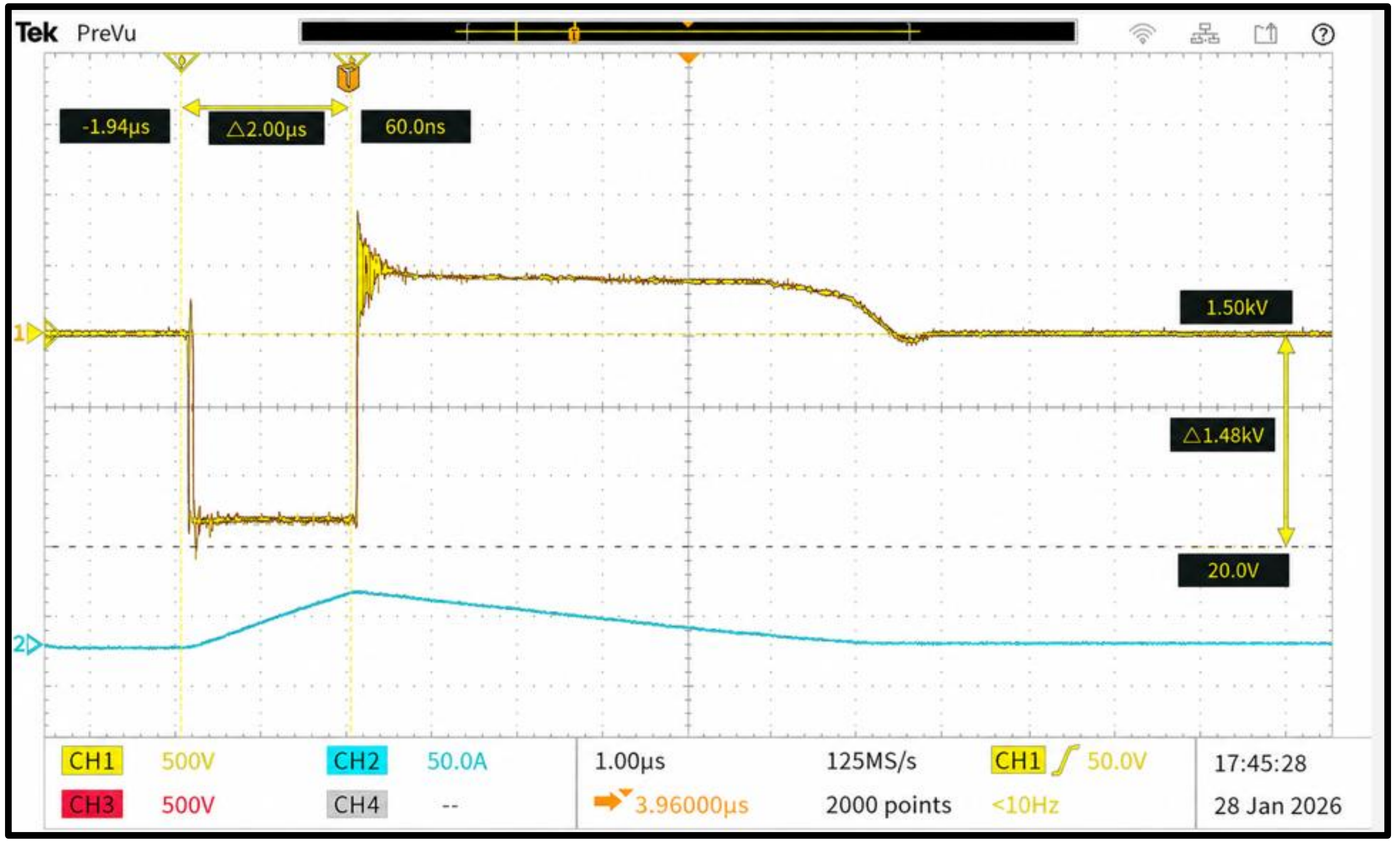

A. Ashraf, M. Meraj, O. Omotoso, C. Phelan, P. Weston, and P. Tricoli, , “Design and safety-oriented development of high-voltage testing of solid-state circuit breakers for all DC marine applications”, in Proc. of 2026 IEEE Transp. Electrific. Conf. & Expo + IEEE Elect. Aircraft Technol. Symp., Novi, MI, USA, 10-12 Jun. 2026

# *3 kV Solid State Circuit Breaker Test Rig*

- 3kV blocking capability obtained with 2 SiC modules in series.
- TVS diodes used to mitigate overvoltage during circuit opening

- Current rise time: 2us
- Short circuit current peak: 60A
- Current extinguishing time: 8us

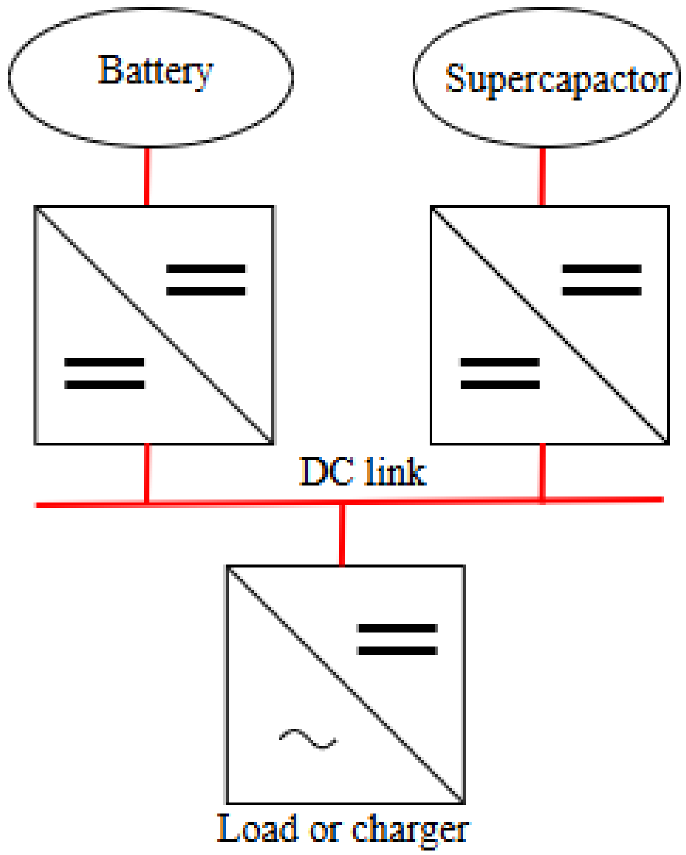
- Nominal DC voltage: 3kV
- Peak Clamping DC voltage: 3.5kV
- Peak DC voltage overshoot: 3.75kV



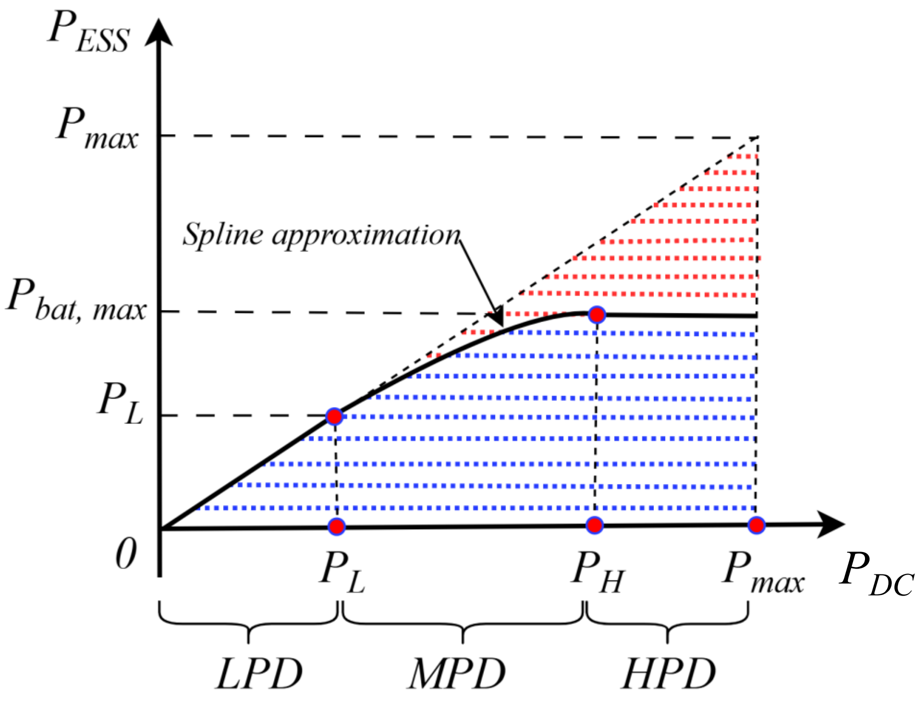

A. Ashraf, M. Meraj, O. Omotoso, C. Phelan, P. Weston, and P. Tricoli, , "Design and safety-oriented development of high-voltage testing of solid-state circuit breakers for all DC marine applications", in Proc. of 2026 IEEE Transp. Electrific. Conf. & Expo + IEEE Elect. Aircraft Technol. Symp., Novi, MI, USA, 10-12 Jun. 2026

# *Battery-Supercapacitor Energy Storage Architecture*

- **Hybrid Energy Storage System (HESS):** Integrates a battery and supercapacitor via bidirectional DC-DC converters.
- **Battery:** Supplies average and sustained power.
- **Supercapacitor:** Manages transient power fluctuations.
- **DC link:** Enables power exchange with the load.
- **PMSM (FOC) drive/charger**: Acts as the load or charging interface.
- **Power management:** Coordinates battery and supercapacitor power to regulate the DC-link voltage and extend battery life.



# *Battery-Supercapacitor Energy Storage Architecture*

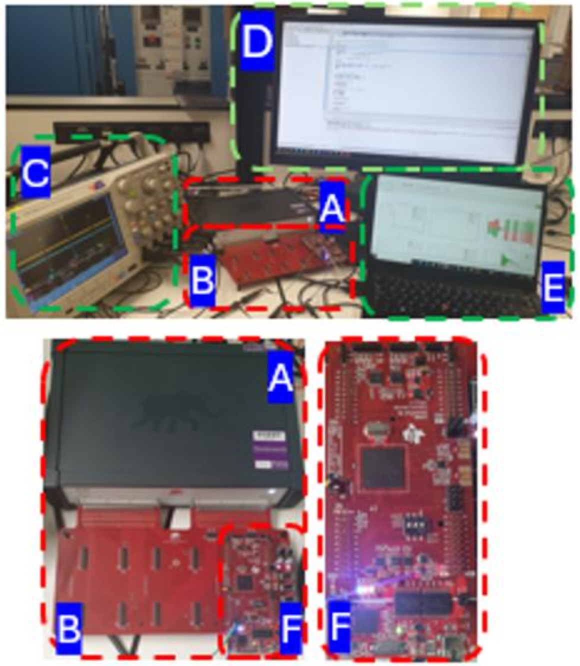


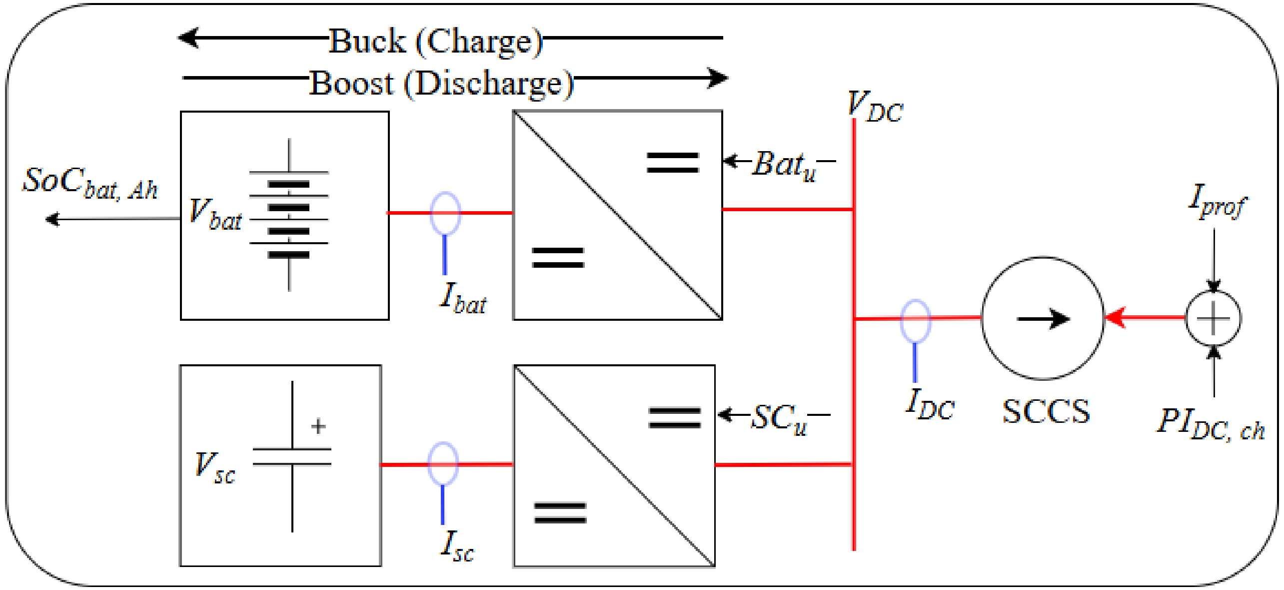

$$\left.\begin{array}{c} LPD: P_{DC} < P_L \\ MPD: P_L \le P_{DC} \le P_H \\ HPD: P_{DC} > P_H \end{array}\right\}$$

- **Power zones during discharge**:
- Low ($P_{DC} < P_L$), Moderate ($P_L < P_{DC} < P_H$), and High ($P_L > P_H$) power demand.
  - **Low power demand (LPD)**: Battery supplies the entire load.
  - **High power demand (HPD)**: Battery output is limited to $P_H$, with the supercapacitor supplying the remaining power.
  - **Moderate power demand (MPD)**: Battery power follows a fitted curve, while the supercapacitor supplies the difference.
  - **Curve fitting**: Maximises supercapacitor energy utilisation while maintaining at least 15% state of charge for supercapacitor and converter voltage limits.
- **Power zones during charging**:
  - Power capped at fixed value for supercapacitors
  - The remainder of the available power for the battery

# *Hardware-in-the-Loop Verification of the Cubic Power Sharing*

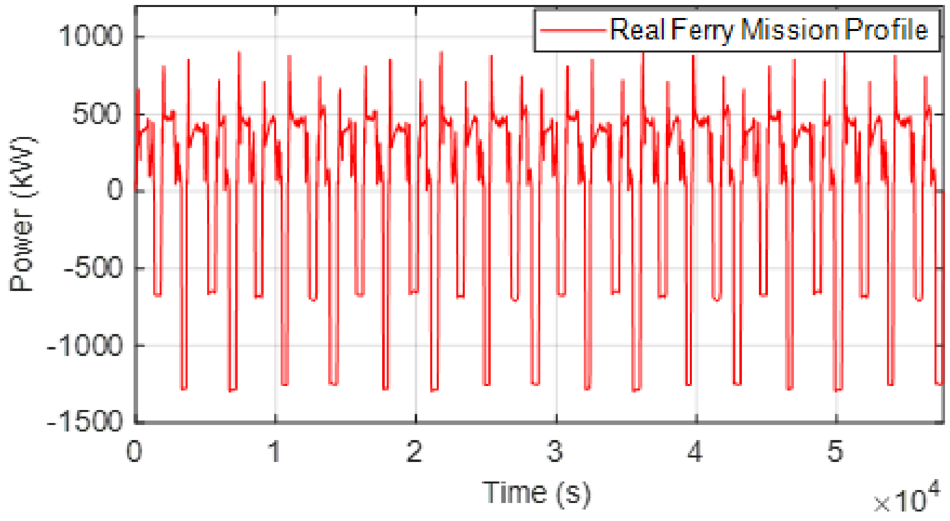
- Marine power system simulated on Typhoon HIL404 real-time simulator (A)
- Signals extracted using interface card (B)
- Simulated variables captured by the oscilloscope (C) and screen (D)
- Code developed in TI code composer studio (E)
- Control system implemented on TI LaunchPad (LAUNCHXL-F28379D) (F)



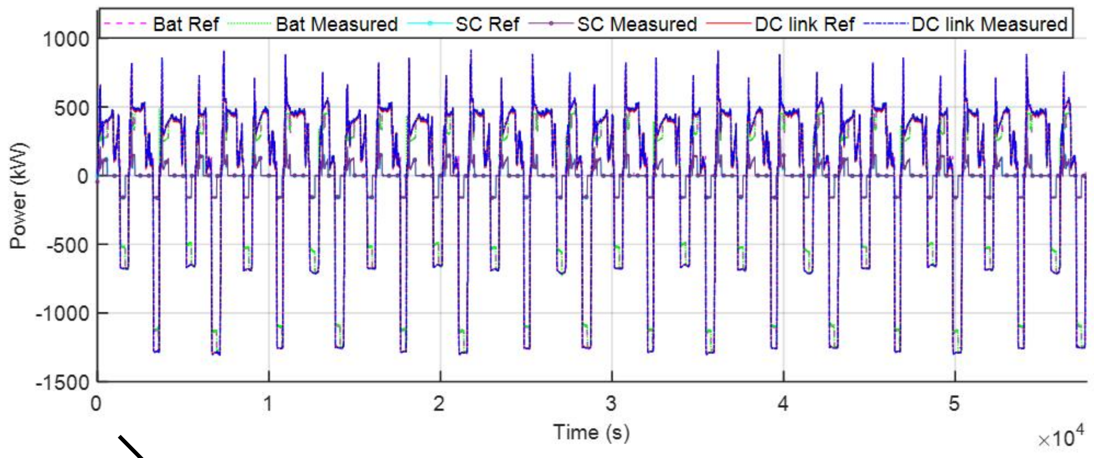



# *Real-Life Ferry Profile and Test Results*

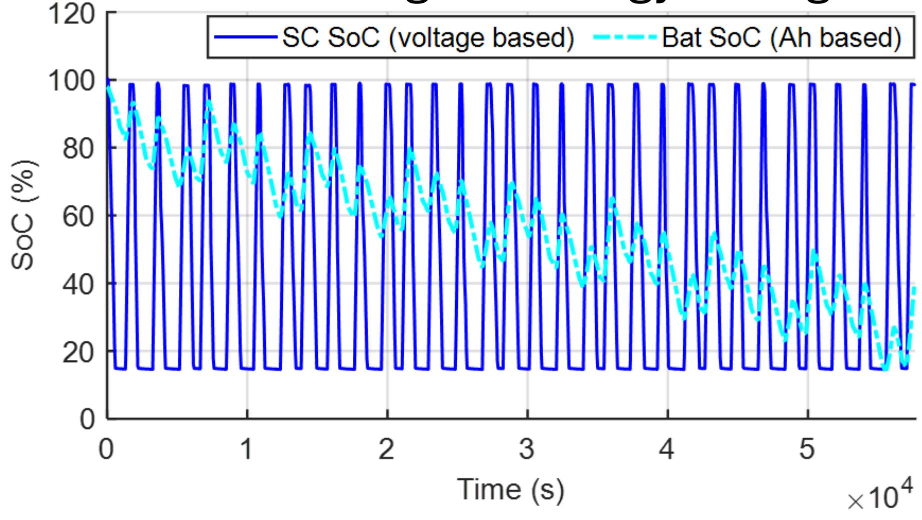
Real Ferry Mission Profile



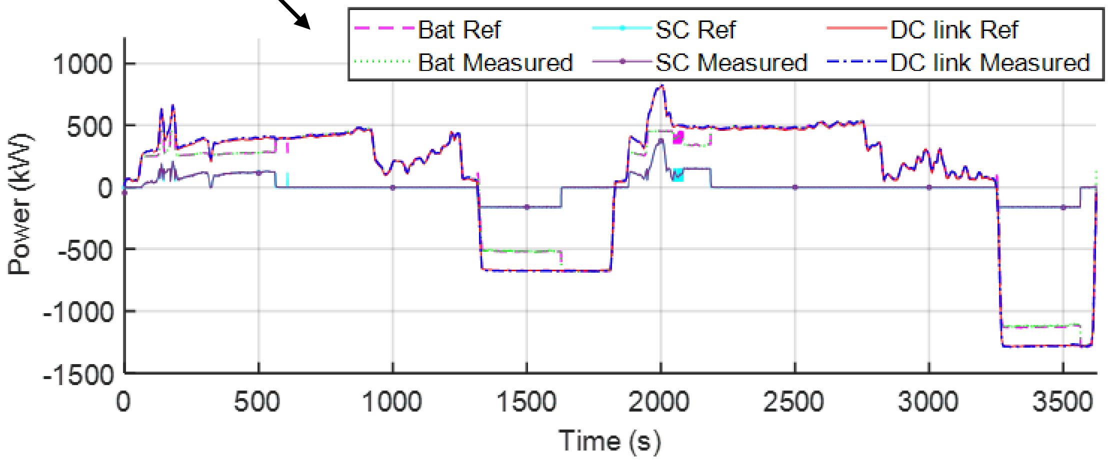

Power split between energy storage




State of Charge of energy storage




Close-up view of waveforms



# *Acknowledgments*


- EPSRC UK National Clean Maritime Research Hub EP/Y024605/1
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ALL·DC·SHIPS

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Department for Transport

TRIG Transport Research and Innovation Grants
Department for Transport

UK National Clean Maritime Research Hub

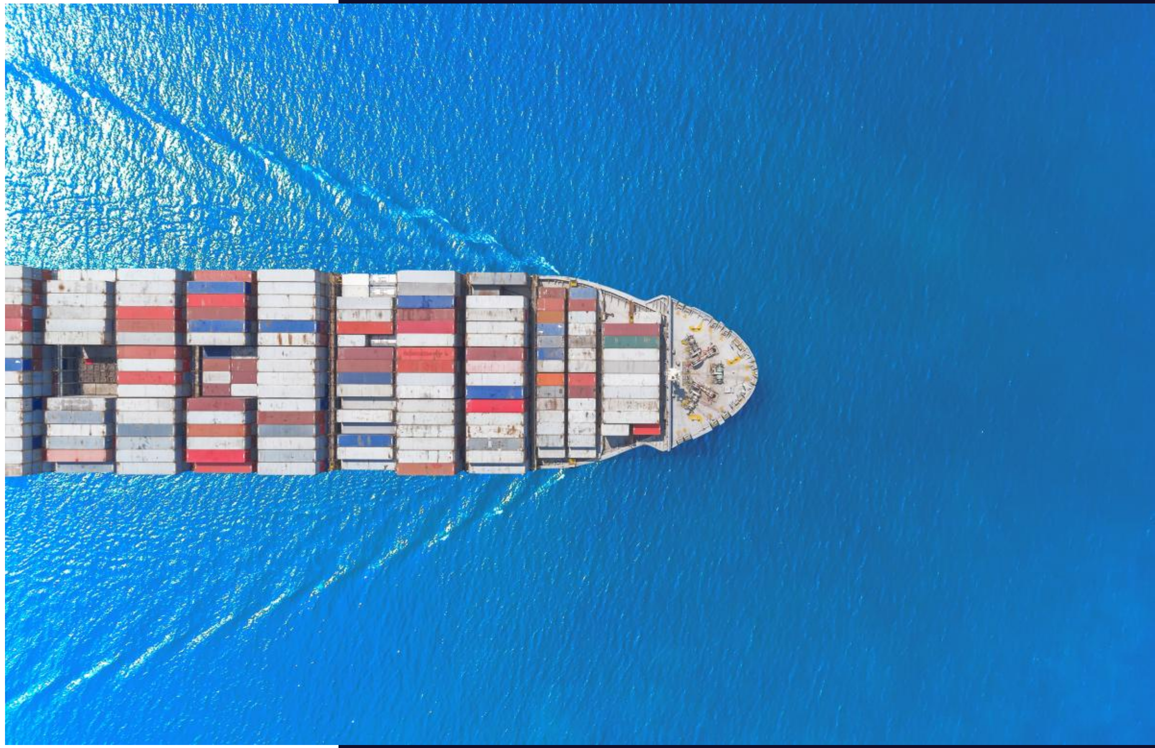
# Vessel Design, Efficiency & Innovation in Action of Theme 4 at Newcastle University

Zhiqiang Hu
Lloyds Professor of Offshore Engineering
School of Engineering
Newcastle University

Funded by UK Government
UKRI Engineering and Physical Sciences Research Council

# Outlines

- Introductionand challenges on AI application in Maritime Engineering
- ISPS method, an AI-enabled solution for vessel design considering hull-propeller interaction
- AI-enabled method of Dynamic application in Offshore Wind and Marine Engineering
- Conclusions



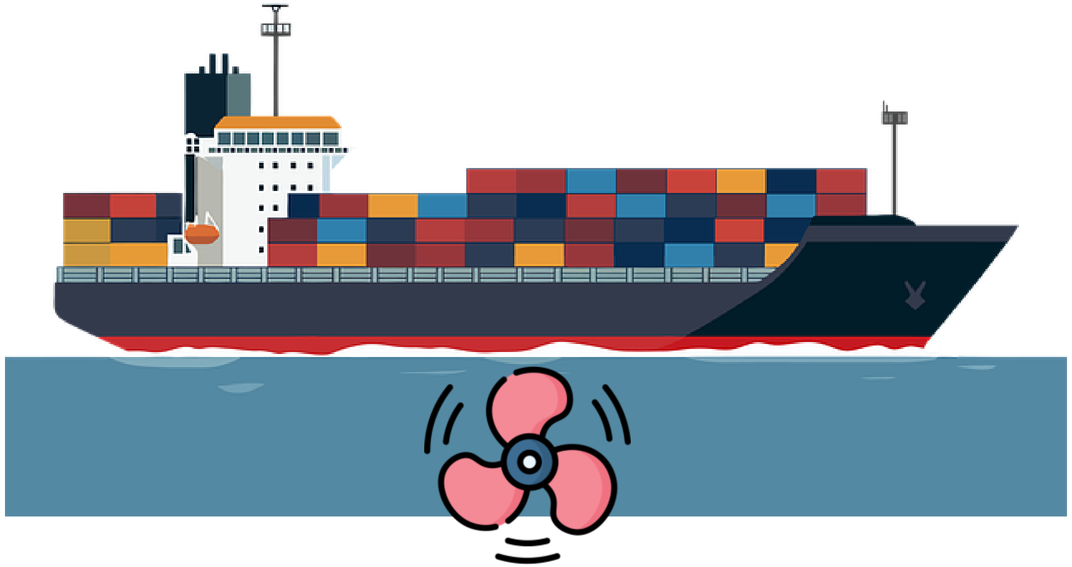
# Introduction and challenges on AI application in Maritime Engineering

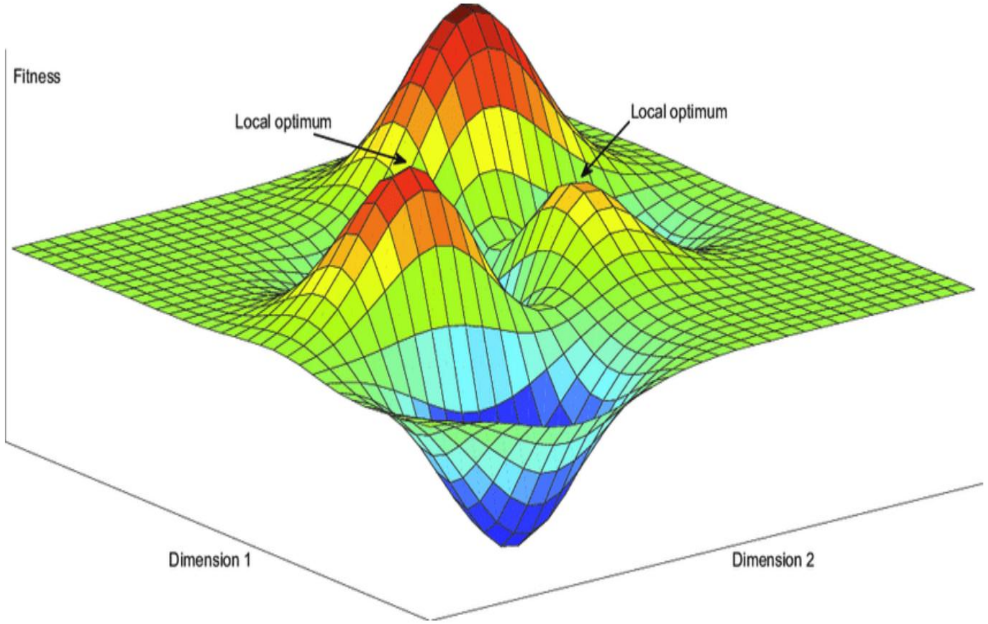
## Challenge in Maritime Engineering:

**Challenge 1**

**Decoupled Design Creating an Efficiency Ceiling**

- Conventional propulsion design optimizes the hull and propeller independently, neglecting their hydrodynamic interaction.
- Component-level optima fail to guarantee system-level optima, creating a persistent efficiency ceiling.






Hull | Propeller | Independent | Sub-Optimal

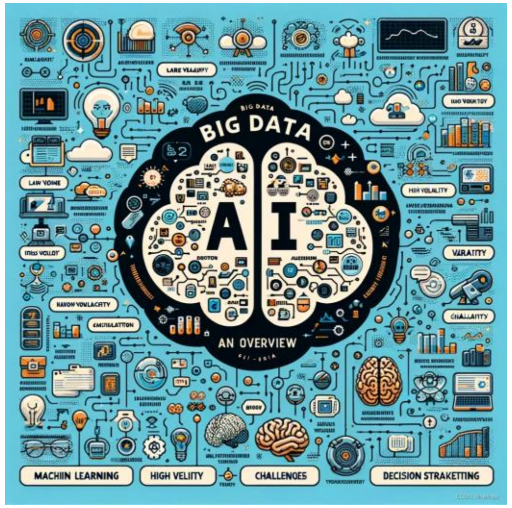
# Introduction and challenges on AI application in Maritime Engineering

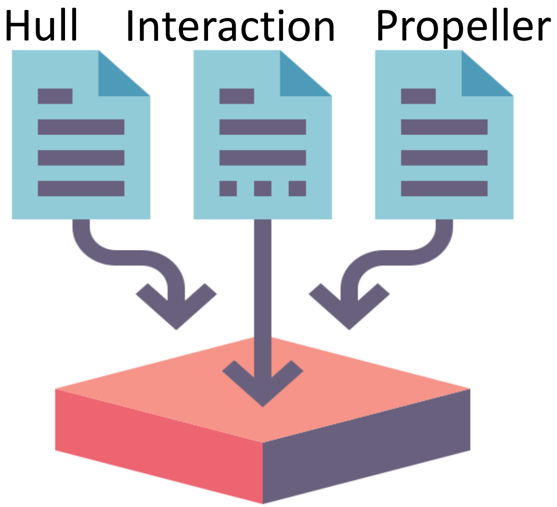
## Challenge in Maritime Engineering:

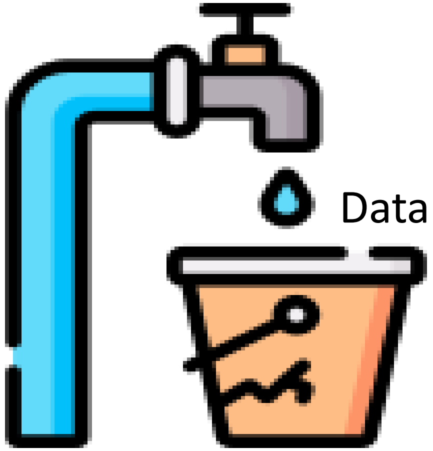
**Challenge 2**

**Data Scarcity for AI-Enabled Integrated Design**

- AI-based models require large-scale training data with adequate design-space coverage.
- However, the nature of shipbuilding and the high cost of experiments result in a severe scarcity of integrated performance data.




Big Databases

AI Models

Shipbuilding

Scarcity

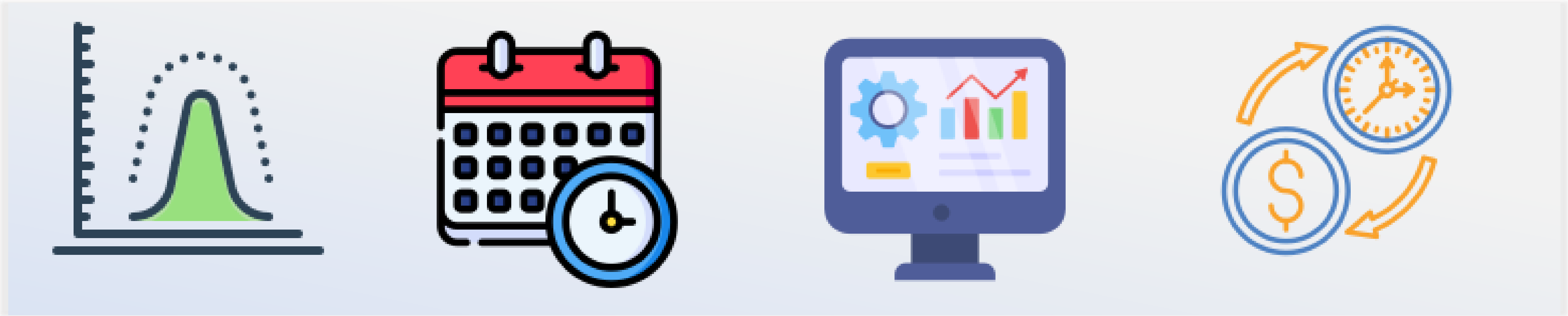
# Introduction and challenges on AI application in Maritime Engineering

## Challenge in Maritime Engineering:

**Challenge 3**

**The Scale-Accuracy Trade-off in Data Generation**

- Generating training data forces a fundamental dilemma between scale and accuracy.
- Physics-based methods provide necessary scale but limited accuracy, while high-fidelity CFD provides accuracy but at a prohibitive cost for large-scale exploration.



Accuracy | Long Time | Complex | **Trade-off**

# Introduction and challenges on AI application in Maritime Engineering

## Question to be answered

- **How can artificial intelligence technologies be effectively utilized to address maritime engineering problems in situations where insufficient full-scale data are available for AI model training?**

## Aim of research conducted in Theme 4

- To develops an **Intelligently Synergized Propulsive System (ISPS),** a physics-informed AI framework addressing the three critical challenges to achieve substantial propulsion efficiency improvements in ship design. (Quasi-static condition)
- To employ the **AI-Enabled Smart Updating Method (AESUM)** into marine engineering field and apply AESUM on wind-assisted propulsion vessel design and operation. (Dynamic condition)

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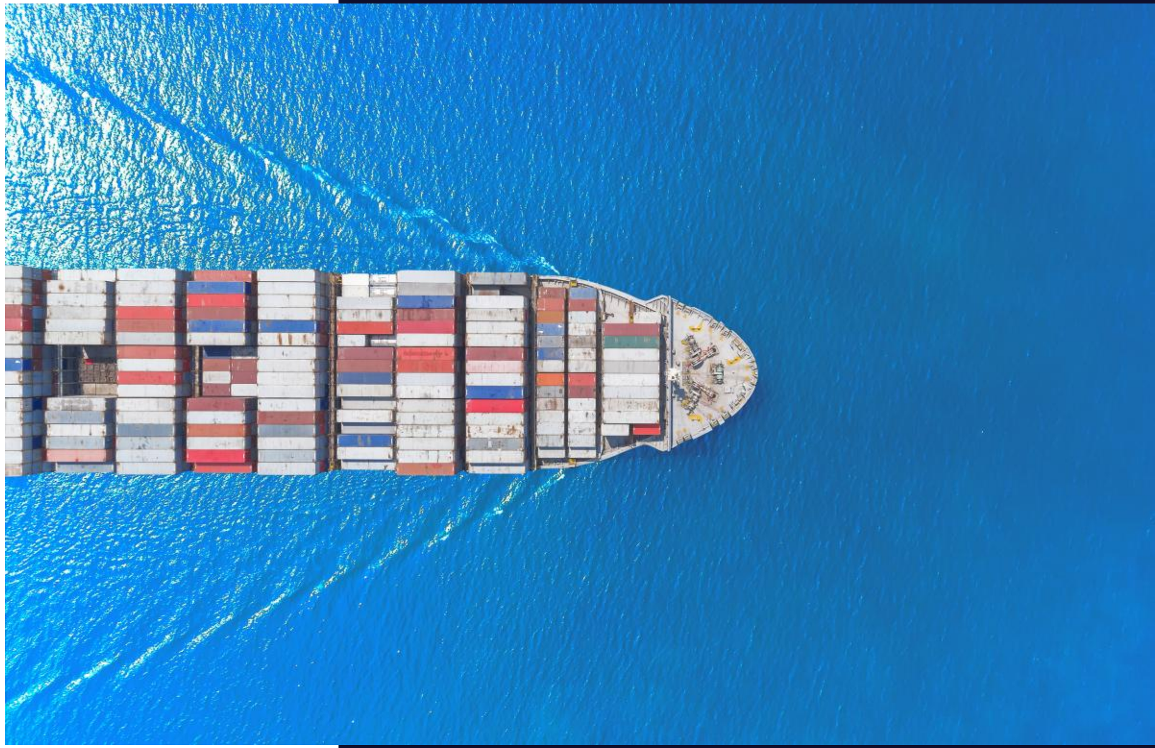


# ISPS method, AI-enabled solution for vessel design

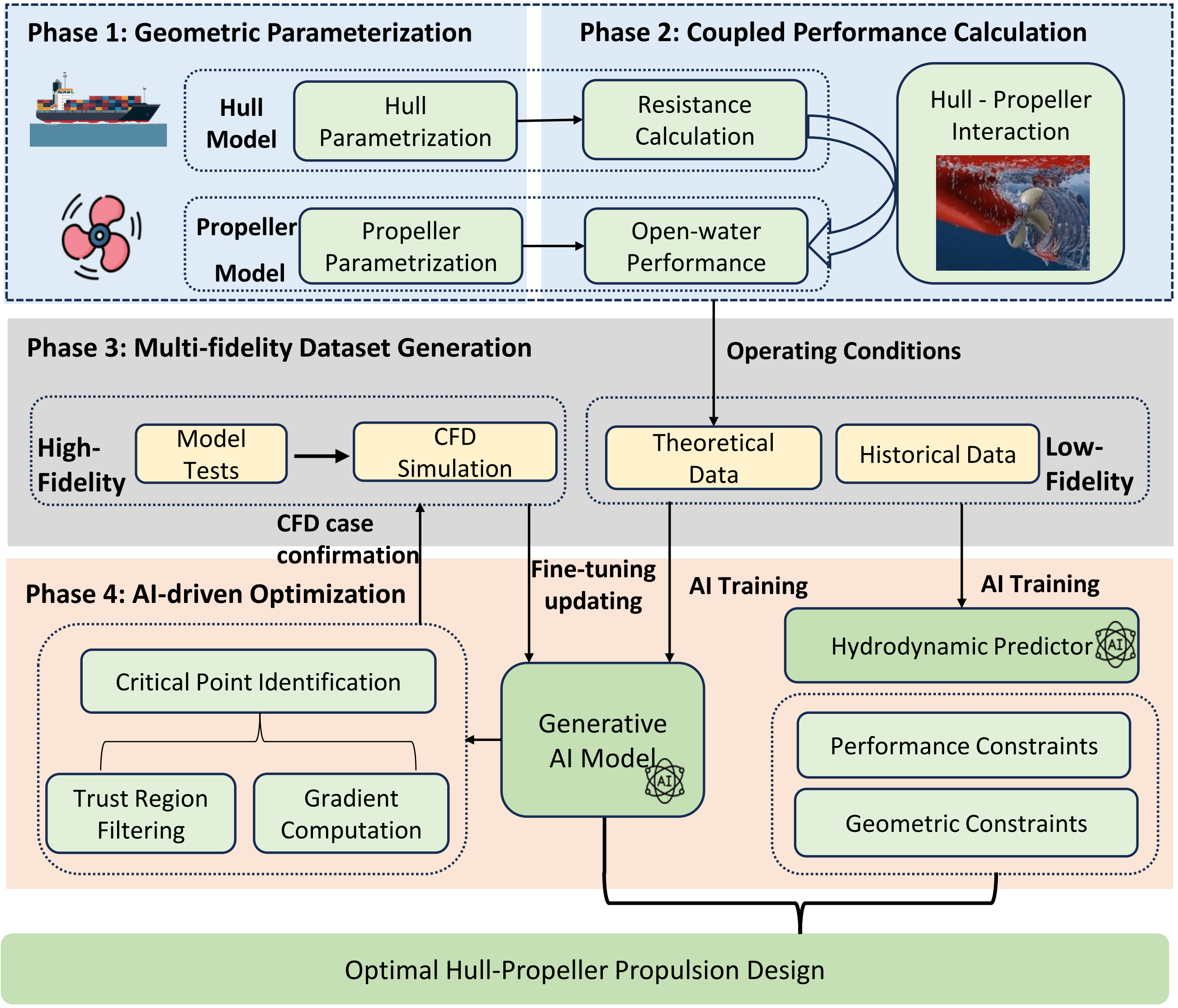
**System-Level Integration**: A novel framework that treats hull-propeller interaction as a coupled, system-level design problem rather than isolated components.

**Strategic Synergization**: Integrates physics-based modeling, multi-fidelity data, and uncertainty-aware learning to overcome efficiency plateaus and data scarcity.

**Four-Phase Architecture**: Organizes the propulsion design process into four interconnected phases:

**Phase 1: Geometric Parameterization**
**Phase 2: Coupled Performance Calculation**
**Phase 3: Multi-Fidelity Dataset Generation**
**Phase 4: AI-Driven Optimization**

- **Framework of Intelligently Synergized Propulsive System (ISPS)**



# ISPS method, AI-enabled solution for vessel design

- **Phase 1: Geometric Parameterization**

Establishing high-dimensional, parametric representations for both hull and propeller geometries.

- **Phase 2: Coupled Performance Calculation**

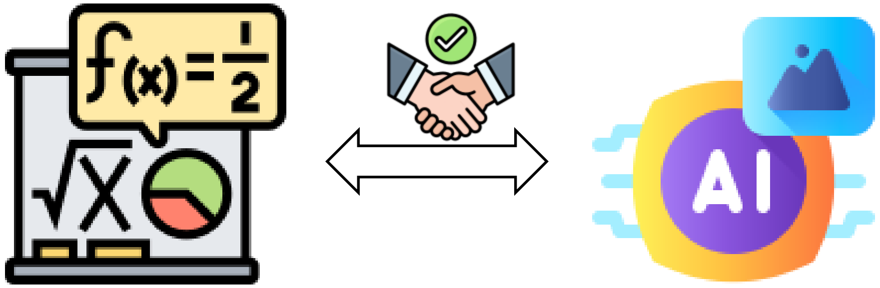
Rapidly evaluating hydrodynamic performance and interaction effects (wake/thrust deduction) using physics-based methods.

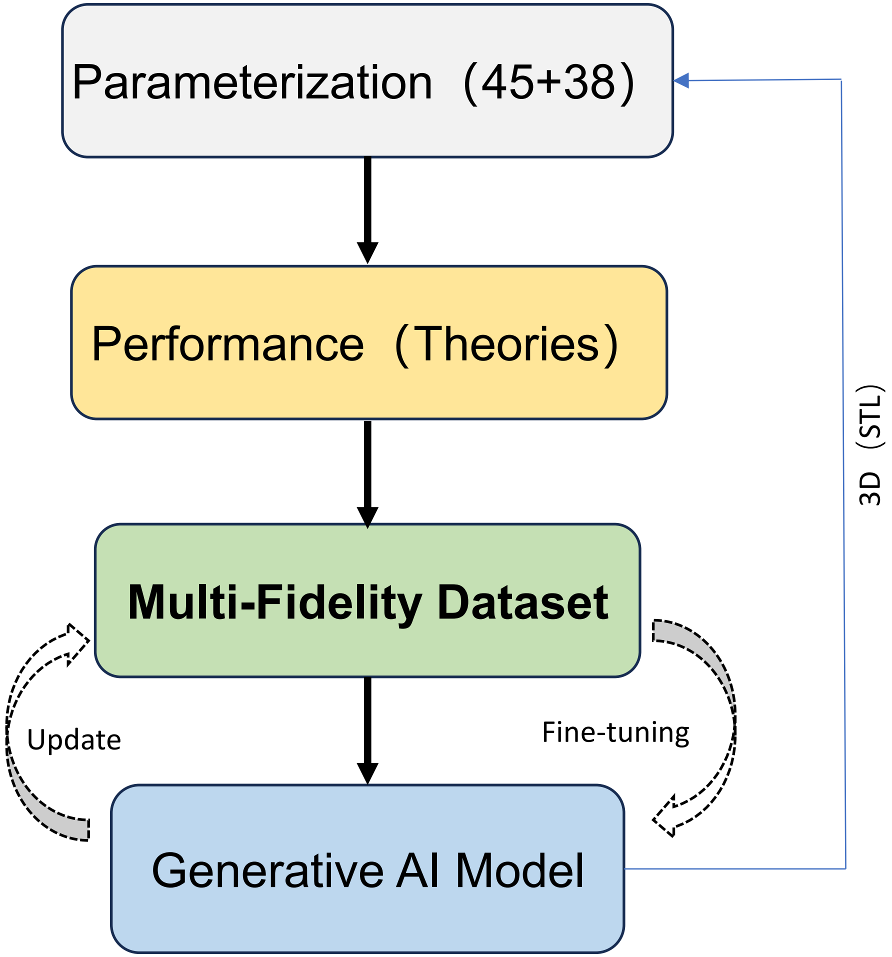
- **Phase 3: Multi-Fidelity Dataset Generation**

Integrating large-scale theoretical calculation data with strategically allocated high-fidelity CFD results to build AI database.

- **Phase 4: AI-Driven Optimization**

Employing conditional generative AI and uncertainty-aware learning to identify and refine optimal designs.



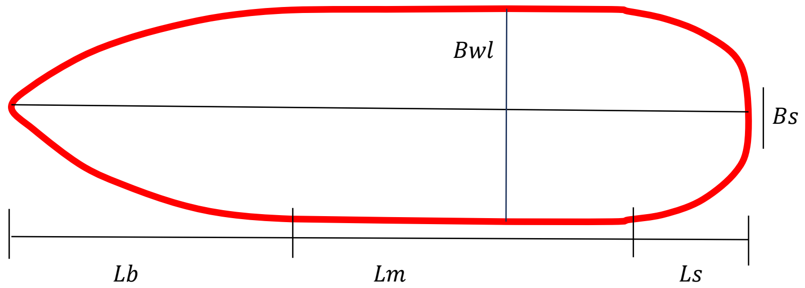


# ISPS method, AI-enabled solution for vessel design

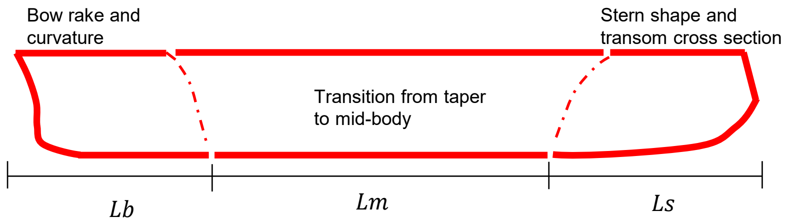
## 1. Geometric Parameterization

- **Ship hull geometric parameterization:**

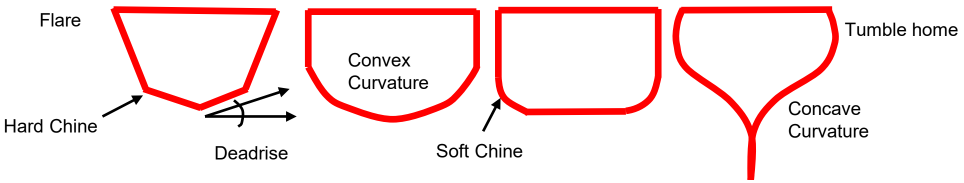
Principal dimensions; midship cross-section parameters; longitudinal transition parameters; **stern hull geometry parameters.**



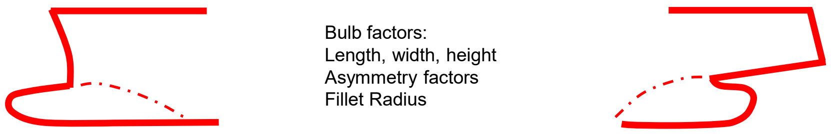

(a) Principal Dimensions




(b) Tapered Regions




(c) Cross section of the hull




(d) Bow and Stern bulb geometries

# ISPS method, AI-enabled solution for vessel design

## 1. Geometric Parameterization

- **Propeller geometric parameterization:**

Global parameters; Radial distributions; Blade section parameters.

**Bézier-to-B-Spline blade section definition with 14 parameters**:

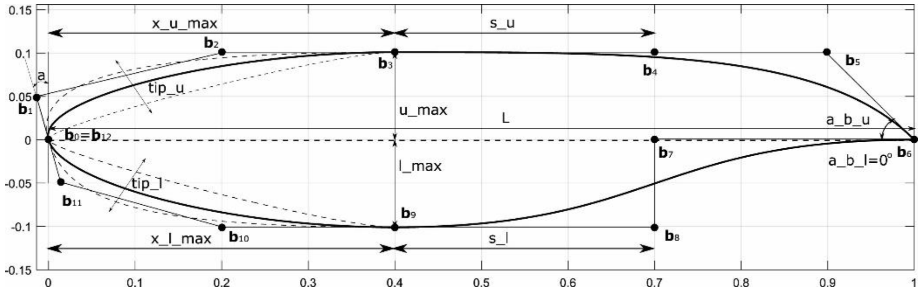



Fig.1 Blade Section Parametric model

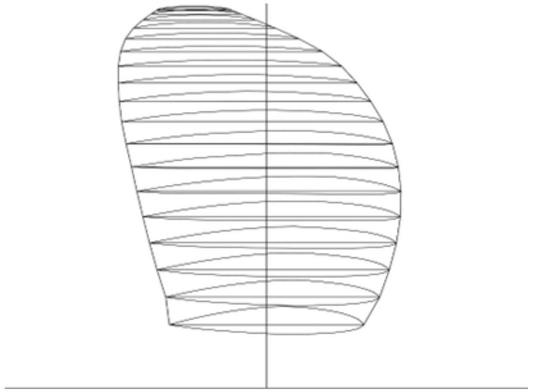
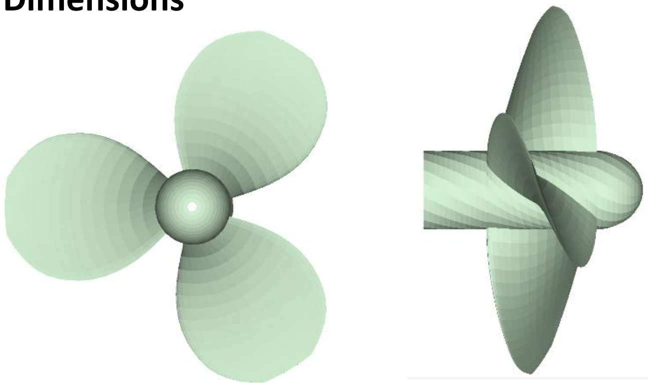
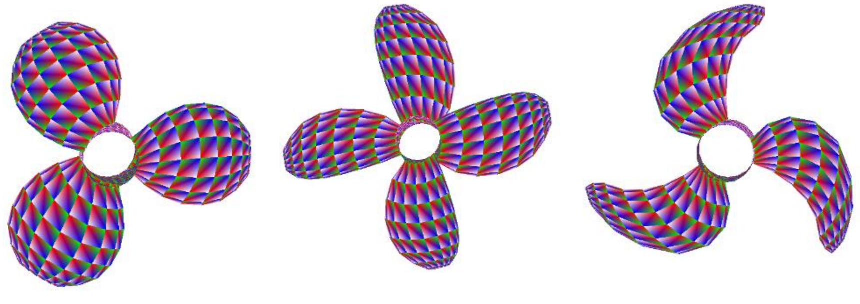


Fig. 2 Radial Distributions

**Global Dimensions**



**Three computational case samples:**



# ISPS method, AI-enabled solution for vessel design

## 2. Coupled Performance Calculation

- **Hull resistance** is estimated using a hybrid approach that combines **Michell's thin ship theory** for wave-making resistance and **ITTC-1957 friction line** for viscous friction resistance.

**Total resistance**:

$$R_t = R_w + R_f$$

**Wave-making resistance**:

$$R_w = \frac{A\rho g^2}{\pi U^2} \int_1^\infty (I^2 + J^2) * \frac{\lambda^2}{\sqrt{\lambda^2 - 1}} d\lambda$$

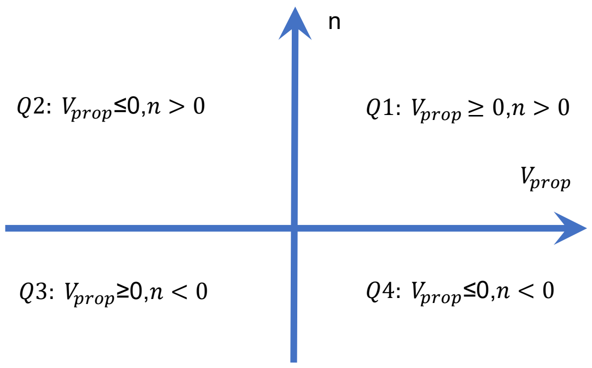
**Frictional resistance**:

$$C_f = \frac{0.075}{\left(\log_{10}(Re) - 2\right)^2}$$

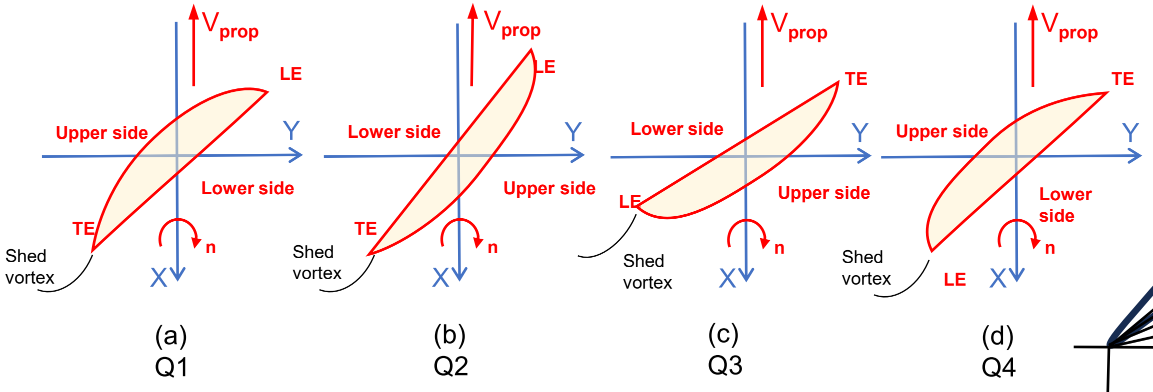
# ISPS method, AI-enabled solution for vessel design

## 2. Coupled Performance Calculation

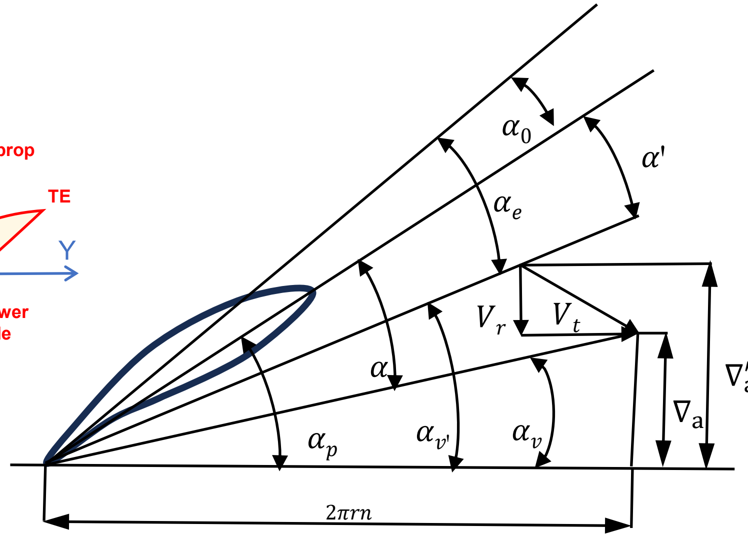
- **Propeller open-water performance** calculation was conducted by Potential flow panel method (Liu, 1996; Xu et al., 2019).




**Operating Condition Quadrants for Marine Propellers**
*(Four quadrants defined by propeller advance velocity and rotational speed)*




**Blade Section Flow Characteristics Across Operating Quadrants**
(Vortex shedding and flow reversal patterns in Q1–Q4 modes)




**Velocity and Angle Decomposition at a Propeller Blade Section**
*(Geometric definition of the effective angle of attack αe )*

# ISPS method, AI-enabled solution for vessel design

## 2. Coupled Performance Calculation

- **Ship hull-propeller interaction effects**

Estimated by **Holtrop's empirical formulas** to calculate wake fraction and thrust deduction fraction.

**Hull efficiency**:

$$\eta_H = \frac{1-t}{1-\omega}$$

$$t = 0.25014(B/L)^{0.28956}(\sqrt{BT}/D)^{0.2624} / \\ /(1 - C_P + 0.0225lcb)^{0.01762} + 0.0015C_{stern}$$

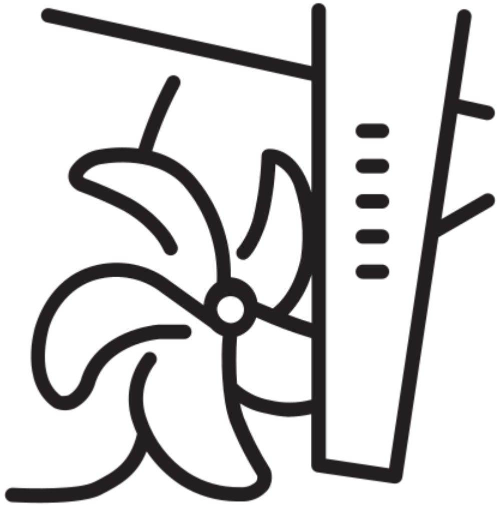
$$w = c_9 c_{20} C_V \frac{L}{T_A}\left(0.050776 + 0.93405 c_{11} \frac{C_V}{(1-C_{P1})}\right) \\ +0.27915 c_{20}\sqrt{\frac{B}{L(1-C_{P1})}} + c_{19}c_{20}$$

**Relative rotational efficiency**:

$$\eta_R = 0.9922 - 0.05908 A_E/A_O + \\ +0.07424(C_P - 0.0225lcb)$$

**Overall propulsion efficiency**:

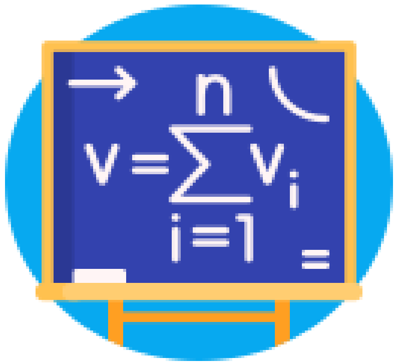
$$\boldsymbol{\eta_D = \eta_0 \cdot \eta_H \cdot \eta_R}$$



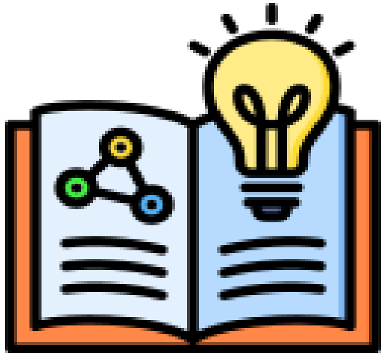
# ISPS method, AI-enabled solution for vessel design

## 3. Multi-Fidelity Dataset Generation

Mid-fidelity



Theoretical Data obtained from Phase 2

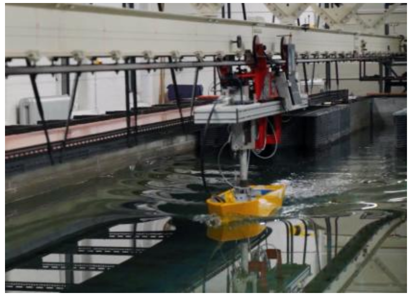


Historical Data

AI database generation


AI model updating via *CFD* simulation results on critical points

High-fidelity



Model Tests

Validate *CFD* models

CFD Simulations

- **Selection of critical points is of significant importance.**

# ISPS method, AI-enabled solution for vessel design

## 4. AI-Driven Optimization

- **Critical Point Identification**

Two complementary metrics guide selective high-fidelity deployment:

**(i) Gradient-based sensitivity** — quantifies how responsive propulsive efficiency is to geometric perturbations at design point **x***j* :

$$S(\mathbf{x}_j) = \| \nabla_{\mathbf{x}} f_\theta(\mathbf{x}_j) \|_2$$

**(ii) Prediction uncertainty** — reflects model confidence via Monte Carlo dropout:

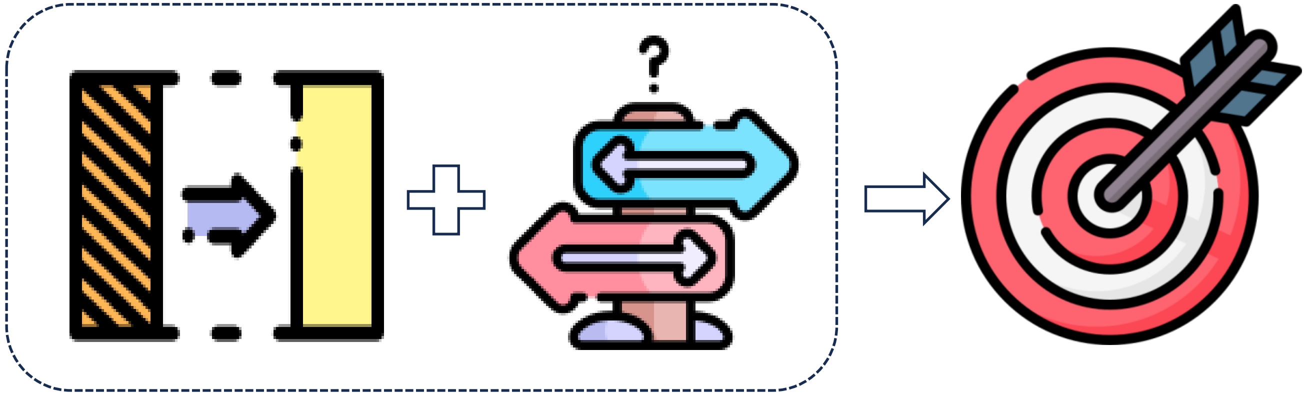
$$U(\mathbf{x}_j) = \frac{1}{M} \sum_{m=1}^{M} \left( f_\theta^{(m)}(\mathbf{x}_j) - \bar{f}_\theta(\mathbf{x}_j) \right)^2$$

High $U(\mathbf{x}j)$ indicates insufficient training data coverage; the model is extrapolating in that region.

- **Critical Point Judging Criteria：**

High sensitivity and high uncertainty

| Sensitivity | Uncertainty(Trust Region Filtering) | Critical Point |
|---|---|---|
| High | High | Yes ( CFD / Model Tests ) |
| High | Low | No |
| Low | High | No |
| Low | Low | No |



# ISPS method, AI-enabled solution for vessel design

## 4. AI-Driven Optimization

- **Iterative Fine-Tuning with Confidence Region Expansion**

① **Initialize** — Define an initial confidence region over the design space.

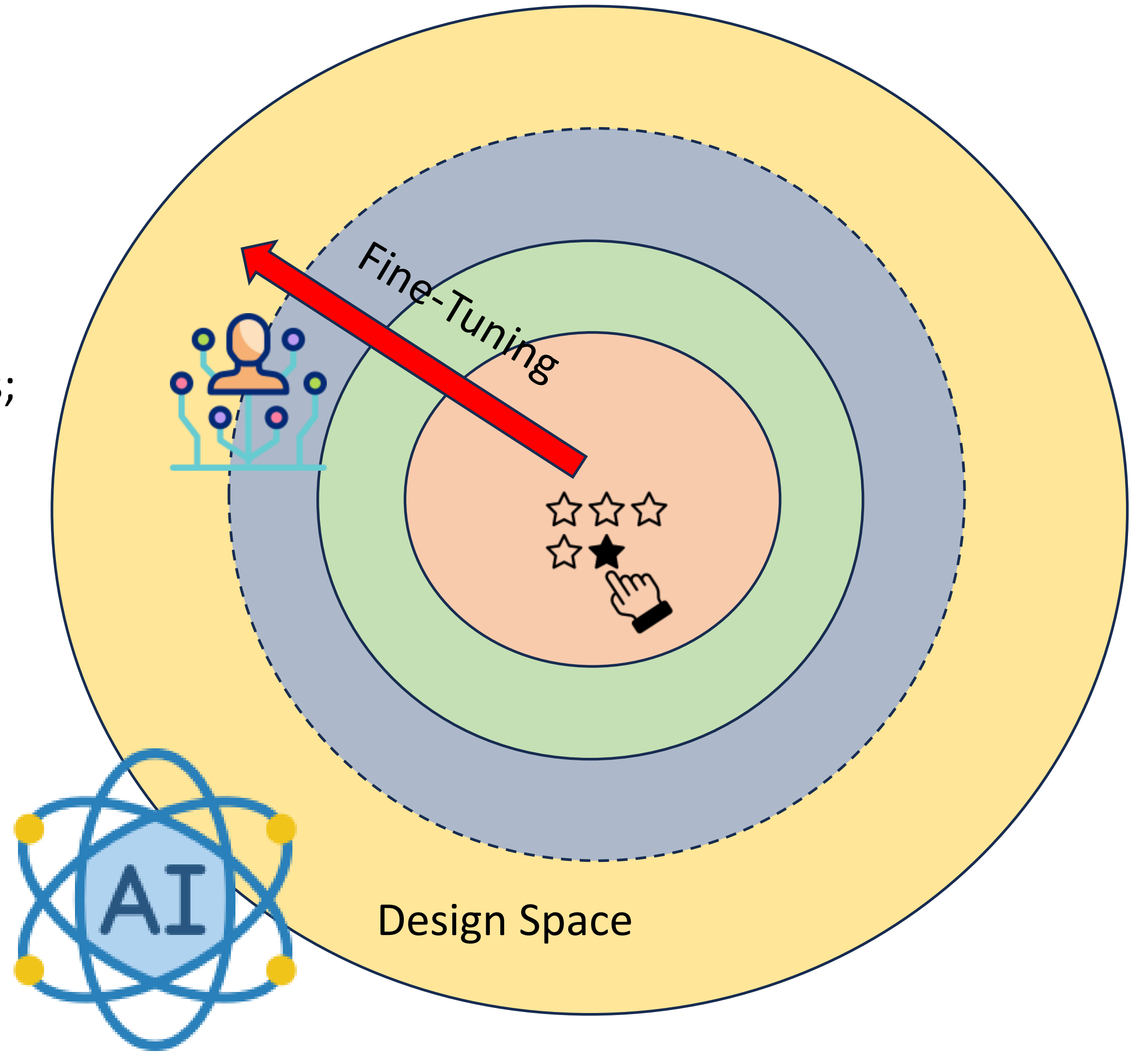
② **Validate** — Deploy targeted CFD simulations (validated by model test) at critical points; compare AI predictions against high-fidelity results.

③ **Fine-tune** — Incorporate validated data to update both AI models; refine prediction accuracy within the confidence region.

④ **Expand** — Enlarge the confidence region; repeat the sample-validate-fine-tune cycle.

⑤ **Converge** — Continue until the confidence region has been expanded multiple times but propulsive efficiency shows negligible improvement.

This targeted allocation ensures expensive evaluations are invested where they provide maximum information gain.



# ISPS method, AI-enabled solution for vessel design

## 4. AI-Driven Optimization

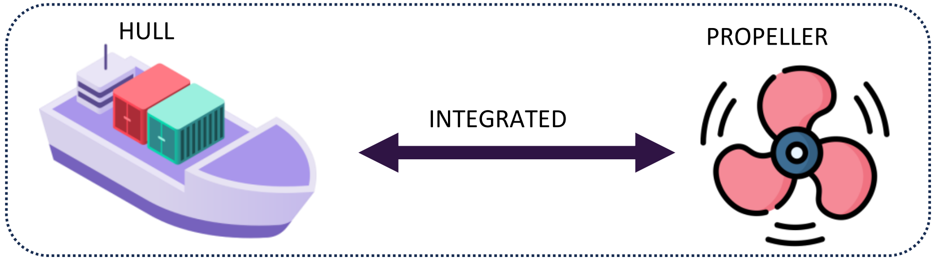
**System-level integration** — treats hull-propeller as a coupled system rather than isolated components, overcoming efficiency plateaus inherent in sequential design.

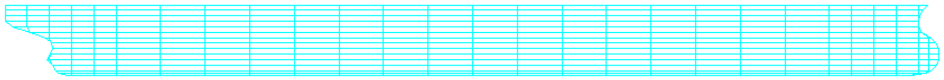
**Hierarchical parameterization** — balances geometric flexibility with engineering interpretability; designers specify constraints using conventional parameters while AI explores complex variations internally.

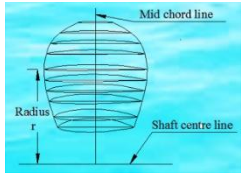
**Strategic multi-fidelity data** — integrates low-fidelity predictions with selectively deployed high-fidelity evaluations at critical points, ensuring computational feasibility under realistic constraints.

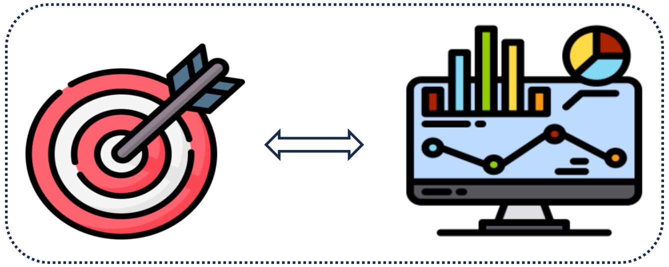
**Modular extensibility** — adaptable across diverse vessel types (container ships, tankers, bulk carriers) by adjusting geometric constraints and performance evaluation methods.

**Engineers will be able to optimize the ship hull and propeller designs considering the coupling effect between ship hull and propellers, via the AI-model generated in Phase 3.**





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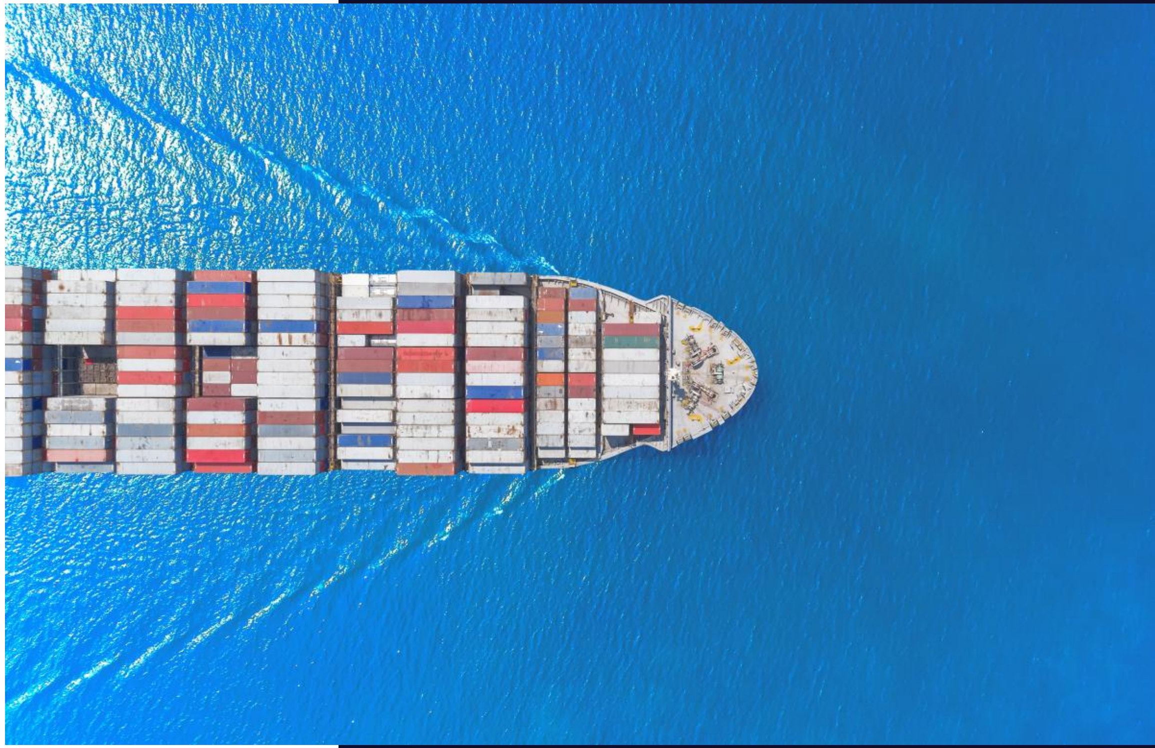


# Dynamic application in Offshore Wind and Marine Engineering

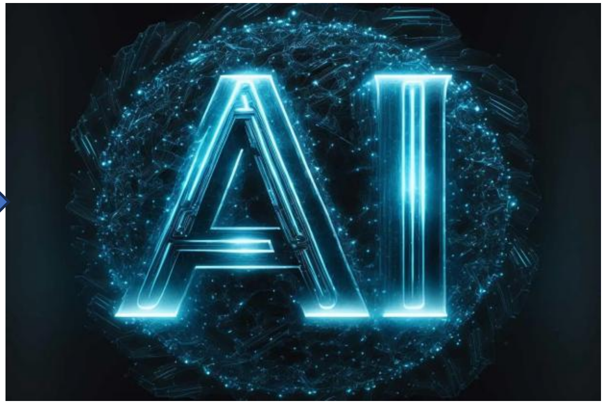
- **Dynamic application in Wind Assisted Ship Propulsion**

## Purpose

- Energy saving and $CO_2$ emission reduction by the employment of wings installed onboard.

- How to employ AI technology to optimize the energy consumption? Application of novel AESUM method.

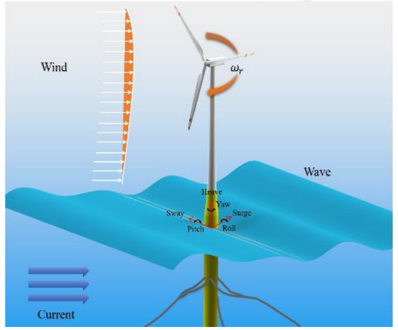

- How to employ AI technology?

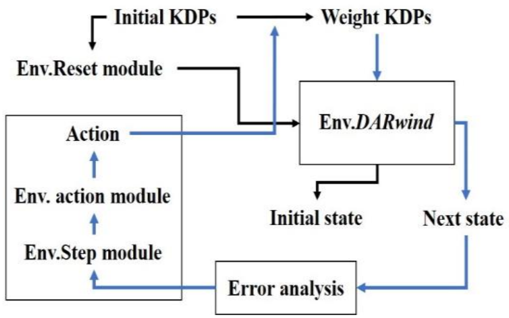


# Dynamic application in Offshore Wind and Marine Engineering

- ***AESUM*: an AI-based Smart Updating Method developed by NU team**
- It was originally named *SADA* and was proposed in the investigation of dynamic analysis for floating offshore wind turbines.
- Validated by the database from ORE Catapult and Equinor.

- Peng Chen, Chunjiang Jia, Chong Ng, Zhiqiang Hu. Application of SADA method on full-scale measurement data for dynamic responses prediction of Hywind floating wind turbines. Ocean Engineering 239 (2021) 109814





## ☐ Key Elements in AESUM

- ***A physics-informed mathematical model and programme*** (Coupled aero-hydro-servo-elastic in-house program, *DARwind*)
- ***Machine Learning*** (Reinforcement Learning: *DDPG* algorithms)
- ***KDPs*** (Key Disciplinary Parameters)

# Dynamic application in Offshore Wind and Marine Engineering

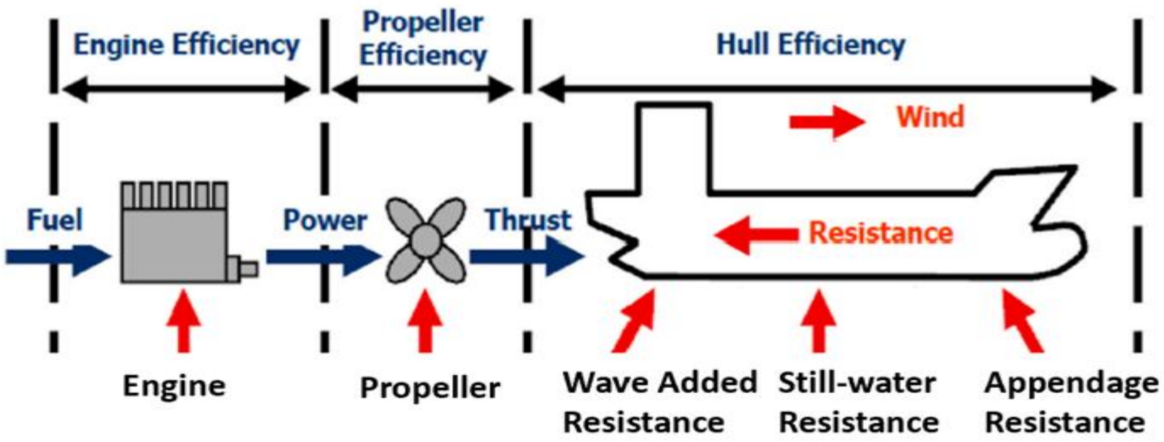
## ○ Physics-informed mathematical model and programme

**Multiple dynamic loads**

- Engine propulsion
- Wind propulsion
- Wind resistance
- Still water resistance
- Wave-making resistance
- Frictional resistance
- Wave added resistance
- Appendage resistance
- Other loads

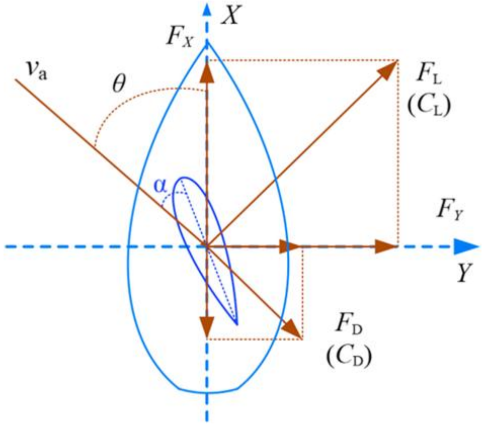
**Ship Manoeuvring calculation**

**Engine power and energy consumption**





Wave added force




Wind force calculation

# Dynamic application in Offshore Wind and Marine Engineering

## ❑ Case of study

- **Reference Ship data**
  - Equipped with two pairs of wings
  - Service speed 13 knots


- **Full-scale database from collaborator**

| time point | Wind angle 1 | Wind velocity 1 | 1#wing angle | Wing ang | #Wing ang | Wing ang | 1#Wing height | #Wing heigh | Wing heig | Wing heig | ship velocity | engine power |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 349.4962 | 8.4307 | 77.757 | 78.4523 | 78.0268 | 78.401 | 38.4777 | 38.2321 | 38.1264 | 38.2994 | 6.1166 | 13484.26424 |
| 2 | 349.1823 | 8.3112 | 77.757 | 78.4523 | 78.0268 | 78.401 | 38.4775 | 38.2321 | 38.1275 | 38.2991 | 6.168 | 13955.8216 |
| 3 | 349.0085 | 8.3278 | 77.757 | 78.4523 | 78.0268 | 78.401 | 38.4777 | 38.2321 | 38.1274 | 38.2991 | 6.168 | 13955.8216 |
| 4 | 347.765 | 8.5544 | 77.757 | 78.4523 | 78.0268 | 78.401 | 38.4777 | 38.2321 | 38.1275 | 38.2991 | 6.1166 | 13484.26424 |
| 5 | 348.2076 | 8.5874 | 77.757 | 78.4523 | 78.0268 | 78.401 | 38.4777 | 38.2321 | 38.1274 | 38.2991 | 6.1166 | 13484.26424 |
| 6 | 348.4309 | 8.9726 | 77.757 | 78.4523 | 78.0268 | 78.401 | 38.4777 | 38.2321 | 38.1274 | 38.299 | 6.1166 | 13955.8216 |
| 7 | 349.3625 | 8.9723 | 77.757 | 78.4523 | 78.0268 | 78.401 | 38.4777 | 38.2321 | 38.1275 | 38.2991 | 6.1166 | 13484.26424 |
| 8 | 349.5227 | 8.9905 | 77.757 | 78.4523 | 78.0268 | 78.401 | 38.4775 | 38.2321 | 38.1274 | 38.2991 | 6.1166 | 13484.26424 |
| 9 | 348.4713 | 8.628 | 77.757 | 78.4523 | 78.0268 | 78.401 | 38.4773 | 38.2321 | 38.1262 | 38.299 | 6.168 | 13484.26424 |
| 10 | 348.7852 | 8.442 | 82.3155 | 81.6259 | 78.0268 | 78.401 | 38.4778 | 38.2321 | 38.1274 | 38.299 | 6.168 | 13484.26424 |
| 11 | 348.927 | 8.4071 | 86.3083 | 87.3809 | 78.0268 | 78.401 | 38.4778 | 38.2316 | 38.1275 | 38.2991 | 6.2194 | 13484.26424 |

# Dynamic application in Offshore Wind and Marine Engineering

## ○ KDP selection

| No. | Name | Unit |
|---|---|---|
| 1 | Ship velocity correction | (m/s) |
| 2 | Ship length | (m) |
| 3 | Ship breadth | (m) |
| 4 | Ship draft | (m) |
| 5 | Wetted area coefficient | - |
| 6 | Kinematic viscosity | (m^2/s) |
| 7 | Roughness height | (m) |
| 8 | Wind wing breath | (m) |
| 9 | Wind angle correction | (Deg) |
| 10 | Wind velocity correction | (m/s) |
| 11 | Main engine efficiency | - |
| 12 | Gravity | (m/s^2) |
| 13 | WaterDensity | (Kg/m^3) |
| 14 | AirDensity | (Kg/m^3) |
| 15 | Kr/Kf | - |
| 16 | Air drag coefficient | - |
| 17 | Lift coefficient | - |
| 18 | Drag coefficient | - |

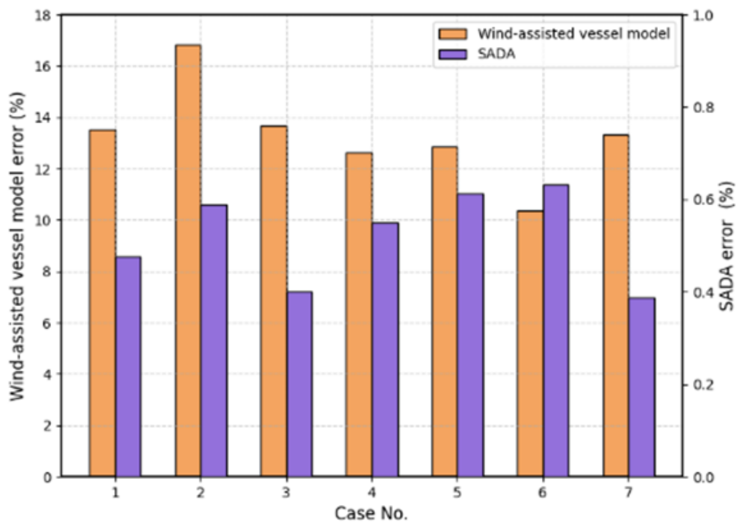
❖ KDPs including:

❖ Disciplinary parameters: nonlinear variations, such as the Lift/Drag coefficient.

❖ Measured correction factors: measured physical quantities, such as wind velocity and angle.

❖ Empirical coefficients :Others can be determined from empirical or semi-empirical formulas, such as $K_r/K_f$

## ○ AI training process



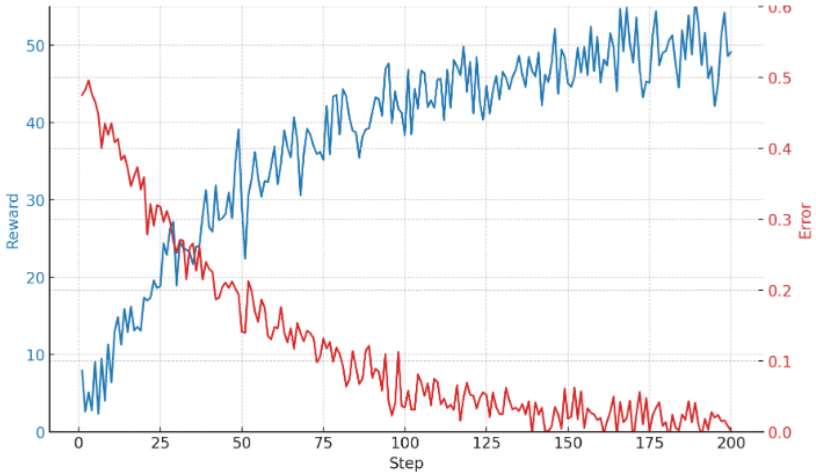

Mean errors between results of training tests

# Dynamic application in Offshore Wind and Marine Engineering

## ○ Training with real-time data

- **Training cases**

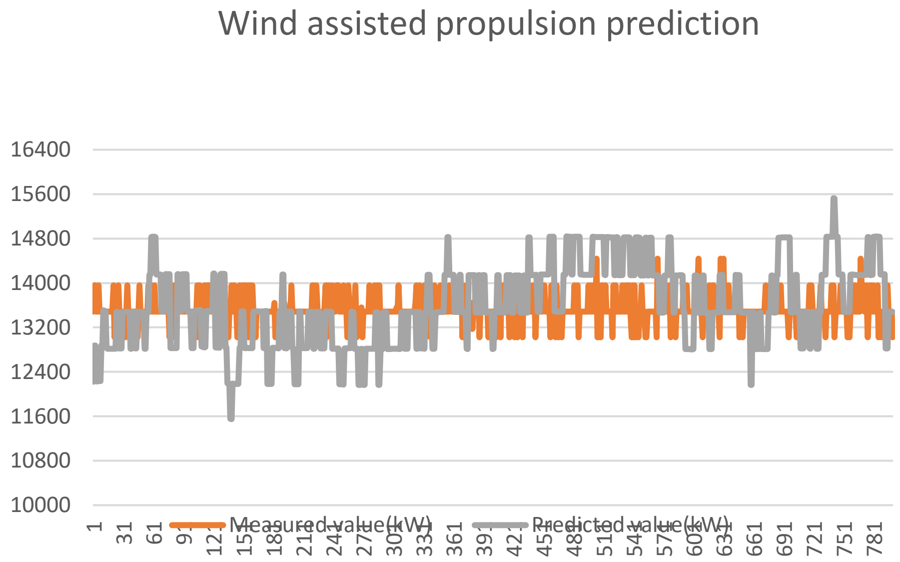
| Case No. | Date |
|---|---|
| 1 | 2023-1-27T00.00.00+2023-1-27T02.13.00 |
| 2 | 2023-1-27T02.14.00+2023-1-27T04.27.00 |
| 3 | 2023-1-27T04.28.00+2023-1-27T06.41.00 |
| 4 | 2023-1-27T06.42.00+2023-1-27T08.55.00 |
| 5 | 2023-1-27T08.56.00+2023-1-27T11.09.00 |
| 6 | 2023-1-27T11.10.00+2023-1-27T13.23.00 |
| 7 | 2023-1-27T13.24.00+2023-1-27T15.37.00 |
| 8 | 2023-1-27T15.37.00+2023-1-27T17.50.00 |




## ○ Comparison and Prediction

- **Prediction cases**

| Case No. | Date |
|---|---|
| 1 | 2023-1-27T17.51.00+2023-1-27T20.04.00 |
| 2 | 2023-1-27T20.05.00+2023-1-27T22.18.00 |

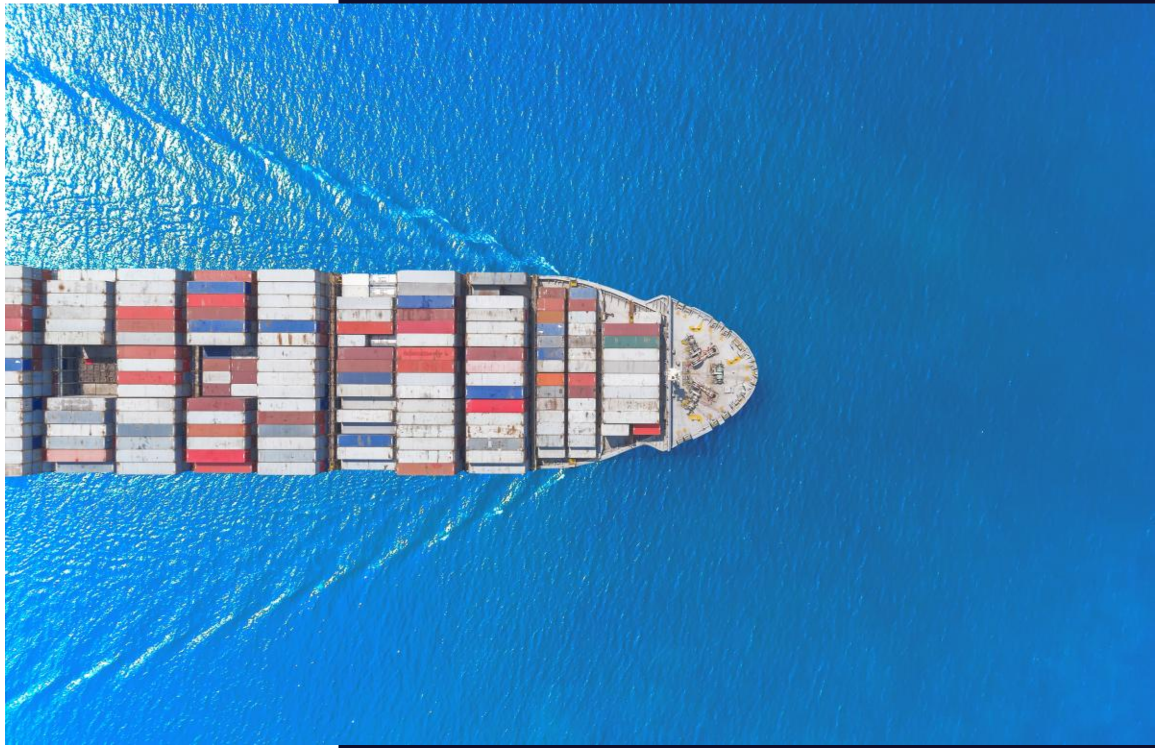



- **The AI trained ship propulsion model is smart and can be used to predict energy consumption considering wind-assisting effect with better accuracy.**

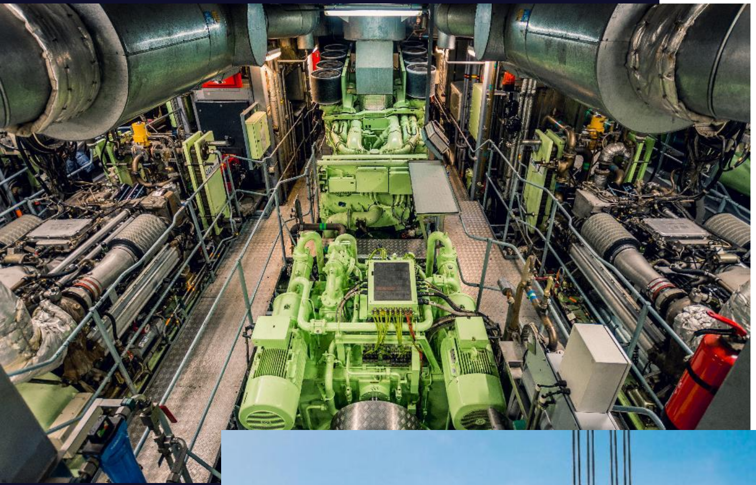
'Application of an AI-based SADA Method in the Prediction of Propulsion Performance and Energy-Saving Optimization for Wind-Assisted Propulsion Vessels', will be published in *International Conference of Ships and Offshore Structures* in Gothenburg, Sweden, September 2025.

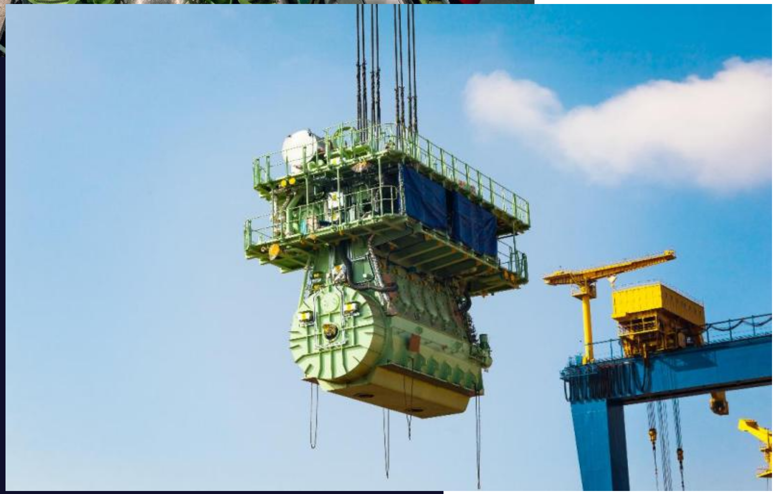
# Outlines

- Introductionand challenges on AI application in Maritime Engineering
- ISPS method, an AI-enabled solution for vessel design considering hull-propeller interaction
- AI-enabled method of Dynamic application in Offshore Wind and Marine Engineering
- Conclusions



# Conclusions





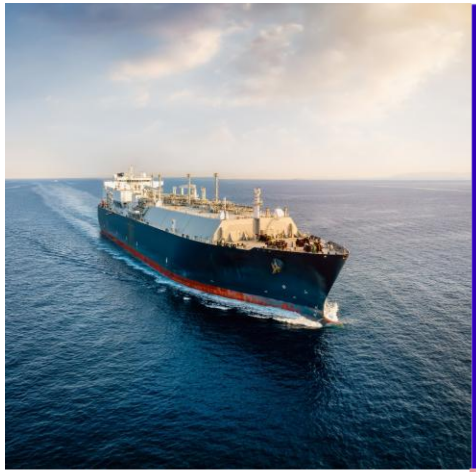
- Artificial intelligence technology has significant potential for applications in maritime engineering. However, the scarcity of full-scale data remains one of the major challenges hindering its widespread adoption and effective implementation.
- Two innovative methods, namely ISPS and AESUM, have been developed and applied in the fields of naval architecture, marine engineering, and offshore renewable energy with support from the EPSRC Clean Maritime Research Hub.
- ISPS and AESUM provide alternative solutions for addressing the challenge of limited data availability. However, greater collaboration among researchers, industry, and other relevant parties is required to overcome obstacles arising from commercial confidentiality restrictions.

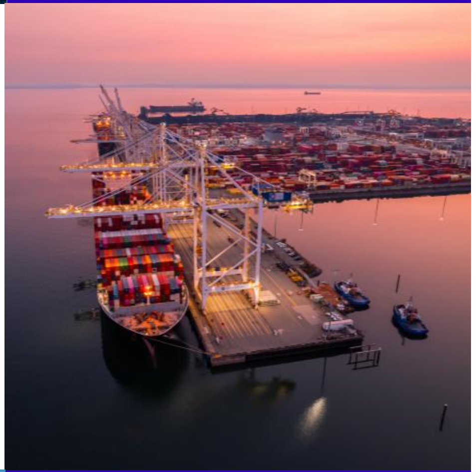
Academic Insights

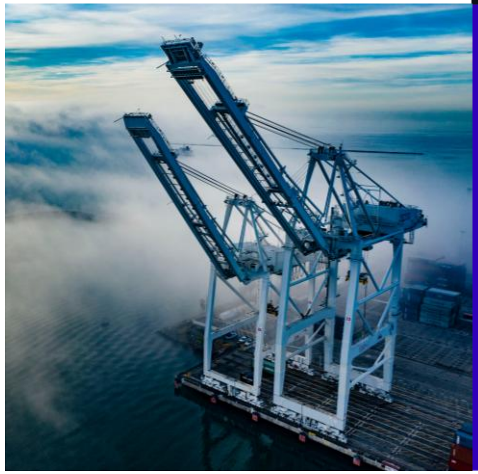
# Session 3

# Advancing Marine Propulsion

- Dr Neeraj Yadav
- Prof John Irvine
- Dr Cliff Dansoh







# Practical Retrofit Pathways to Net-Zero Marine Propulsion: Methanol and Zero-Carbon Fuel Blends

Dr. Neeraj Yadav
June 2026
***Powertrain Research Centre***
***University of Nottingham***

**Acknowledgment: Powertrain Research Center, MAHLE Powertrain, Clean Air Power**

# Outline

- Methanol as a Retrofit Fuel
- Methanol–Ammonia Blends
- Hydrogen-Assisted Combustion
- Towards Net Zero
- Key Takeaways

# UON Working Areas

UK National Clean Maritime Research Hub

***Major Topics: Low and Zero Carbon Fuel***


Decarbonisation

Combustion

Scale up

Emissions

Mono-Fuel operation

Cold start

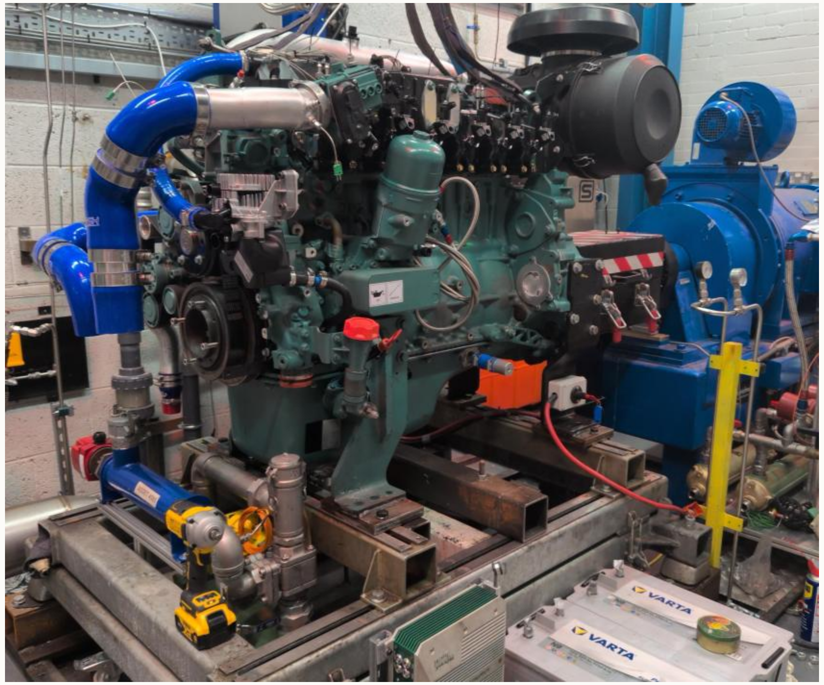
# Experimental Setups

UK National Clean Maritime Research Hub

## 01

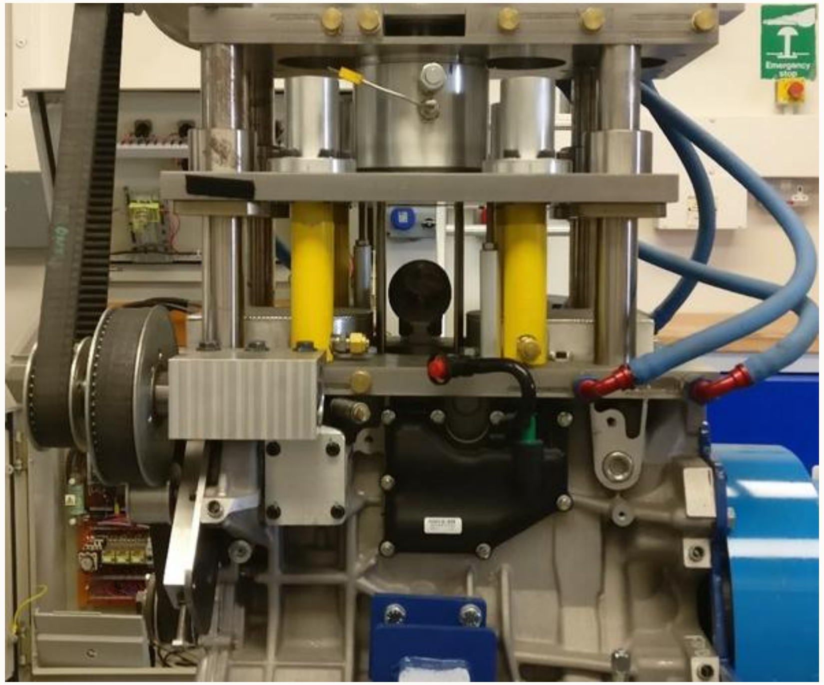

**Single-Cylinder Research Engine (High Tumble); CR:** *12.5 and 17.5*

## 02



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

## 03



**Optical Engine**
Active and Passive Jet Ignition

# Methanol as a Retrofit Fuel

UK National Clean Maritime Research Hub

The main advantages of methanol

MAN B&W dual-fuel engines

Commercial deployment

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Green methanol can be 100% carbon neutral

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Easy storage: Liquid fuel
No cryogenic system

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UK National Clean Maritime Research Hub

The main advantages of methanol

MAN B&W dual-fuel engines

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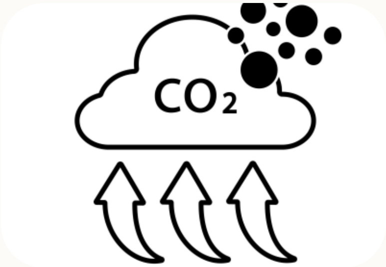
Green methanol can be 100% carbon neutral

Easy storage: Liquid fuel
No cryogenic system

Biomass; $CO_2$ + $H_2$; Waste streams

Challenges:




$CO_2$ Emissions

*Net-zero depends on fuel origin*

# Methanol as a Retrofit Fuel

UK National Clean Maritime Research Hub

The main advantages of methanol

MAN B&W dual-fuel engines

Commercial deployment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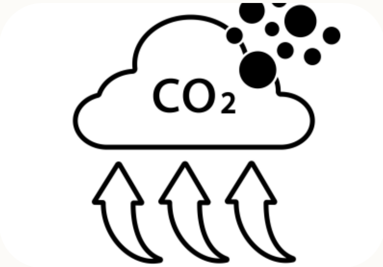



$CO_2$ Emissions

Net-zero depends on fuel origin

Regulated Emissions

*$NO_x$, CO, HC*

# Methanol as a Retrofit Fuel

UK National Clean Maritime Research Hub

## The main advantages of methanol

MAN B&W dual-fuel engines

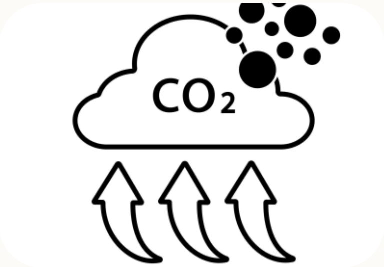
Commercial deployment


Green methanol can be 100% carbon neutral

Easy storage: Liquid fuel
No cryogenic system

Biomass; $CO_2$ + $H_2$;
Waste streams

## Challenges:




$CO_2$ Emissions

*Net-zero depends on fuel origin*

Regulated Emissions

*$NO_x$, CO, HC*

Unregulated Emissions

*HCHO, HCOOH*

Can the carbon intensity of methanol be reduced without compromising its retrofit benefits?

# Methanol-Ammonia Blends

**Lower Carbon Intensity Without Changing the Fuel Platform**

**Liquid Carrier for Ammonia**

Ammonia (10%) in methanol forms a stable compound at ambient condition

**Reduced Toxicity, Enhanced Safety**.

It reduces toxicity hazards associated with pure ammonia handling

Can ammonia reduce the carbon intensity of methanol while retaining methanol-like combustion behavior?

# Methanol-Ammonia Blends

**Lower Carbon Intensity Without Changing the Fuel Platform**

### Liquid Carrier for Ammonia

Ammonia (10%) in methanol forms a stable compound at ambient condition

### Reduced Toxicity, Enhanced Safety.

It reduces toxicity hazards associated with pure ammonia handling

### Reduced Carbon Intensity

Ammonia contains no carbon

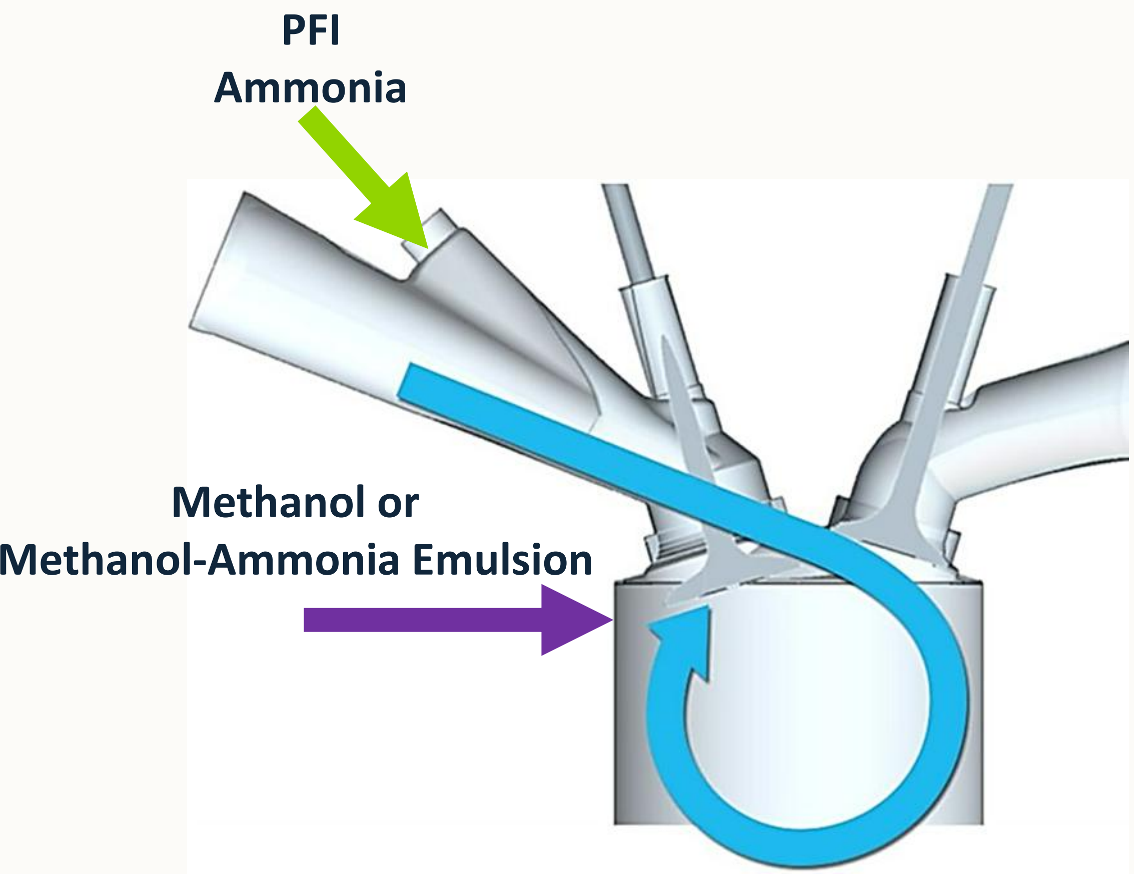
### Improved combustion

Methanol can promote stable ammonia combustion while reducing carbon intensity

Can ammonia reduce the carbon intensity of methanol while retaining methanol-like combustion behavior?

# Methanol-Ammonia Blends

## Experimental Setup

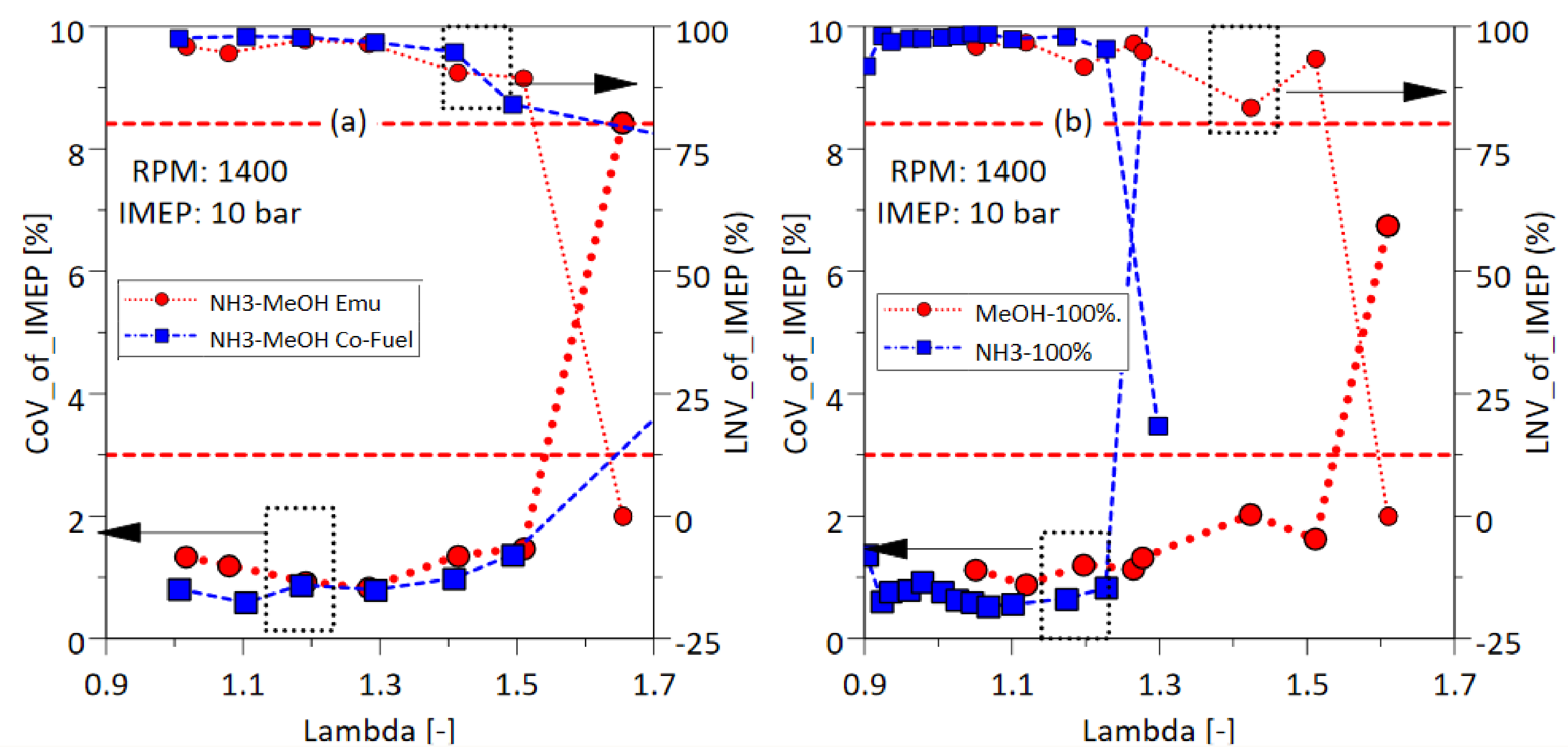



| Parameters | Value |
|---|---|
| Engine Type | Four Stroke Single Cylinder |
| Displaced Volume | 400 cc |
| Stroke | 83 mm |
| Bore | 73.9 mm |
| Compression Ratio | **12.39** |
| Number of Valves | 4 |
| Valvetrain | Dual Independent Variable Valve Timing (40°CA Cam Phasing) |
| Combustion Modes | SI |
| Cylinder Head Geometry | Pent Roof (High Tumble Port) |
| Max Power | 40 kW (Gasoline) |
| Max Torque | 96 Nm (Gasoline) [~30 bar NIMEP] |
| Max In-Cylinder Pressure | 120 bar |
| Max Speed | 5000 rpm |
| Boost System | External Compressor (Max 4barA) |
| Control System | MAHLE Flexible ECU |
| Interface Software | ETAS INCA |

# Methanol-Ammonia Blends

UK National Clean Maritime Research Hub

## Experimental Validation of Methanol-Ammonia Blends

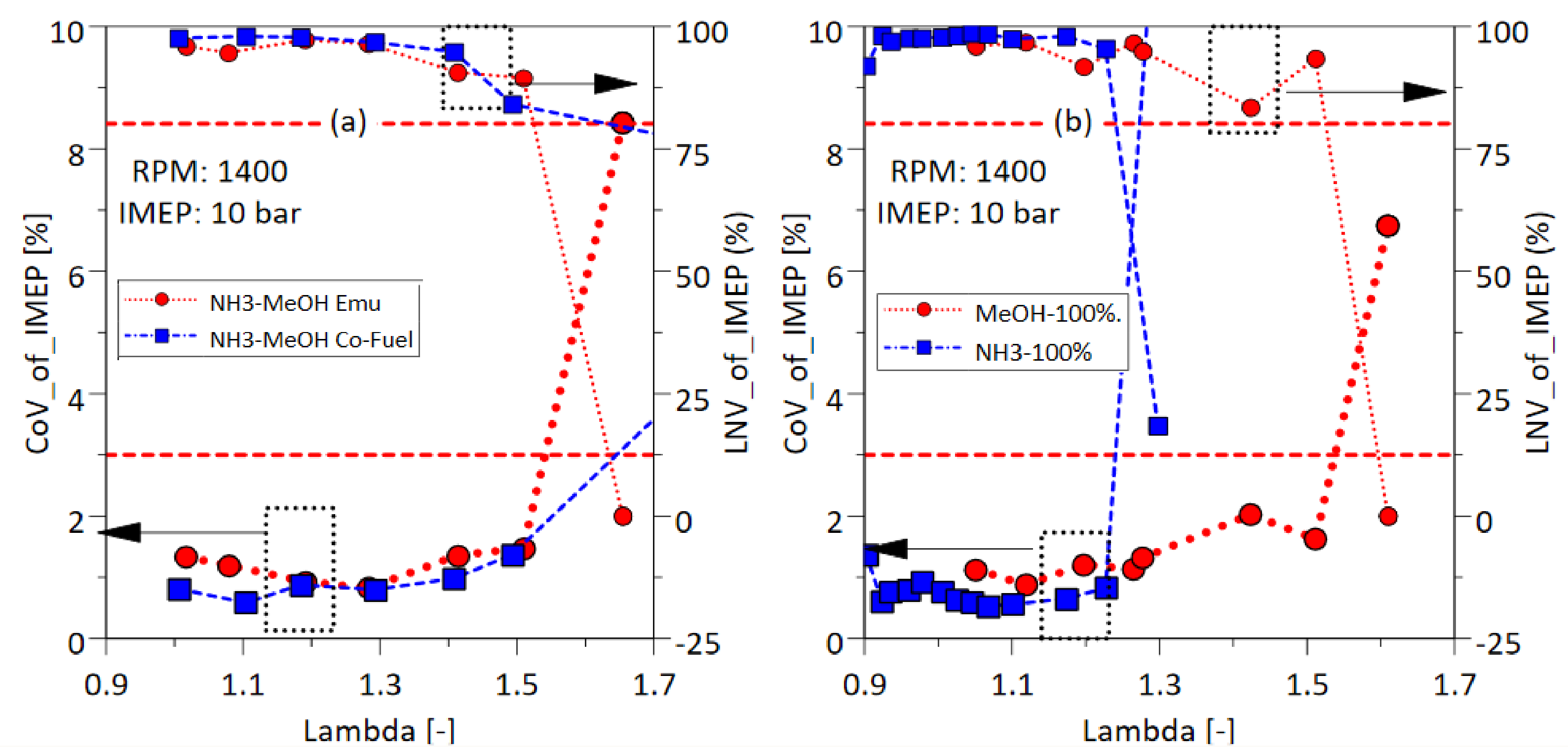



Key Results

- Comparable lean-burn stability to pure methanol

# Methanol-Ammonia Blends

## Experimental Validation of Methanol-Ammonia Blends

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- Stable operation in both emulsion and co-fuelling modes

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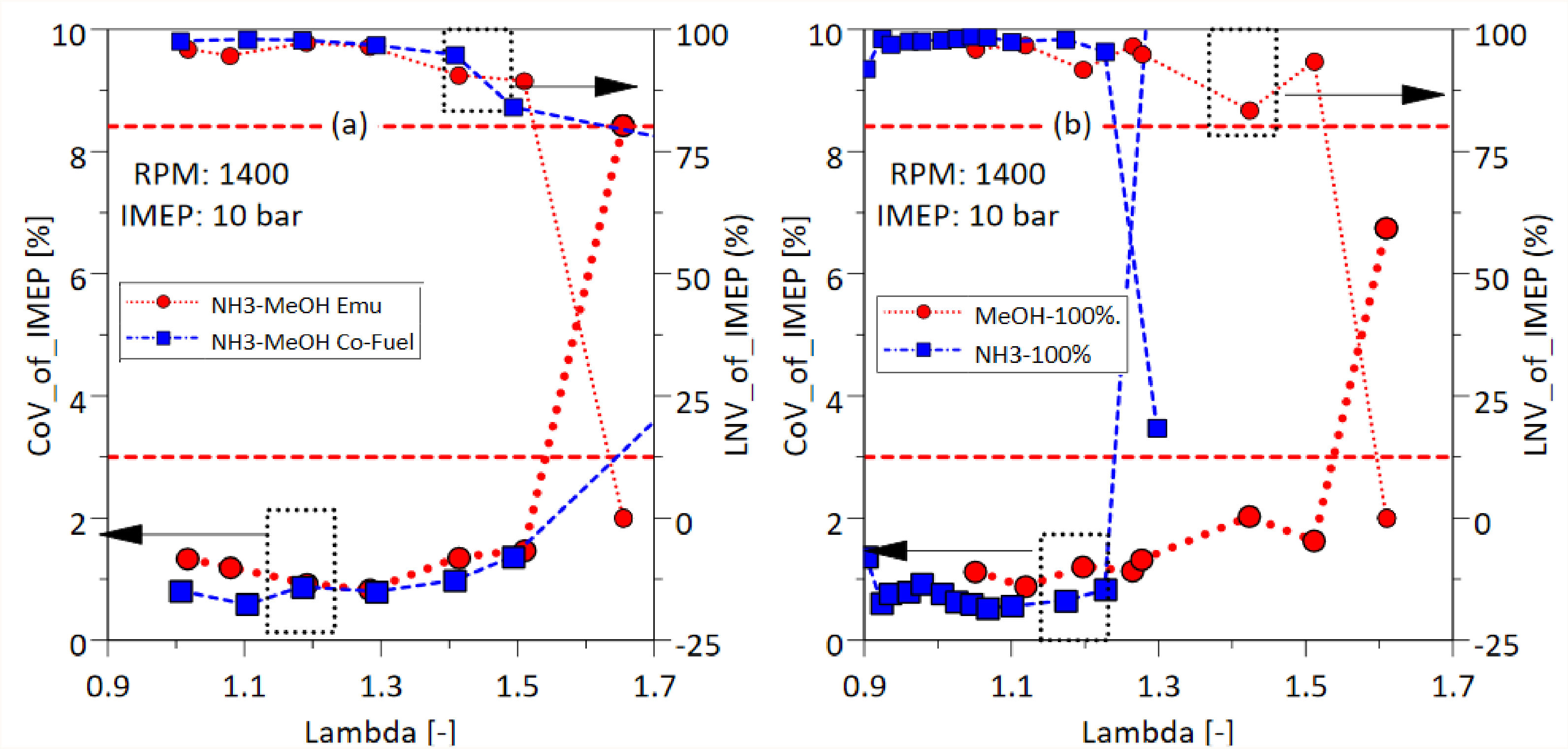


Key Results

- Comparable lean-burn stability to pure methanol
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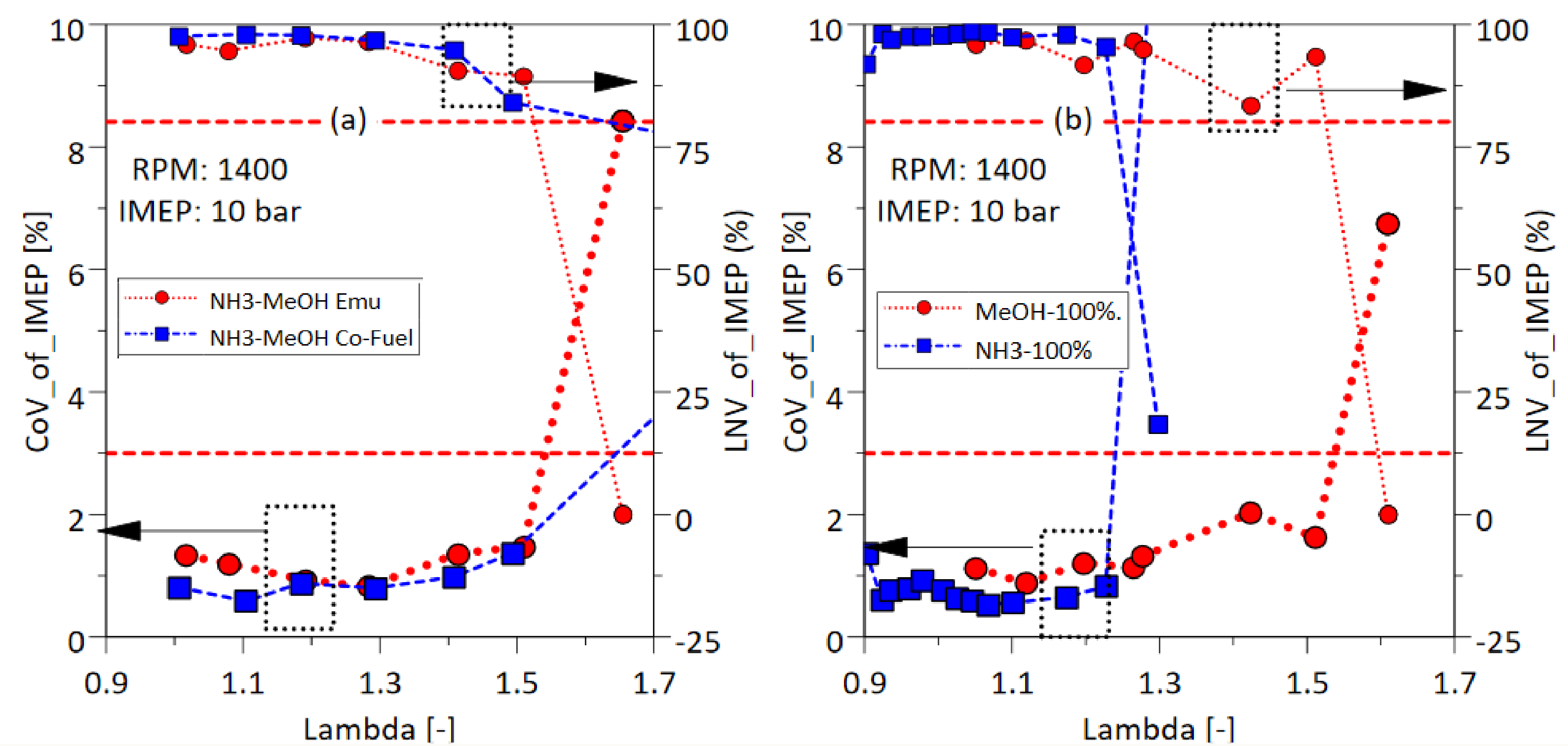
- Ammonia addition did not compromise combustion stability

# Methanol-Ammonia Blends

UK National Clean Maritime Research Hub

## Experimental Validation of Methanol-Ammonia Blends



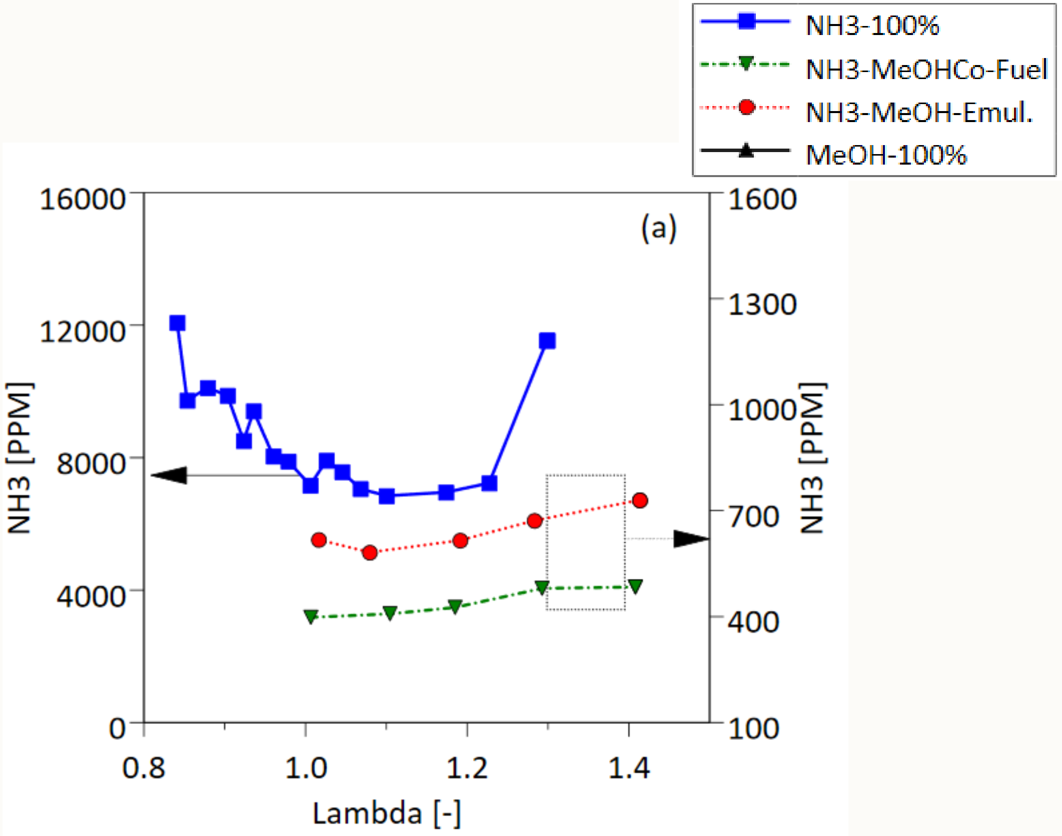

Key Results

- Comparable lean-burn stability to pure methanol
- Stable operation in both emulsion and co-fuelling modes
- Ammonia addition did not compromise combustion stability
- **Demonstrates feasibility of a lower-carbon marine fuel strategy**

**Methanol–ammonia blends offer a practical lower-carbon pathway while retaining methanol-like combustion behavior**

# Methanol-Ammonia Blends

## The Remaining Challenge: Emissions

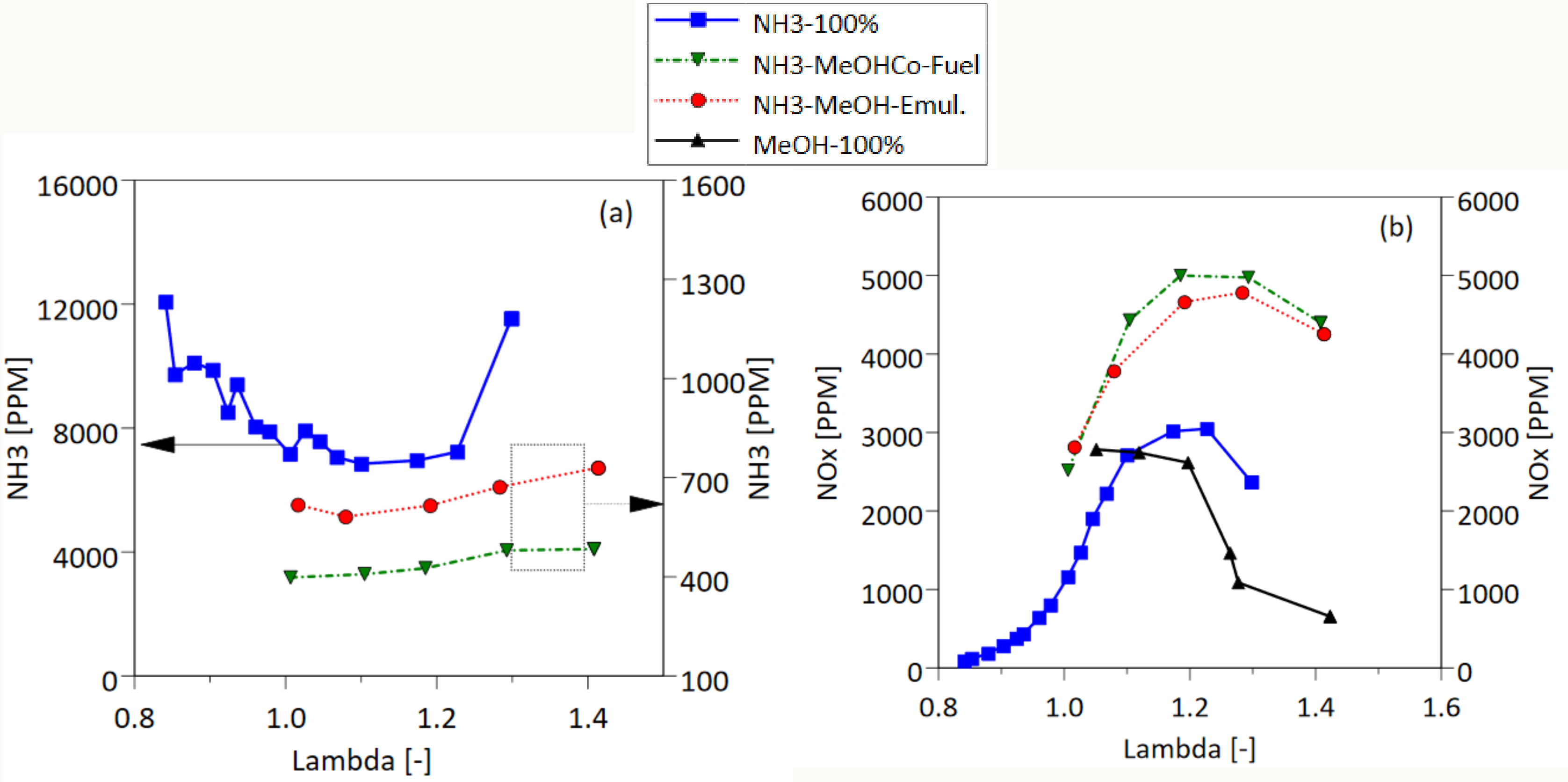



Key Results

- $NO_x$
  - Comparable $NO_x$ to methanol near stoichiometry
  - At lean conditions, $NO_x$ is higher in blends
  - Peak near $\lambda \approx 1.2$

# Methanol-Ammonia Blends

## The Remaining Challenge: Emissions




Key Results

- $NO_x$
  - Comparable $NO_x$ to methanol near stoichiometry
  - At lean conditions, $NO_x$ is higher in blends
  - Peak near $\lambda \approx 1.2$
- $NH_3$ Slip
  - Significantly lower than pure ammonia operation
  - Emulsion produced more $NH_3$ slip than co-fuelling

**Methanol–ammonia blends lower carbon intensity, but further strategies are required to achieve ultra-low emissions.**

# Hydrogen-Assisted Ultra-Lean Combustion

UK National Clean Maritime Research Hub

**Faster Combustion**

Hydrogen accelerates flame propagation and improves ignition stability

**Extends Lean Limit**.

Stable operation beyond the lean limit of methanol–ammonia blends.

# Hydrogen-Assisted Ultra-Lean Combustion

UK National Clean Maritime Research Hub

**Faster Combustion**

Hydrogen accelerates flame propagation and improves ignition stability

**Extends Lean Limit.**

Stable operation beyond the lean limit of methanol–ammonia blends.

**Lower $NO_x$ Formation**

Ultra-lean operation reduces combustion temperature and suppresses $NO_x$ formation

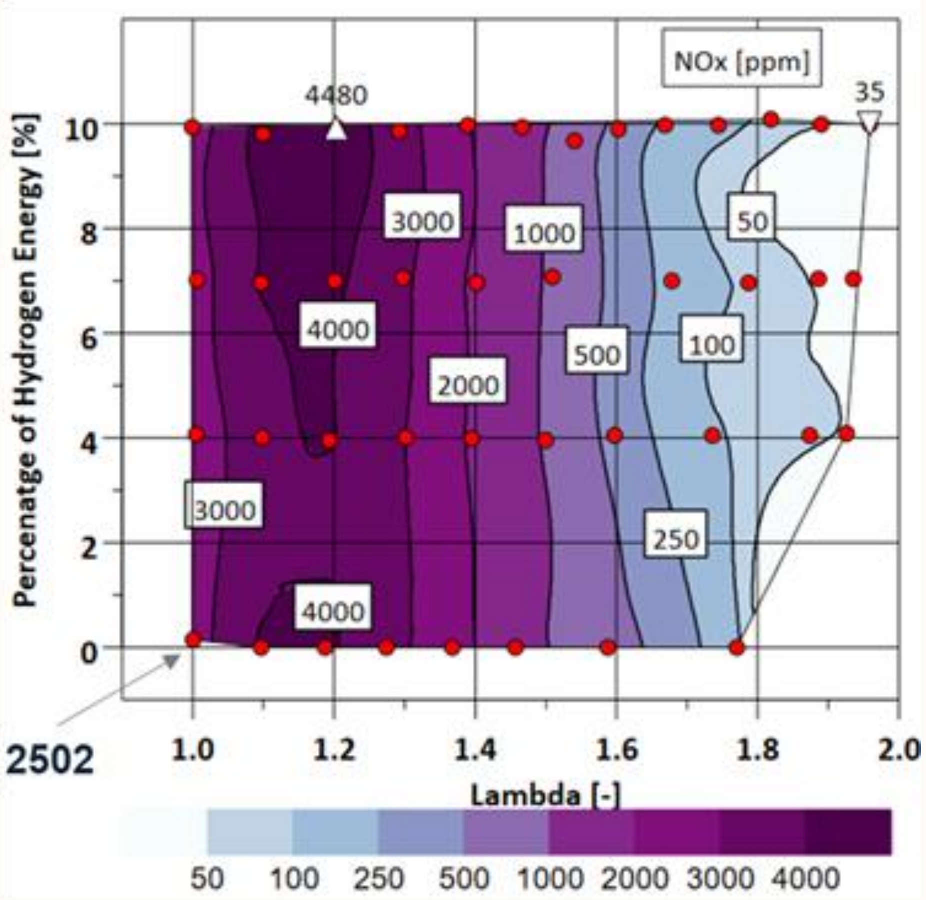
**Methanol Reforming**

A small fraction of methanol can be reformed on-board to **generate hydrogen**, avoiding dedicated hydrogen storage

**Hydrogen enables stable ultra-lean combustion, creating a pathway to near-zero $NO_x$ operation.**

# Hydrogen-Assisted Ultra-Lean Combustion

## Experimental Validation




Key Results

- Hydrogen extended the lean operating limit from **λ ≈ 1.5 to λ ≈ 1.9**
- $NO_x$ reduced by 98%
  - 2502 ppm → 35 ppm
- Ultra-low $NO_x$ achieved with only 10% hydrogen energy fraction

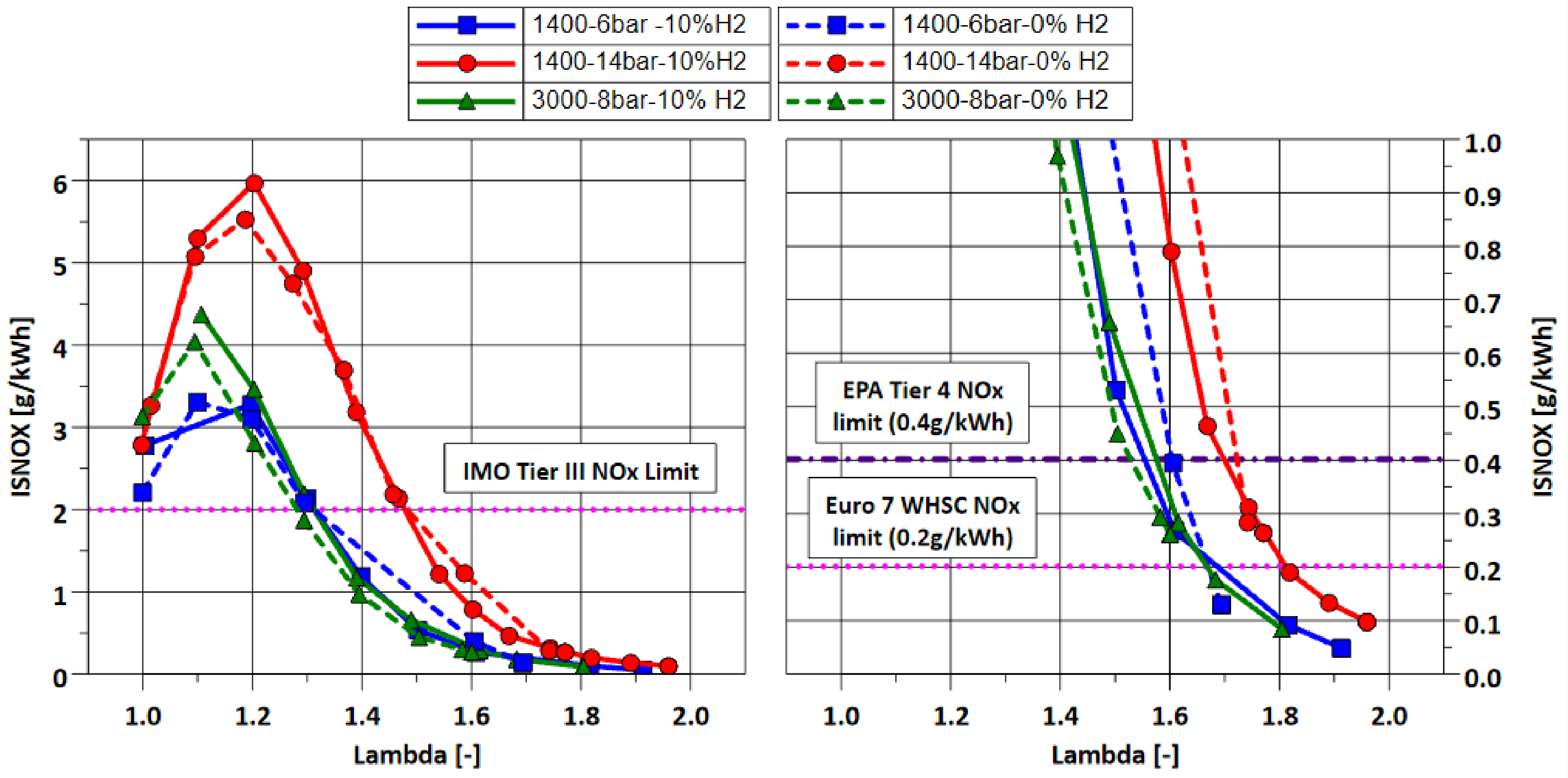
# Hydrogen-Assisted Ultra-Lean Combustion

UK National Clean Maritime Research Hub

## Ultralow NOx at different engine speed and load

NOx Emissions limits in g/kWh

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




Key Results

- Leaner combustion significantly reduces $NO_x$ emissions
- IMO Tier III and EPA Tier 4 limits can be achieved without aftertreatment

# Hydrogen-Assisted Ultra-Lean Combustion

UK National Clean Maritime Research Hub

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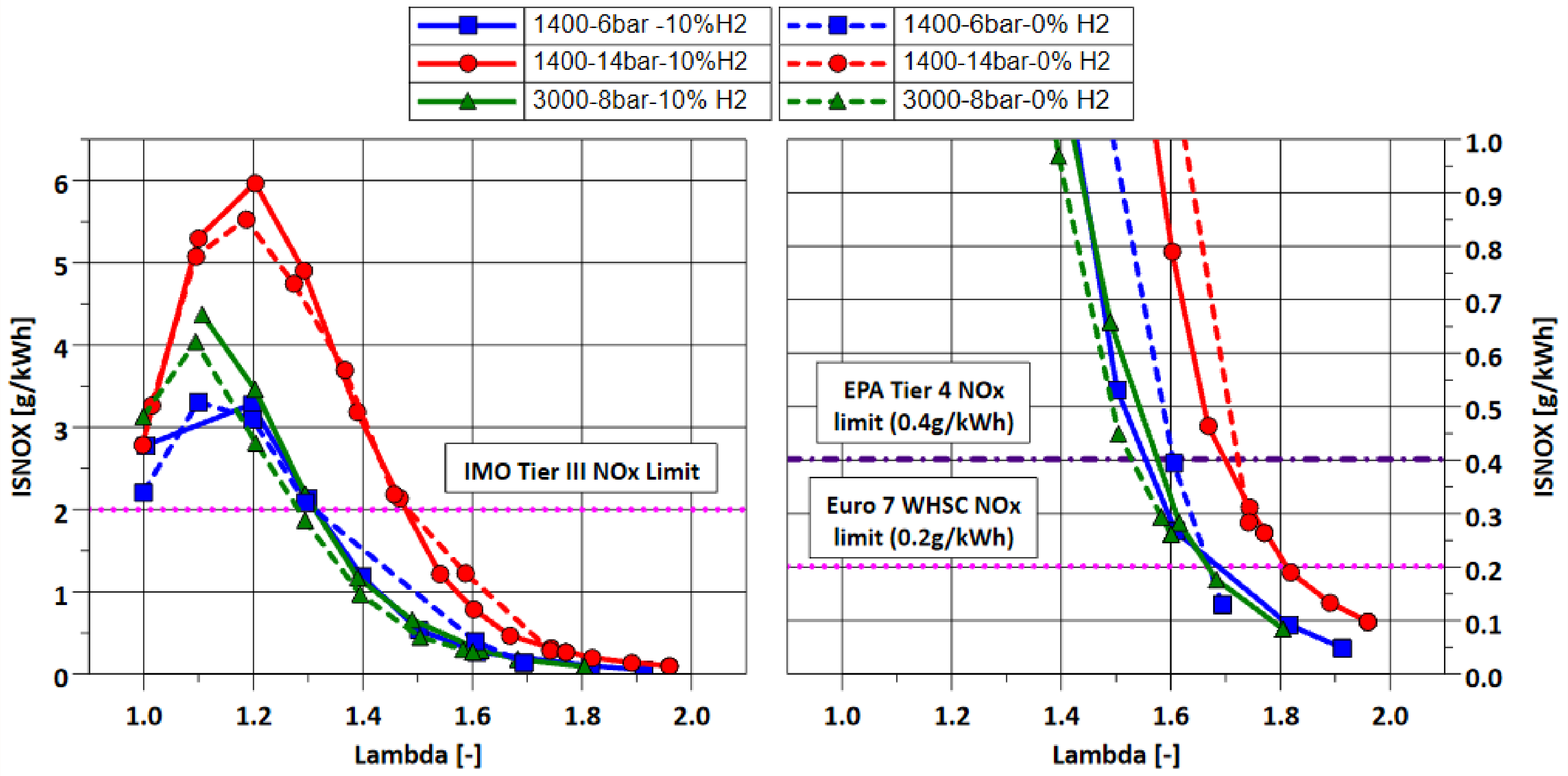
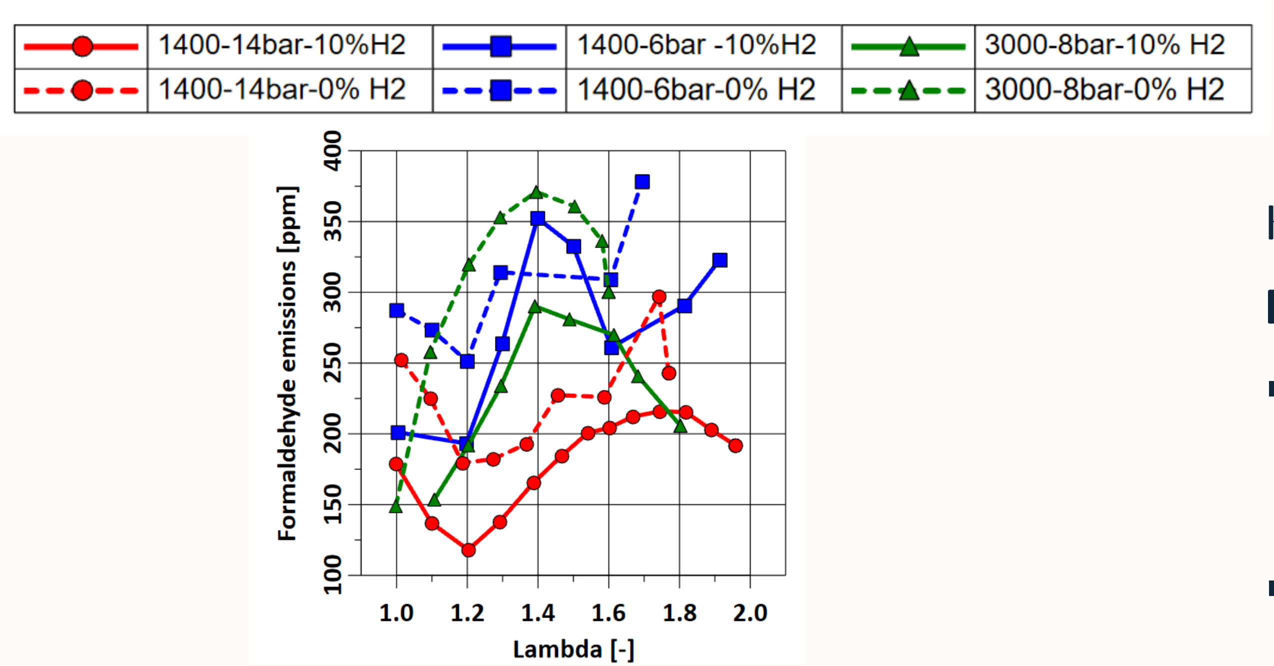



Key Results

- Leaner combustion significantly reduces $NO_x$ emissions
- IMO Tier III and EPA Tier 4 limits can be achieved without aftertreatment
- Euro 7 limits are achievable with hydrogen-assisted ultra-lean combustion
- Hydrogen extends the operating range where low-$NO_x$ combustion is possible

# Hydrogen-Assisted Ultra-Lean Combustion

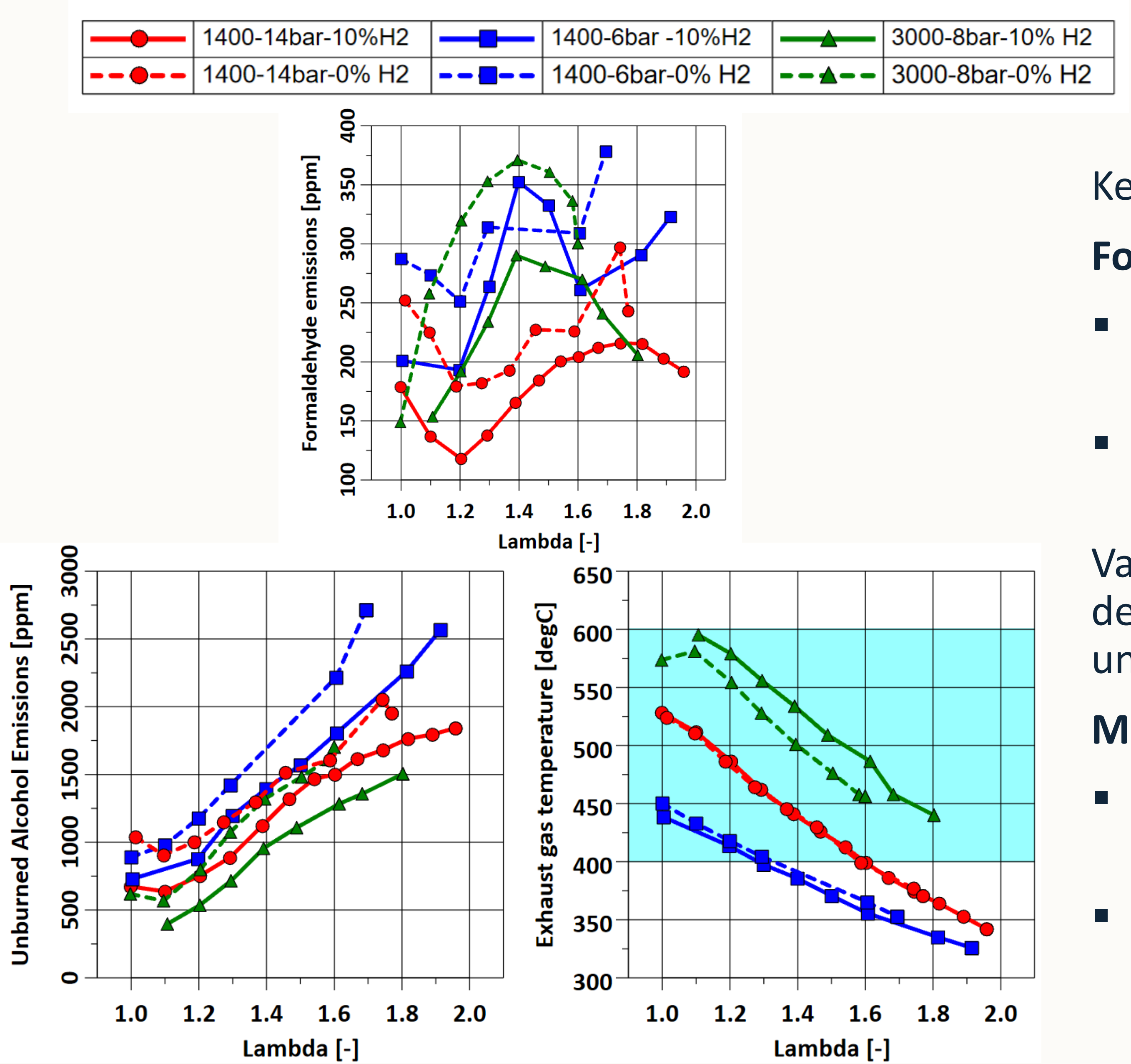



Key Results

**Formaldehyde**

- Leaner combustion generally increases the formaldehyde emissions in both cases
- Hydrogen addition lowers the formaldehyde emissions

# Hydrogen-Assisted Ultra-Lean Combustion




Key Results

**Formaldehyde**

- Leaner combustion generally increases the formaldehyde emissions in both cases
- Hydrogen addition lowers the formaldehyde emissions

Variation in emissions with speed and load depends on exhaust gas temperature and unburned methanol emission

**Methanol**

- Increases with leaner combustion for both cases
- Hydrogen addition lowers unburned methanol emissions

# Towards Net Zero

**A progressive transition pathway using methanol, ammonia, and hydrogen**

UK National Clean Maritime Research Hub




A progressive transition using methanol, ammonia and hydrogen can accelerate the journey towards net-zero shipping.

# Key Takeaways

- Methanol–ammonia blends-maintained combustion stability and efficiency, demonstrating a viable lower-carbon fuel pathway.

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- The practical advantages of emulsion fuels could accelerate adoption of methanol–ammonia retrofit solutions.
- IMO Tier III and EPA Tier 4 $NO_x$ limits were achieved through lean combustion without aftertreatment.
- Hydrogen-assisted ultra-lean combustion enabled compliance with Euro 7 WHSC $NO_x$ limits.

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# Key Takeaways

- Methanol–ammonia blends-maintained combustion stability and efficiency, demonstrating a viable lower-carbon fuel pathway.
- The practical advantages of emulsion fuels could accelerate adoption of methanol–ammonia retrofit solutions.
- IMO Tier III and EPA Tier 4 $NO_x$ limits were achieved through lean combustion without aftertreatment.
- Hydrogen-assisted ultra-lean combustion enabled compliance with Euro 7 WHSC $NO_x$ limits.
- Oxidation catalysts remain important for controlling unregulated emissions such as formaldehyde.

# Acknowledgements


UK National Clean Maritime Research Hub

## University of Nottingham

- Prof Alasdair Cairns
- Prof Antonino La Rocca
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- Dr Ajith Ambalakatte
- Alexander Birch
- Gagan Gopakumar Suja

## MAHLE Powertrain

- Anthony Harrington
- Jonathan Hall

MAHLE Powertrain

## Industry Partners

clean air power™

JM Johnson Matthey

# Thank you

UK National Clean Maritime Research Hub

University of St Andrews

# Fuel-Flexible Solid Oxide Fuel Cells: For Marine Propulsion

**John Irvine**

**Shu Wang**
sw335@st-andrews.ac.uk

# Background

*Bloom energy-Samsung LNG carrier powered solely by SOFC*

- **~3% of global GHG emissions** come from the maritime sector
  **"Shipping = Germany in GHG Emissions"**
  (6th largest if it were a country)

- Despite efforts, **emissions kept rising** due to fossil fuel reliance

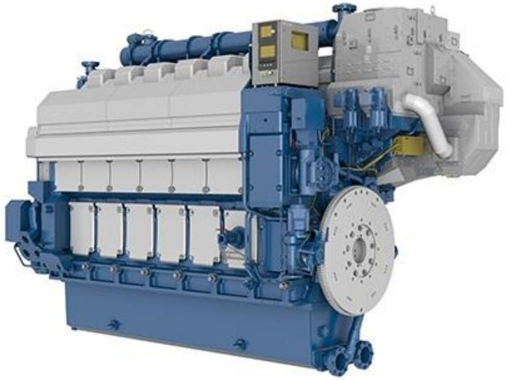
IMO's **Landmark Agreement – April 2025**

- Mandates **cleaner fuel use starting 2028**
- Fines up to **$ 380/ton $CO_2$** for non-compliance

*Maersk Bio-Methanol Container Ship with a dual-fuel engine*

## Urgent Shift to Green Fuels in Shipping

# Marine Power Systems



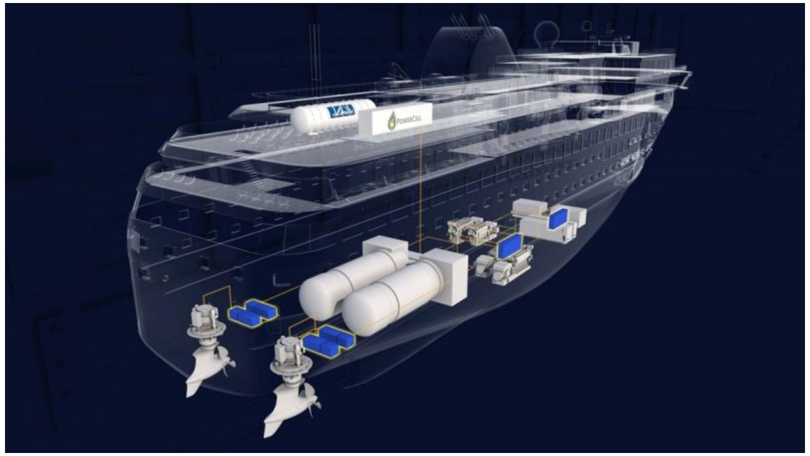

**Internal Combustion Engine (ICE)**
•Fuel: Heavy fuel oil / Marine diesel
•Mature, low cost
•High power density
**High $CO_2$, $SO_X$, $NO_X$ emissions**

**LNG Engine (Dual-fuel)**
•Lower emissions than diesel
•Existing infrastructure
**Still fossil-based**
**Methane slip**

**Battery Electric**
•Zero emissions (operation)
•High efficiency
**Low energy density**
**Only for short distance (ferries)**

# Future Marine Power Systems: Towards Zero-Carbon Shipping

## Route 1: Hydrogen + Fuel Cell

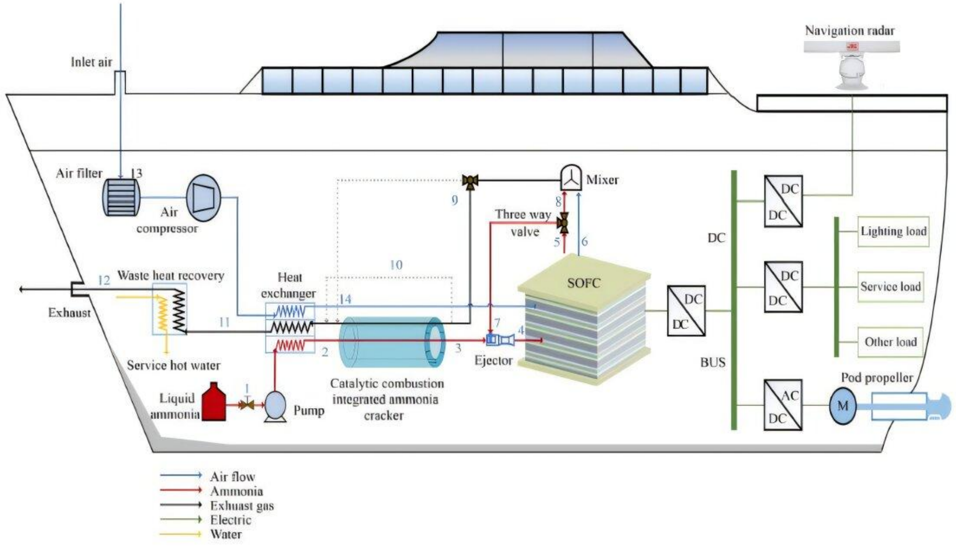


•Zero carbon

**Storage challenges (700 bar / -253°C)**

**Low volumetric energy density**

## Route 2: Methanol/Ammonia + Fuel Cell



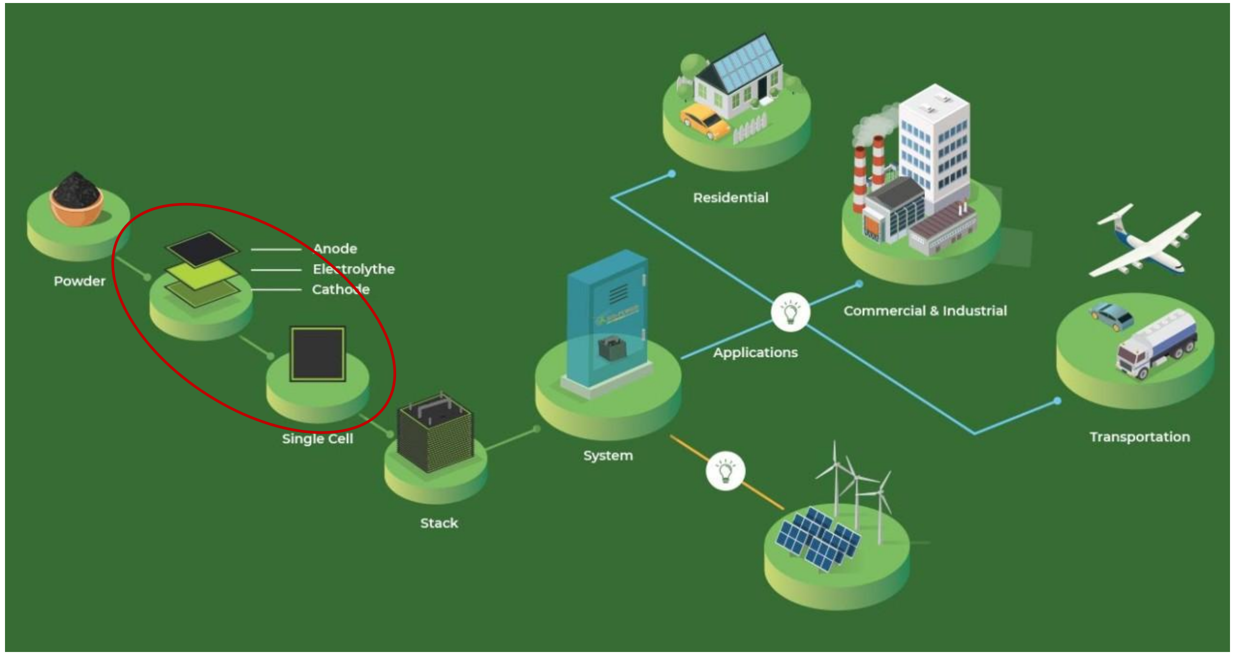

**Methanol / Ammonia + FC**

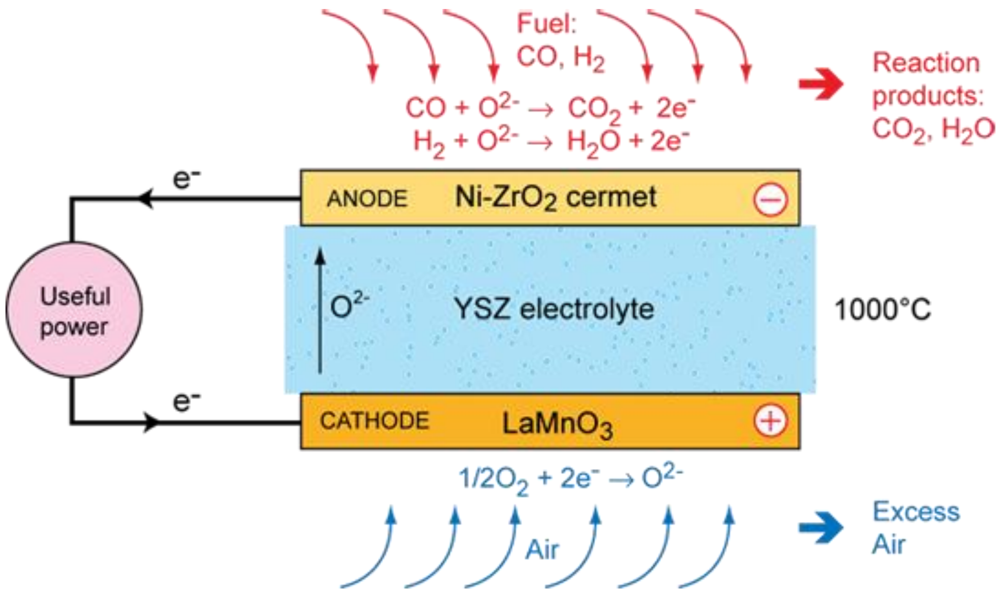
**•High efficiency**

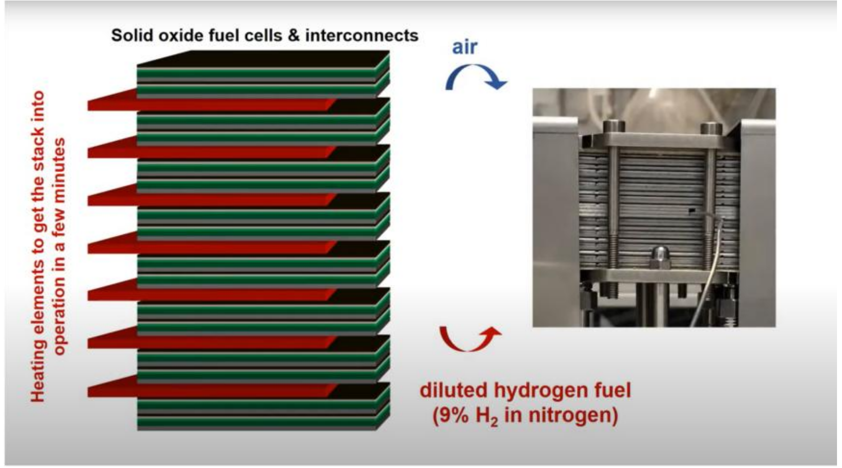
**•Fuel flexible**

**•Scalable for shipping**

# Solid oxide fuel cells(SOFC)



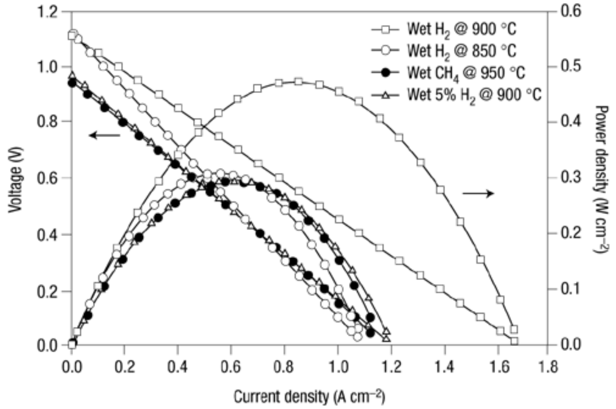

- Air electrode (LSFC-CGO, LSM-YSZ)
- Electrolyte (YSZ, GDC)
- **Fuel electrode** (Ni-YSZ, Ni-CGO)

# Direct Methanol SOFC

- **Direct Methanol** or **Internal Reforming**

  → Enables **simpler system design**
- **Coking** must be **avoided** during reforming/cracking
- **Thermal reforming** poses **stability challenges**
- Requires **improved electrocatalysis** for efficient performance

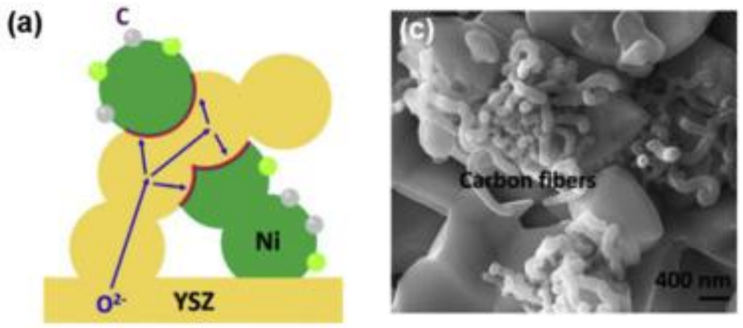
**$La_{0.8}Sr_{0.2}Cr_{0.5}Mn_{0.5}O_3$(LSCM)**




Tao S., Irvine J.T.S., Nat. Mater., 2003, 2, 320–323

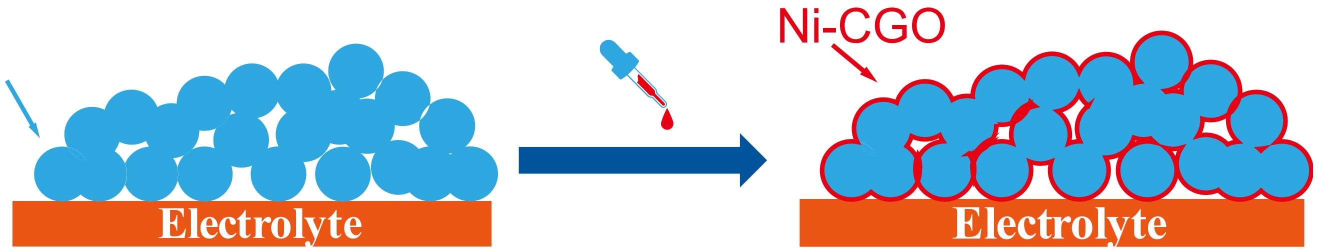
## Our design

Ni-YSZ electrode:




**Prone to coking** under hydrocarbon fuels

B. Yu, Nano Energy, 2019, 62, 64-78.




**LSCM** as backbone:
- **robust redox stability**
- **good coking resistance**
- **promotes methanol pyrolysis**

**Ni-CGO**:
- **enhanced ionic conducting**
- **improved catalyst performance**

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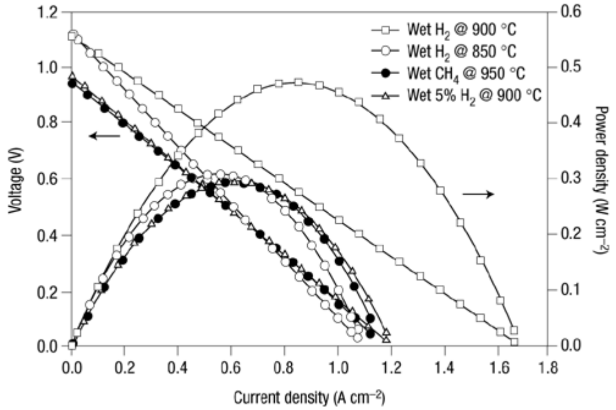


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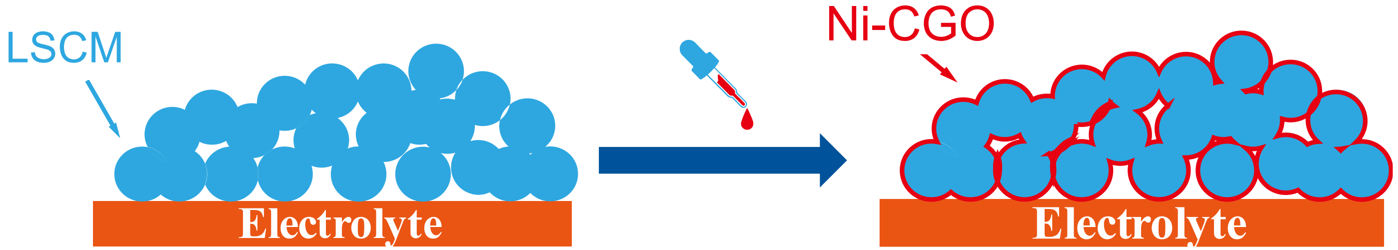


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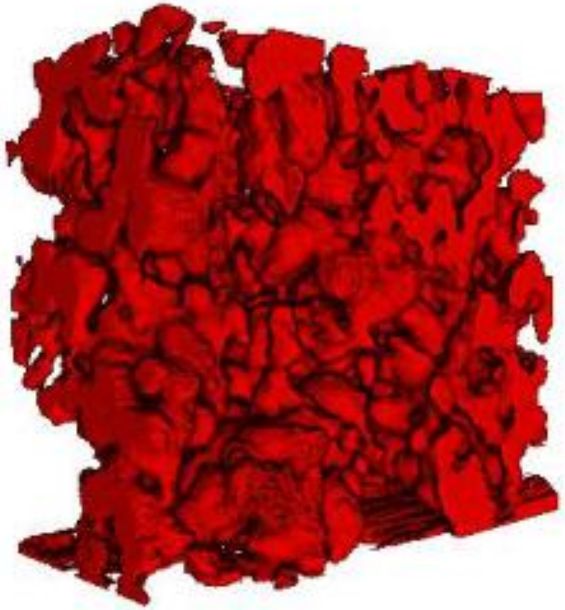
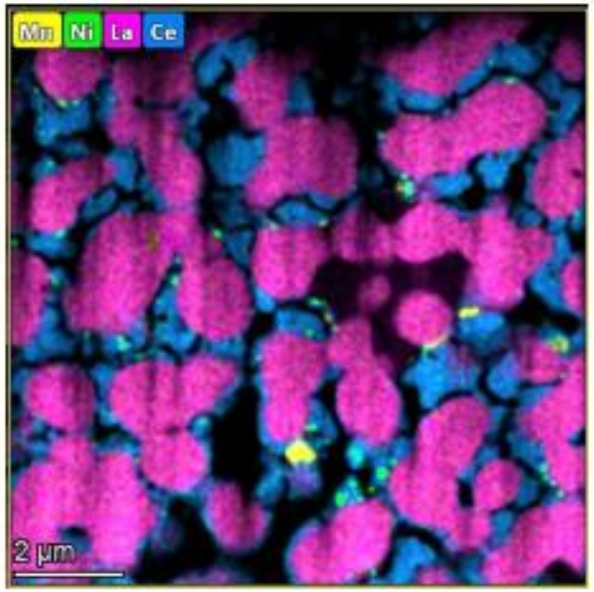
Tao S., Irvine J.T.S., Nat. Mater., 2003, 2, 320–323

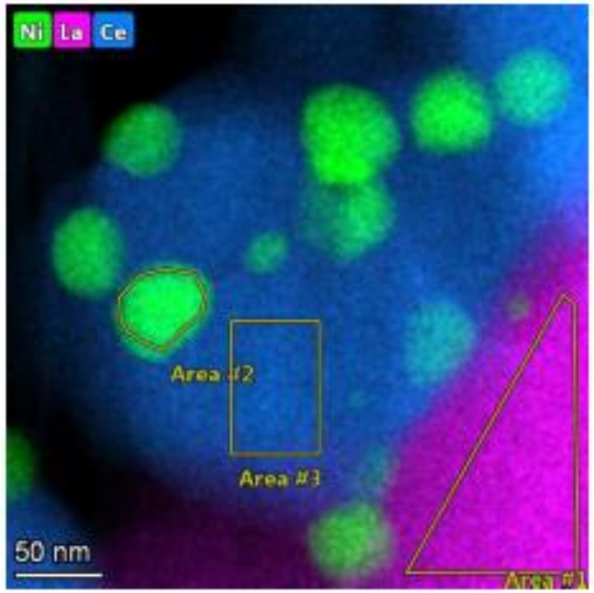
# Fuel-Flexible Solid Oxide Cells for Methanol, Ammonia and Urea

## Ni-CGO infiltrated $La_{0.75}Sr_{0.25}Cr_{0.5}Mn_{0.5}O_3$ electrodes



FIB image for porous LSCM backbone



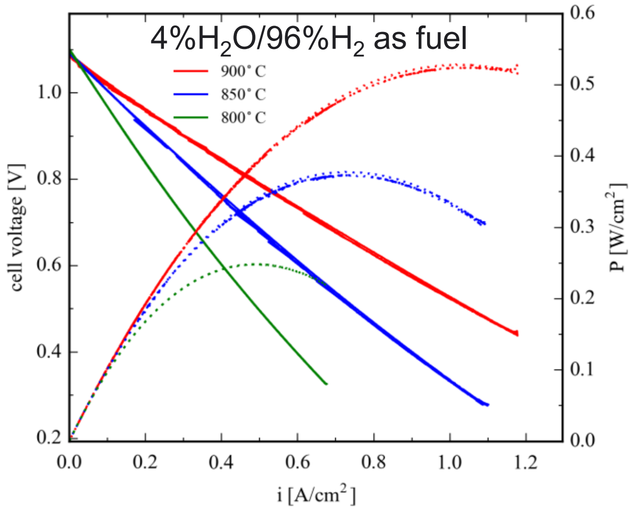




*HAADF-TEM image and EDX elemental mapping on Ni-CGO infiltrated LSCM sample*

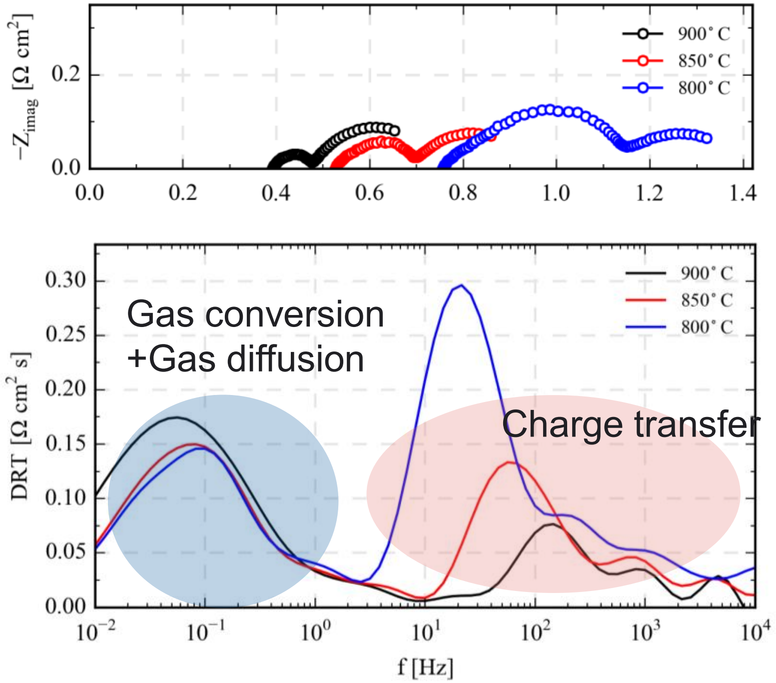
- CGO is well dispersed on LSCM, forming a continuous ionic conduction pathway
- Ni nanoparticles are uniformly distributed at the nanoscale
- Ni is preferentially anchored on the CGO phase

# Humidified $H_2$ as fuel

**StAnd Cells:** Ni-CGO infiltrated LSCM|YSZ|LSM-YSZ



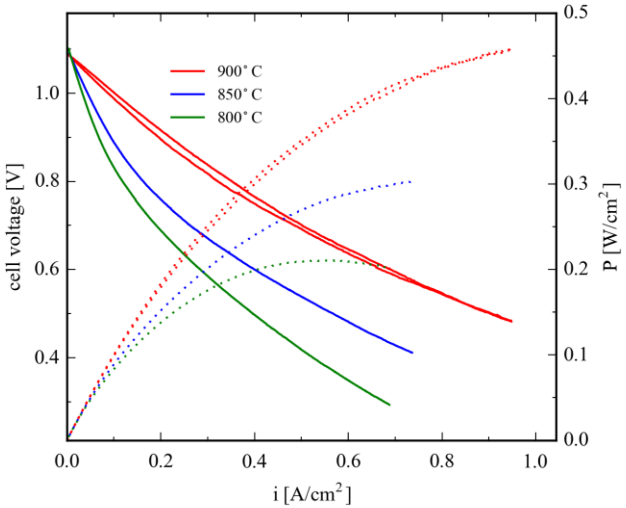

*I–V* and *P–I* curves in 4%$H_2O$/96%$H_2$, at different temperatures




*EI (top) and DRT (bottom) spectra in 4%$H_2O$/96%$H_2$ at different temperatures*

**SoA Cells:** Ni-YSZ|YSZ|LSM-YSZ

4%$H_2O$/96%$H_2$ as fuel

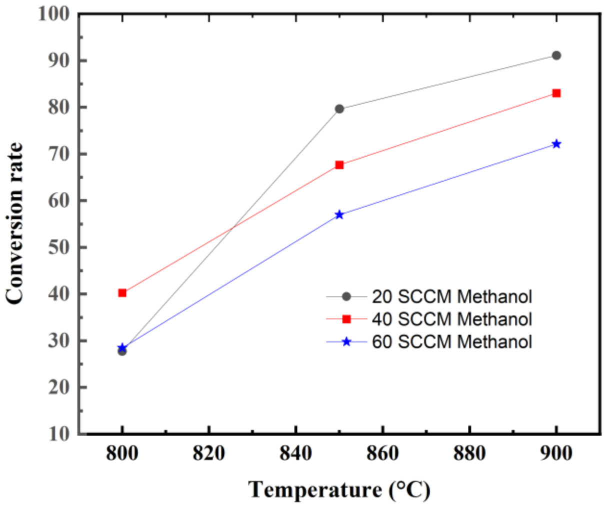



*I–V* and *P–I* curves in 4%$H_2O$/96%$H_2$, at different temperatures

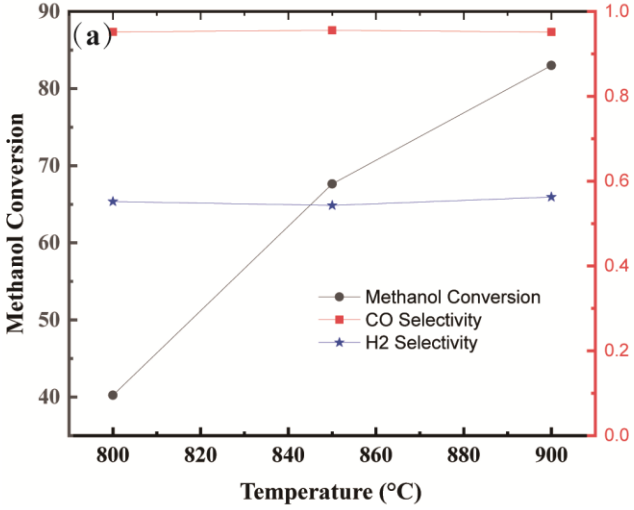
- **Power density of 530 mW·cm$^{-2}$** at 900 °C
- Very small charge transfer resistance **about 0.069 Ω cm$^2$** at 900 °C

# Methanol Pyrolysis at High Temperature

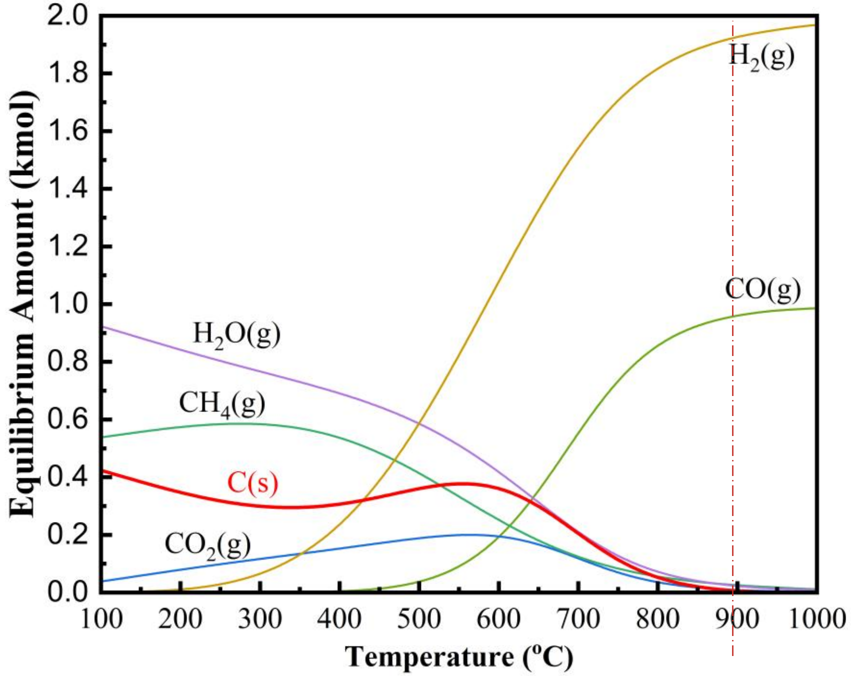
- Test Cells: Ag|YSZ| Ag



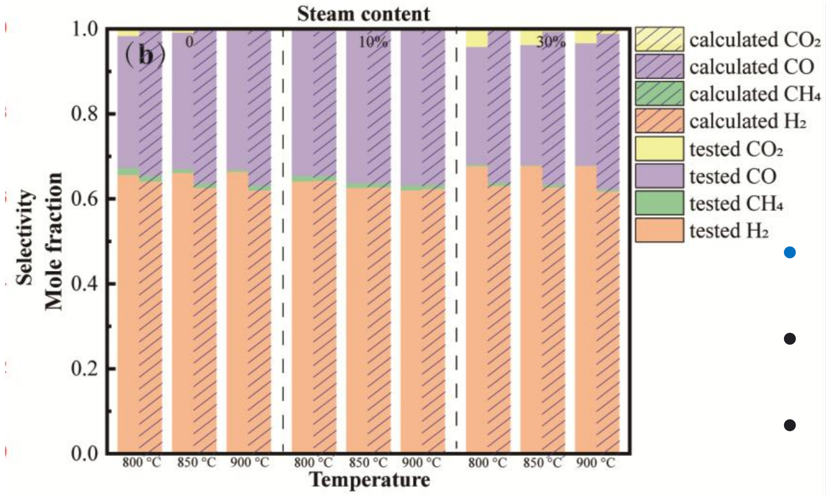

*Methanol conversion rate as a function of temperature under different methanol injection flow rates*




*Product selectivity as a function of temperature*



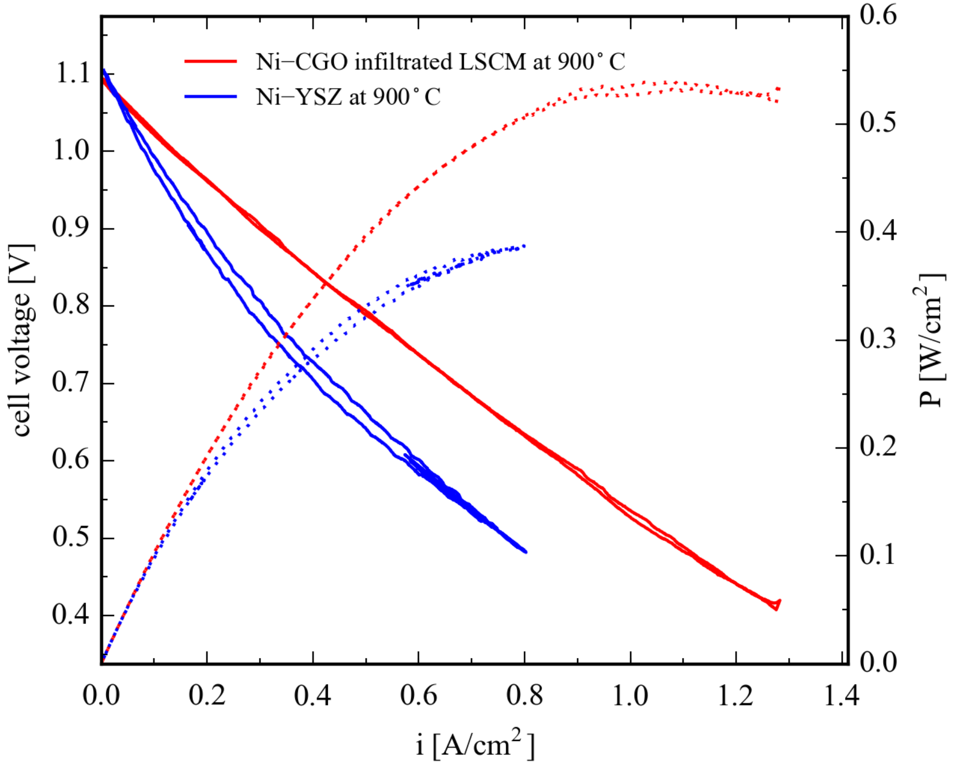

*Simulation results of methanol cracking reactions*



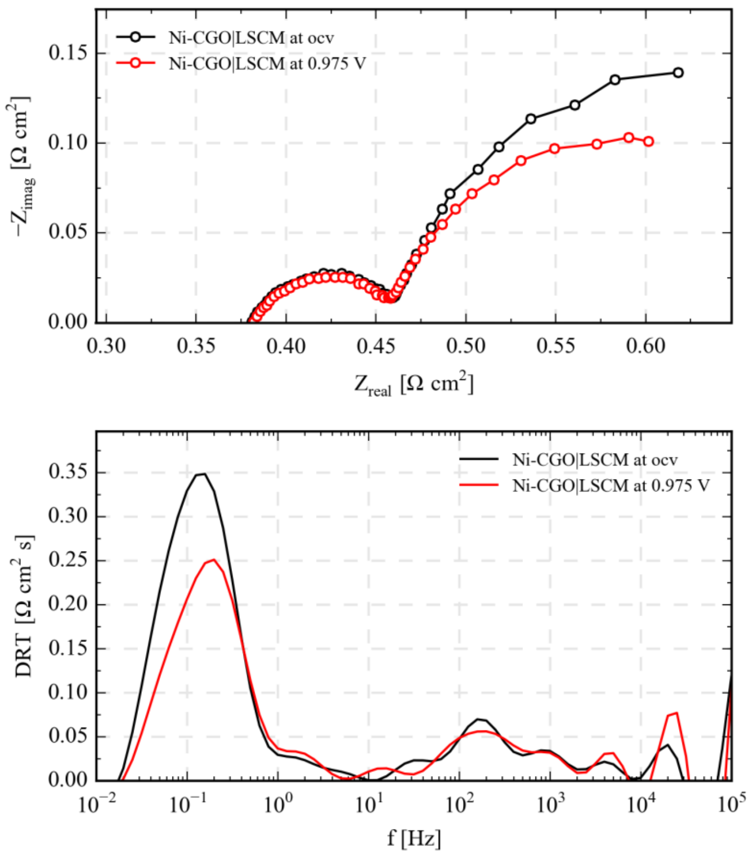

*Composition of product gases from methanol pyrolysis,*

- **High conversion rate** at **900 °C**
- Unconverted carbon remains as **methanol or carbon solids**
- Internal reforming **produces CO and $H_2$ in ~1:2 ratio**

# Pure methanol as fuel



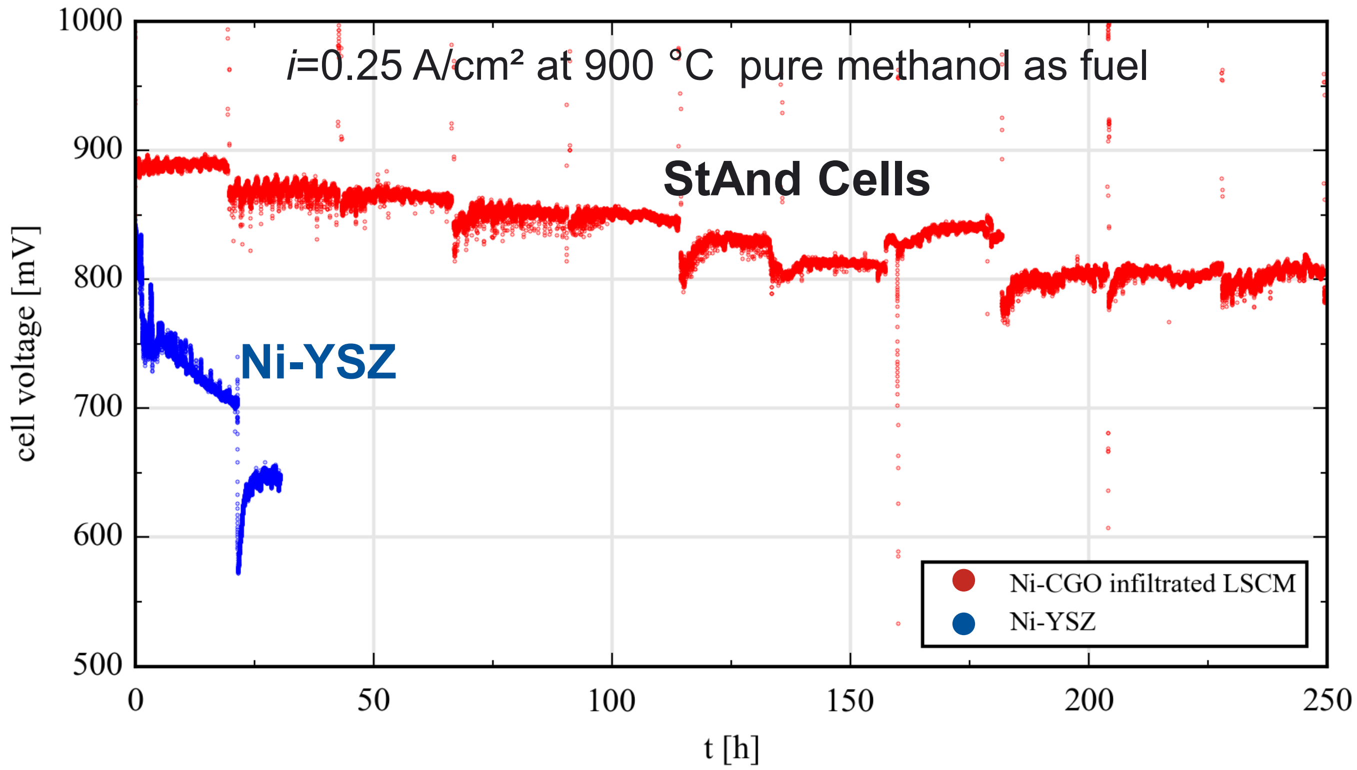

*I–V* and *P–I* curves in pure methanol at 900 °C



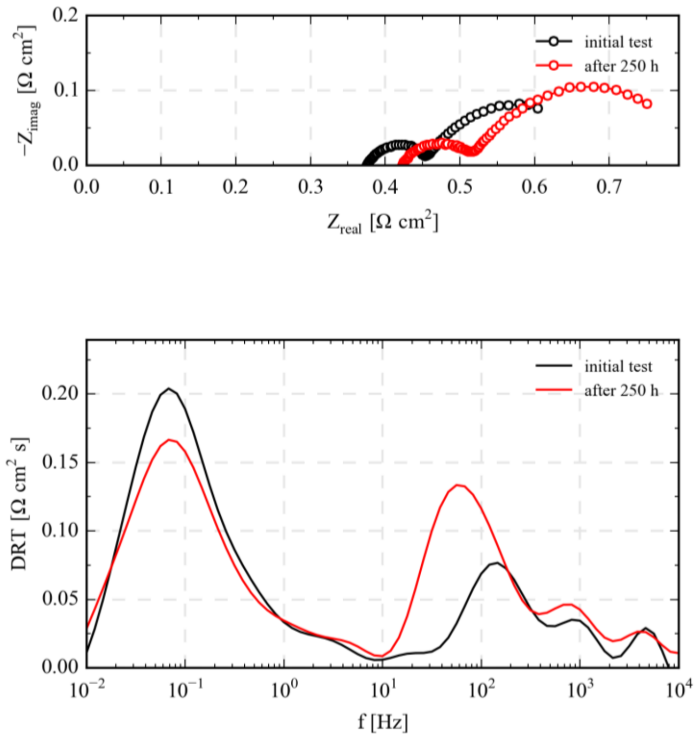

*EI (top) and DRT (bottom)* spectra in pure methanol at different temperatures

- Achieved power density of **540 mW·cm⁻²** at 900 °C, outperforming **Ni-8YSZ (380 mW·cm⁻²)**.

# Short-term stability test




*Short stability test with current density at 0.25 A/cm² in pure methanol at 900 °C*




*EI (top) and DRT (bottom) spectra in pure methanol at 900 °C*

Comparison with Ni-YSZ Electrode:

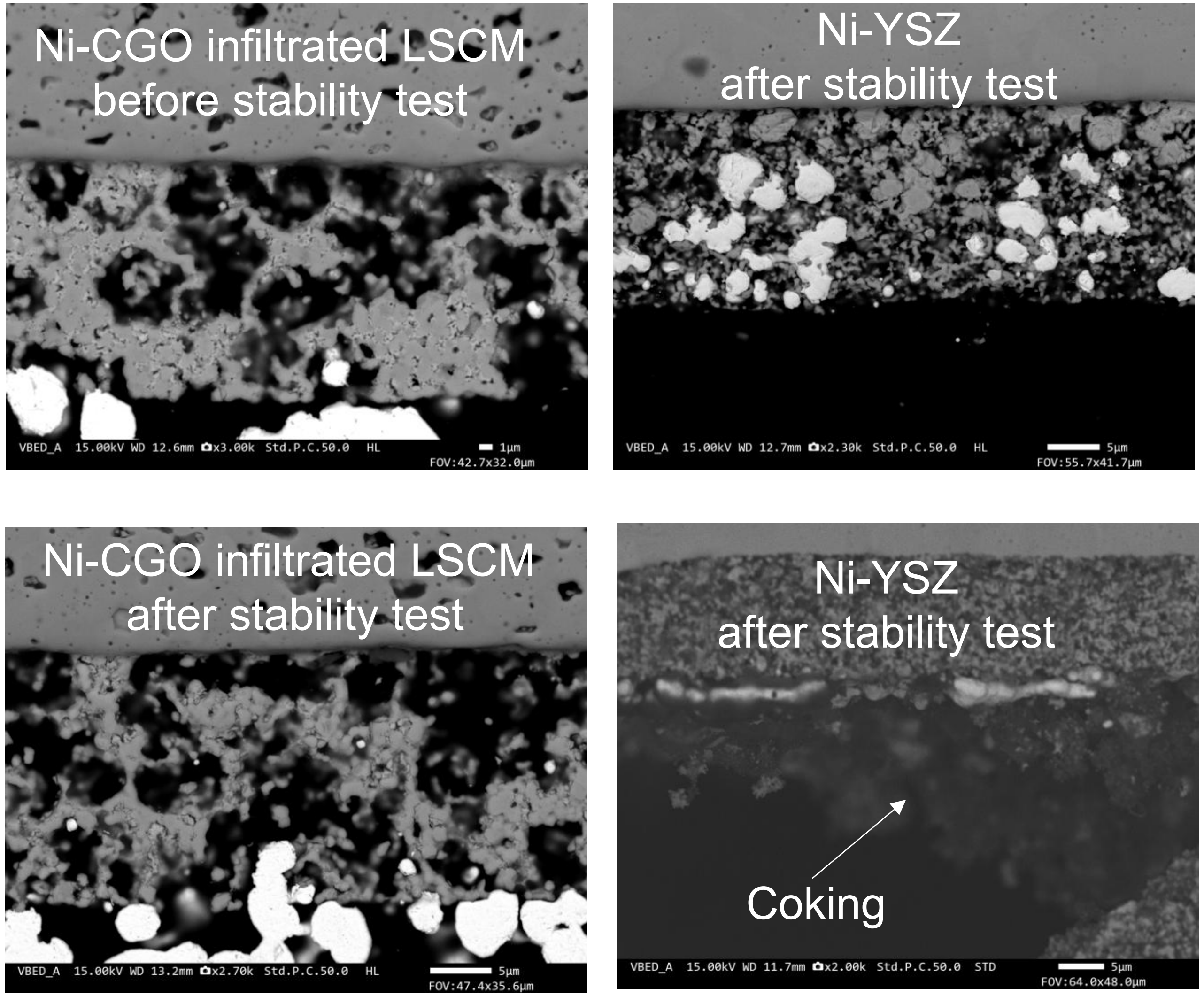
**•Superior electrochemical performance**

**•Enhanced operational stability**

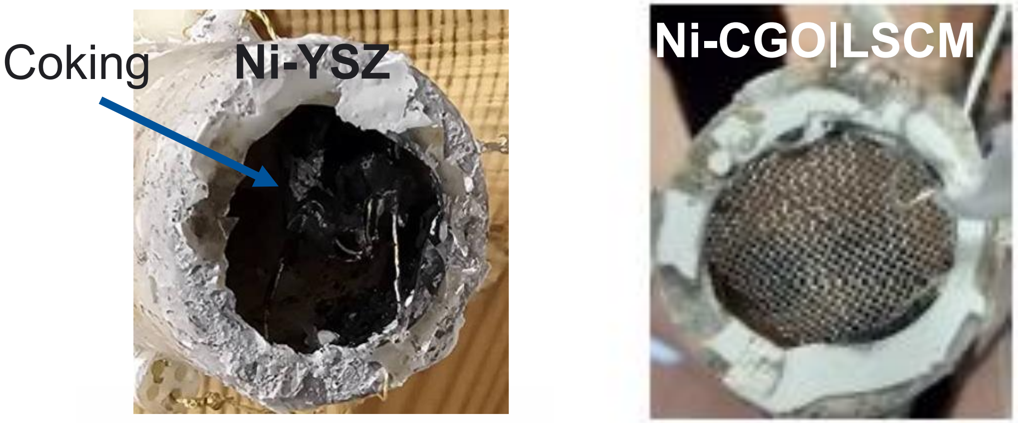
Possiblely cause:

- **Delamination of current collector**

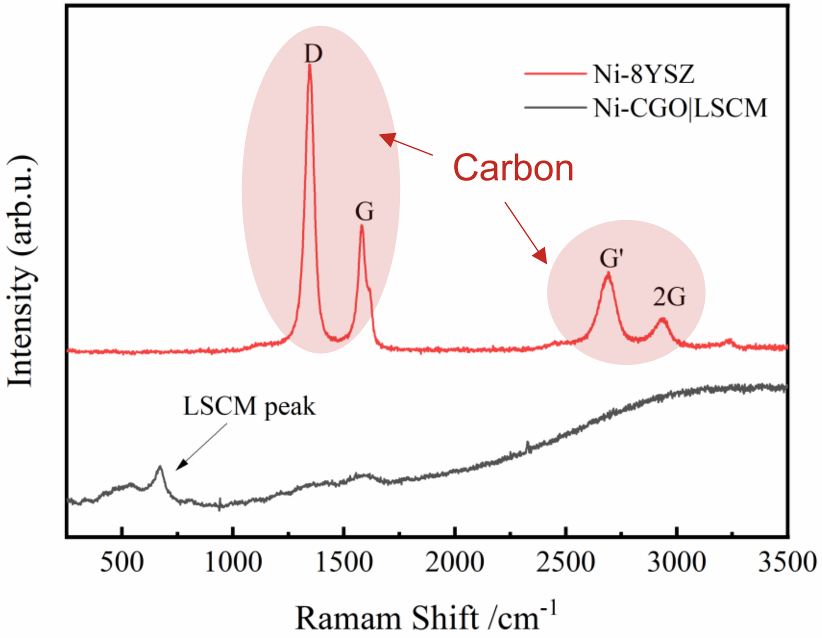
# Morphology post short-term stability test




*Post-test SEM images comparing Ni–CGO infiltrated LSCM and Ni–YSZ electrodes*

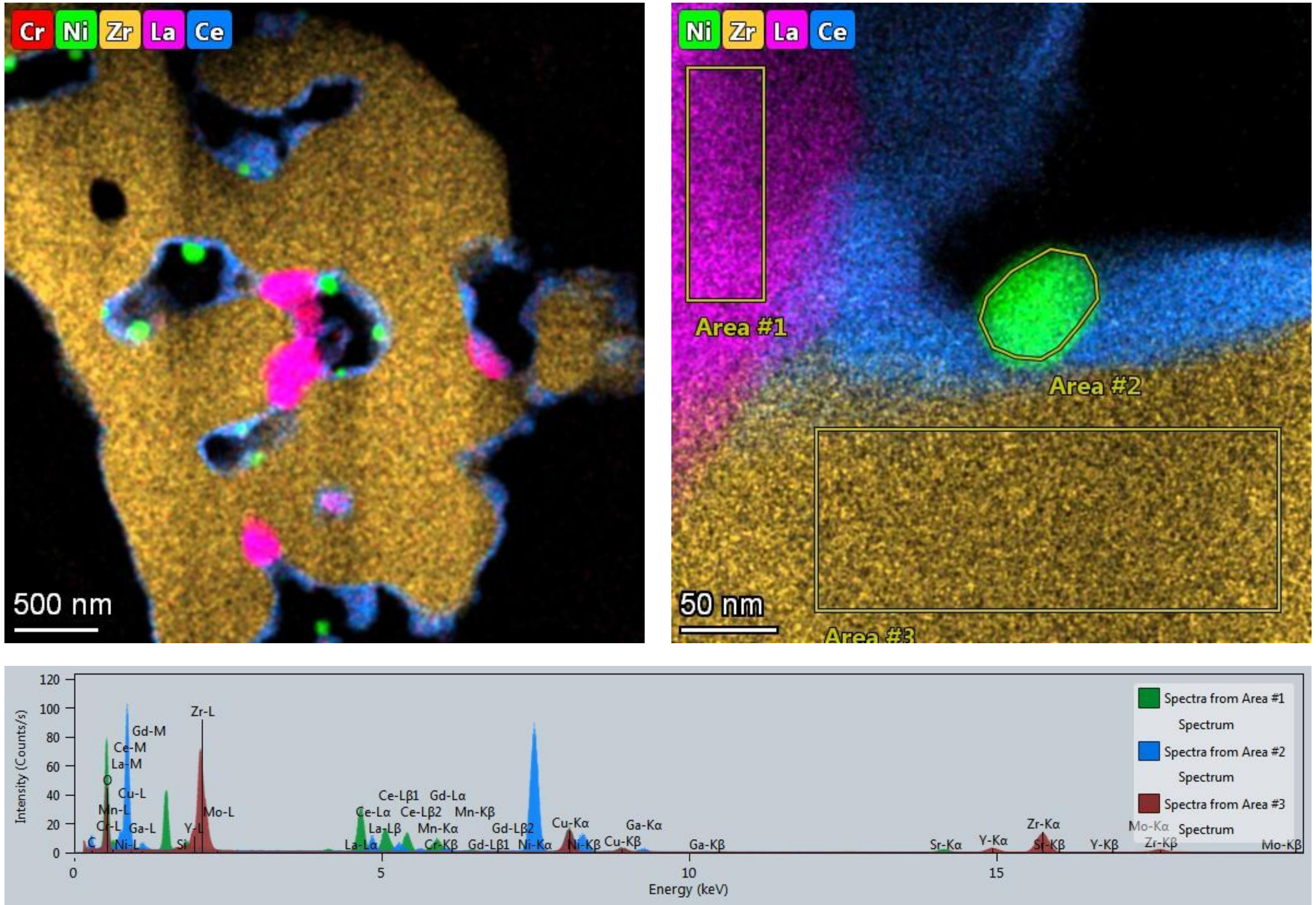



*Photograph of the test rig after operation*




*Raman spectrum of the sample after reaction*

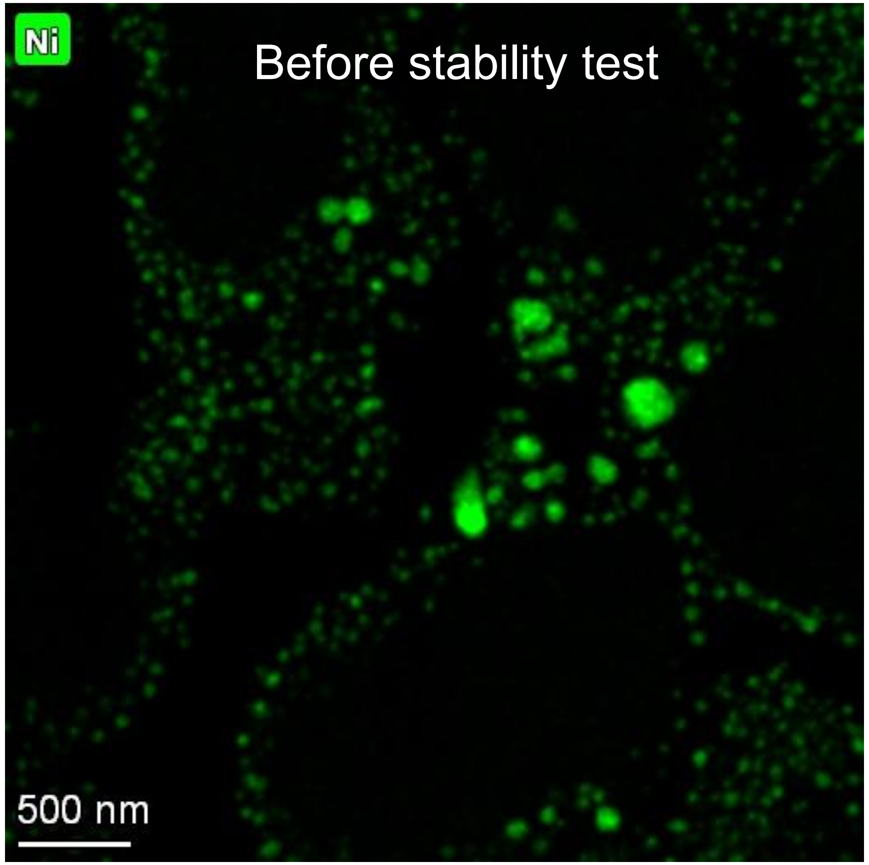
# Morphology post short-term stability test

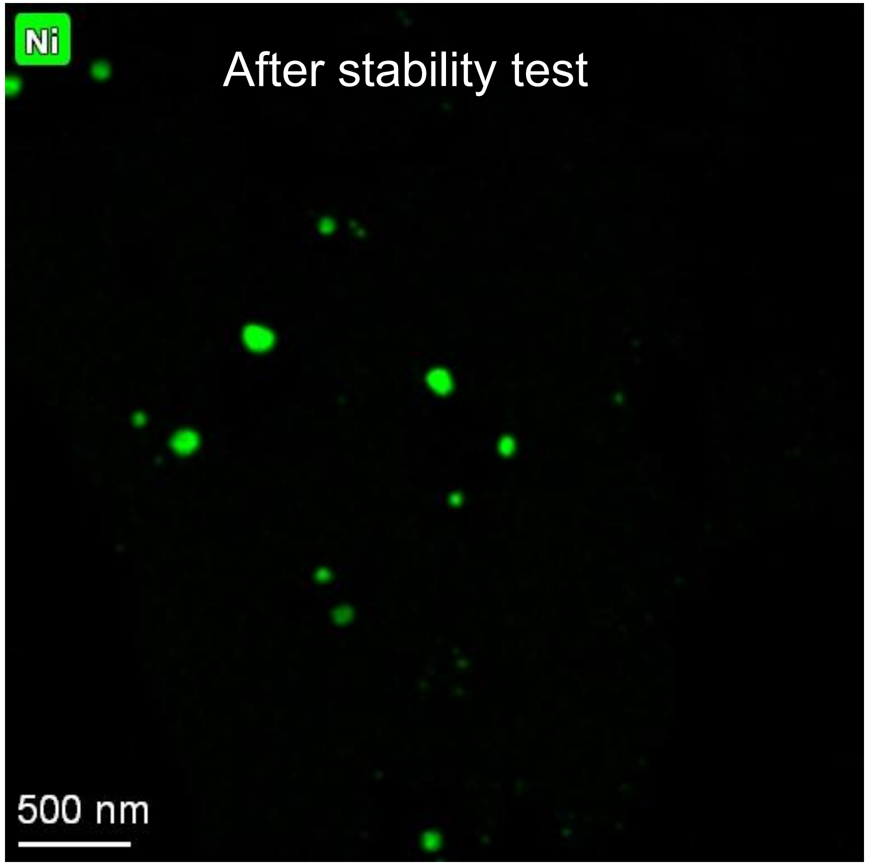



The sample maintained a similar morphology after the reaction.

*HAADF-TEM image and EDX elemental mapping on Ni-CGO infiltrated LSCM sample*

# Morphology




*HAADF-TEM image and EDX elemental mapping on Ni-CGO infiltrated LSCM sample*

- After the reaction, the small Ni particles were no longer observed and were replaced by larger Ni particles.

# Liquid Alternatives: Urea and Ammonia Solutions

## Ammonia Solution ($NH_3 \cdot H_2O$)


- Lower volatility vs $NH_3$
- Safer handling
- Existing infrastructure

**Lower energy density**

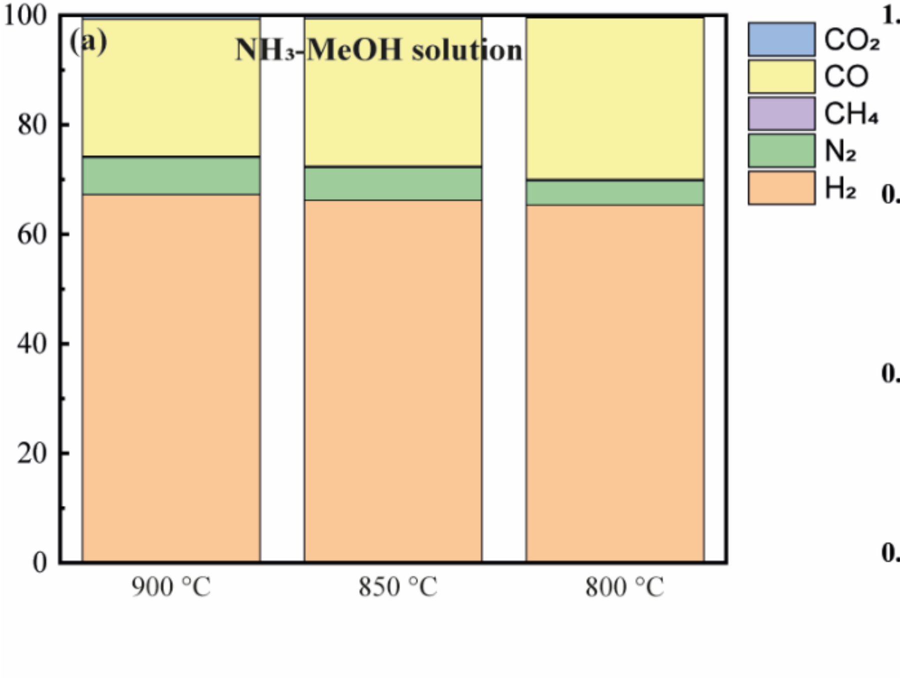
## Urea

- Very safe: stable, non-volatile solid
- Easy global transport
- Simple onboard use, widely accepted
- Can be decomposed to release ammonia

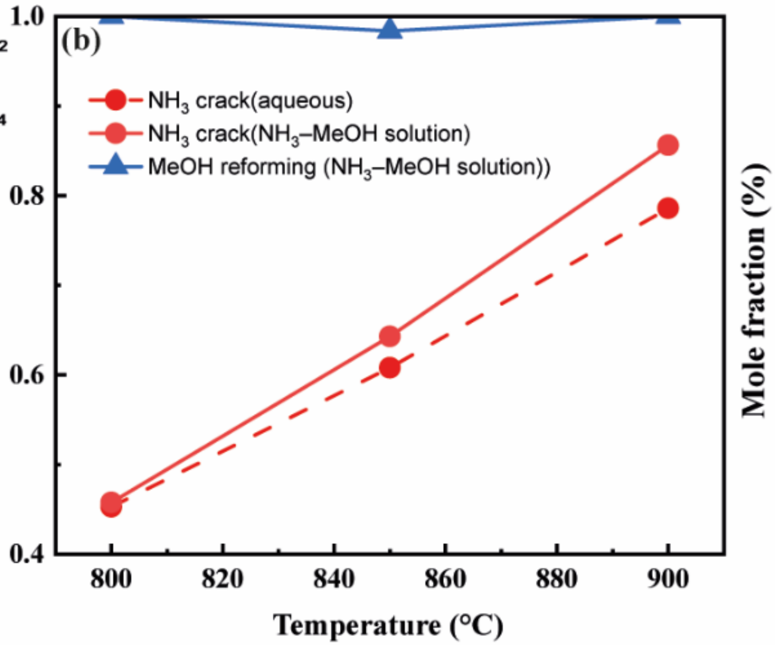
**Risk of deposits / side reactions**

| Fuel (storage form) | Density (kg/L) | Molar Mass (g/mol) | Gravimetric LHV (MJ/kg) | Volumetric LHV (MJ/L) |
|---|---|---|---|---|
| Hydrogen (H2) @ 1 atm | 0.00009 | 2.016 | 120 | 0.01 |
| Hydrogen (H2) @ 700 bar | 0.04 | 2.016 | 120 | 5 |
| Hydrogen (H2) liquid | 0.0708 | 2.016 | 120 | 8.5 |
| Ammonia (NH3) liquid | 0.68 | 17.03 | 18.6 | 12.7 |
| Methanol (CH3OH) liquid | 0.792 | 32.04 | 19.9 | 15.8 |
| Urea (solid, crystalline density) | 1.32 | 60.06 | 9.05 | 11.95 |
| Urea-water solution (50 wt% urea) | 1.14 | | 6 | 6.9 |
| Ammonia solution (33 wt% NH3) | 0.88 | | 6.14 | 5.4 |

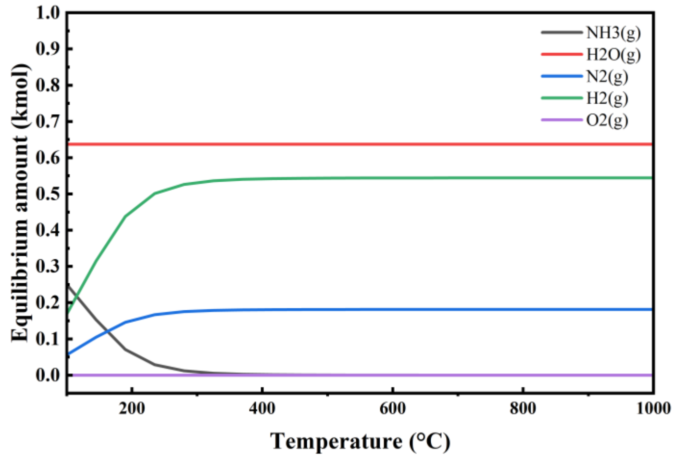
# Alternative ammonia carriers: aqueous ammonia



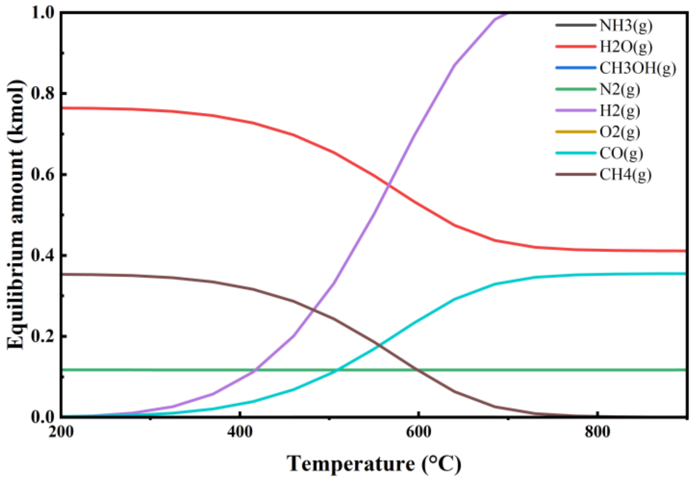

Outlet gas composition for ammonia–methanol solutions




Conversion rate for ammonia crack and methanol reform

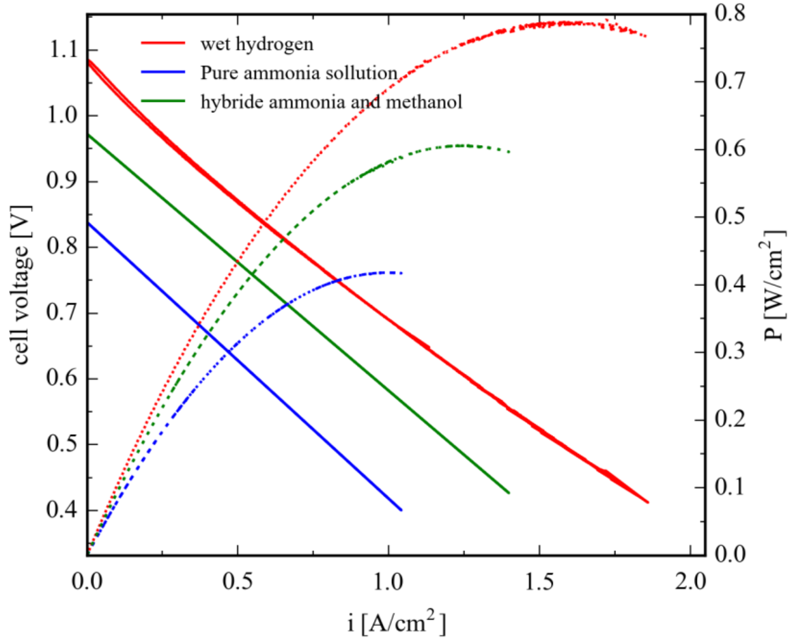



*Simulation results of ammonia aqueous cracking*




Simulation of aqueous ammonia–methanol mixture cracking

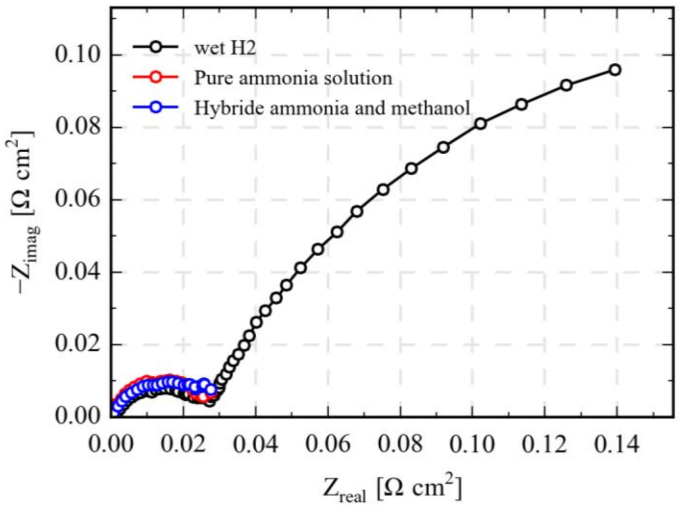
# Alternative ammonia carriers: aqueous ammonia



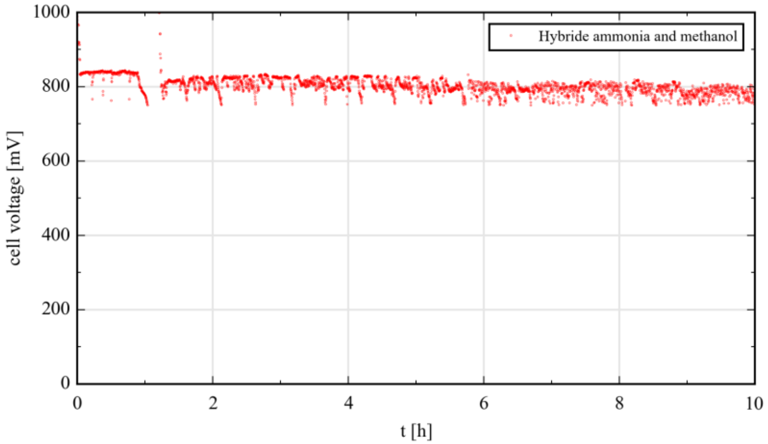

*I–V* and *P–I* curves in different fuels at 900 °C

| Fuel | OCV / V | ASR / Ω cm² |
|---|---|---|
| wet hydrogen | 1.09 | 0.37 |
| Pure ammonia solution | 0.84 | 0.42 |
| hybrid ammonia and methanol | 0.97 | 0.39 |

- Pure ammonia solution---->**relatively low energy density**
- Mixed methanol–ammonia solution---->**potential to improve energy density & usability**




*EIS in different fuels at 900 °C after ohmic correction. Low-frequency data for aqueous ammonia and the mixed solution were not collected due to injection-induced fluctuations.*




*Short-term stability test using a mixed methanol–ammonia solution as fuel at 900 °C.*

# Urea Steam Reforming

**Low Temperature (300-400 ℃)**

**Frequent blockages prevented safe use of the test rig.**

- Primary decomposition:

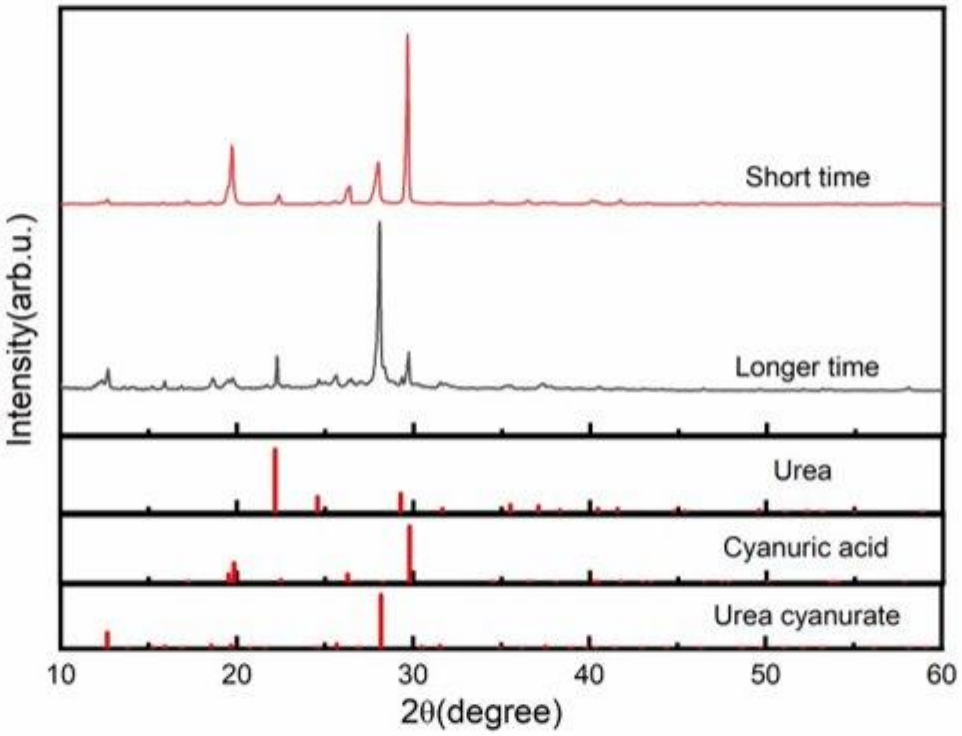
$$CO(NH_2)_2 \rightarrow NH_3 + HNCO$$

- Trimerization of isocyanic acid:

$$3HNCO \rightarrow C_3N_3O_3H_3 \text{ (Cyanuric Acid)}$$

- Supramolecular complex formation:

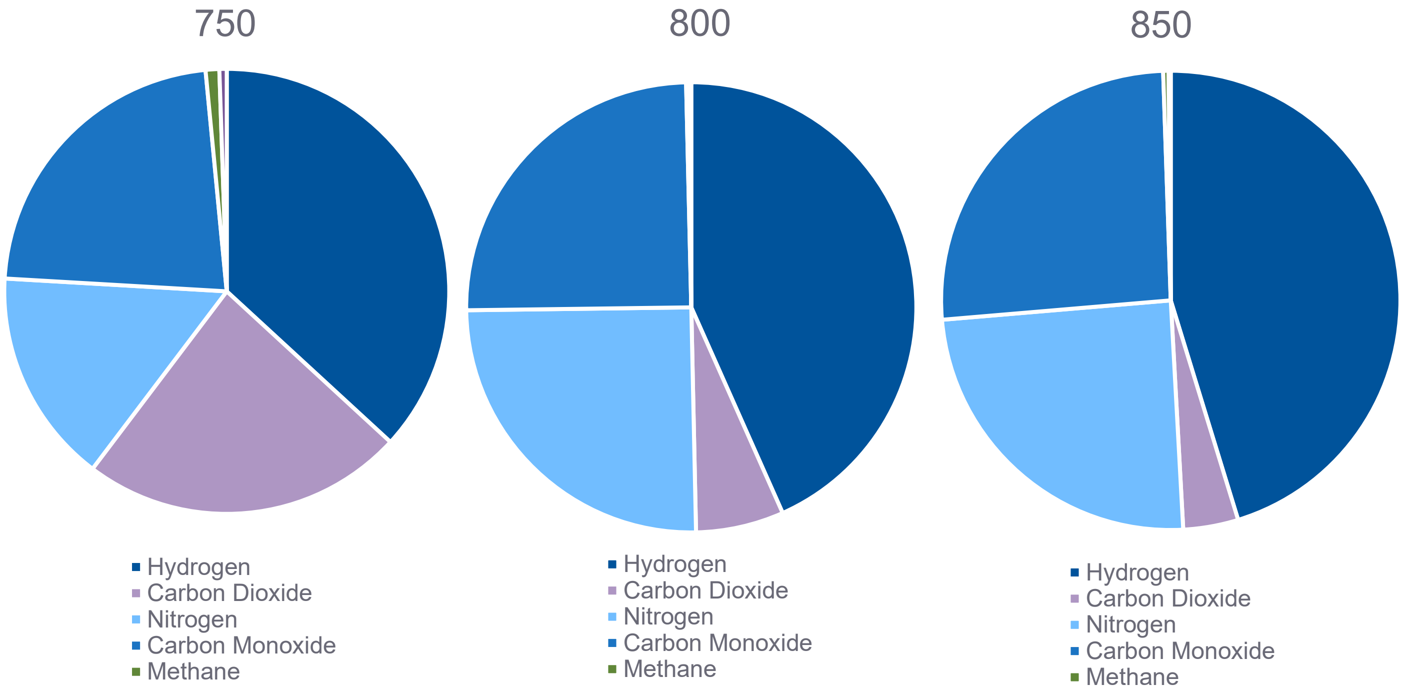
$$\text{Cyanuric Acid} + \text{Urea} \rightleftharpoons \text{Urea–Cyanuric Complex}$$



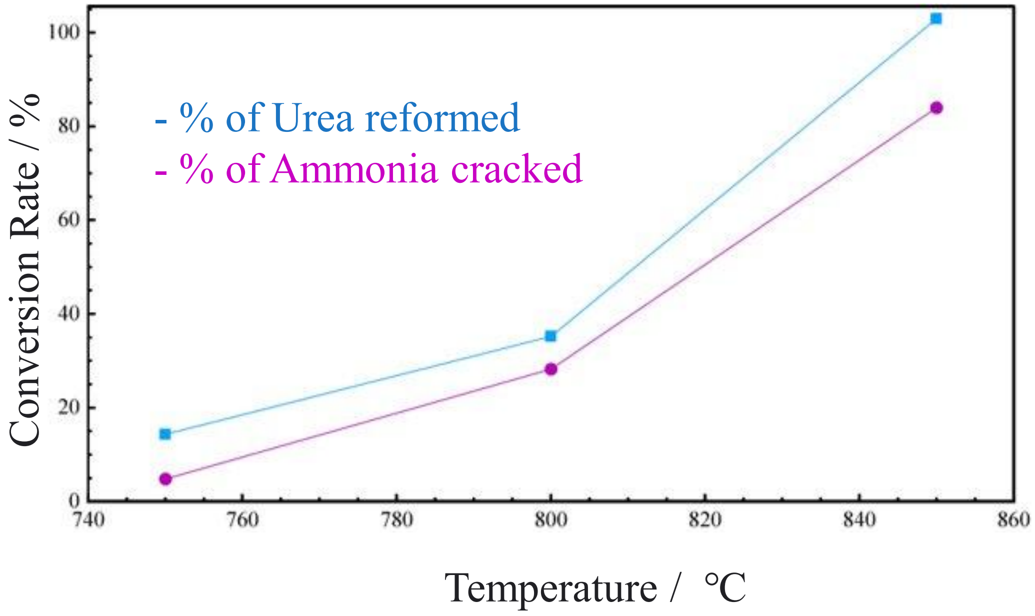

XRD pattern of the solid deposits causing blockage in the test rig.

# Urea Steam Reforming

## High Temperature (750-850℃)




*Gas composition of urea reforming measured by GC ($NH_3$ not included).*




*Conversion rates of urea reforming and ammonia cracking.*

Reverse Water Gas Shift:

$CO_2 + H_2 <-> CO + H_2O$

# Urea as fuel: Cell test results

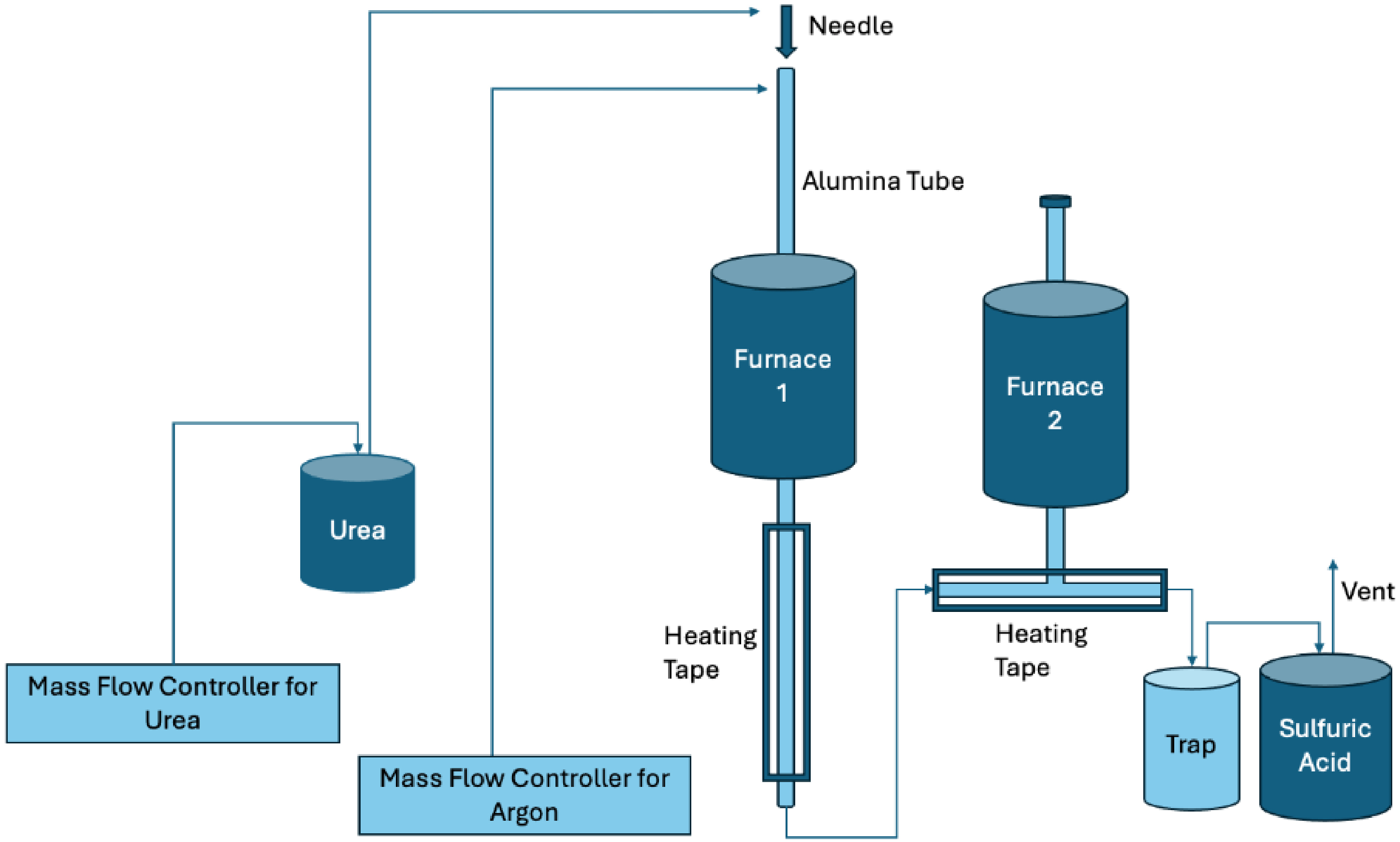
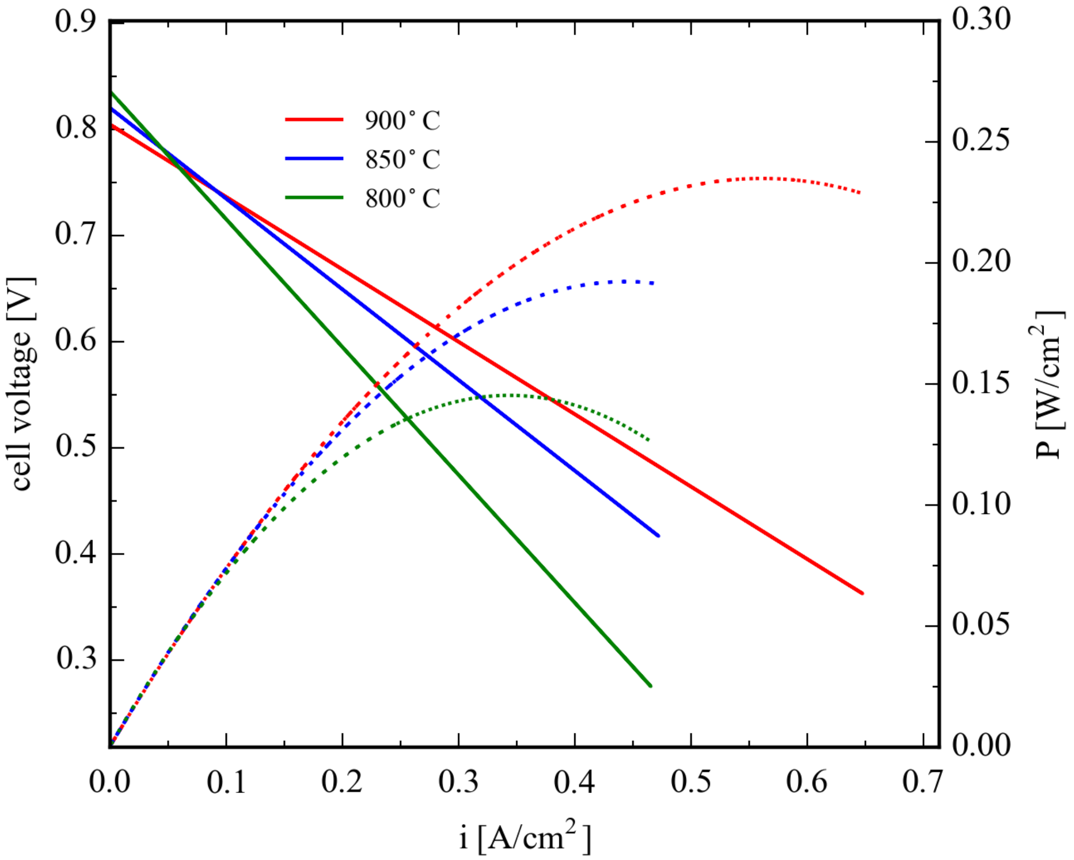
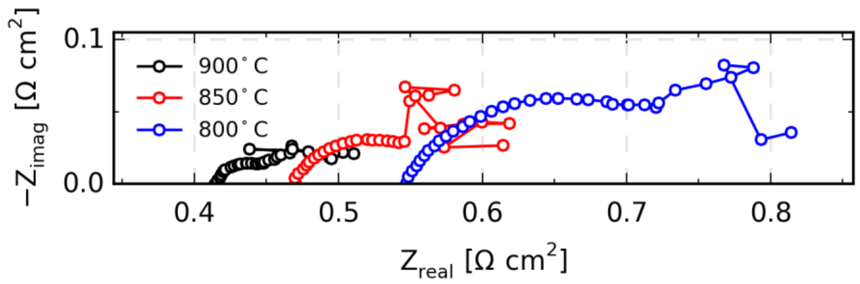



Diagram of the test setup for urea-fuelled SOFC.

# Urea as fuel: Cell test results




*I–V* and *P–I* curves in urea solution at different temperature




*EIS* in urea solution at different temperature

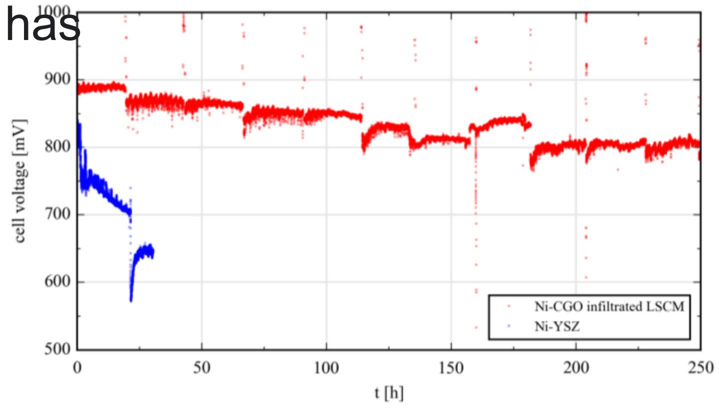
| Temperature | OCV / V | ASR / Ω cm² |
|---|---|---|
| 900 °C | 0.80 | 0.68 |
| 850 °C | 0.81 | 0.84 |
| 800 °C | 0.83 | 1.19 |

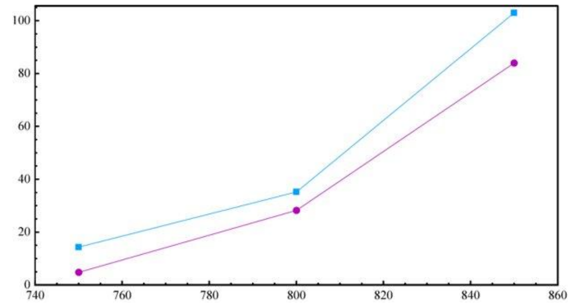
# Conclusion

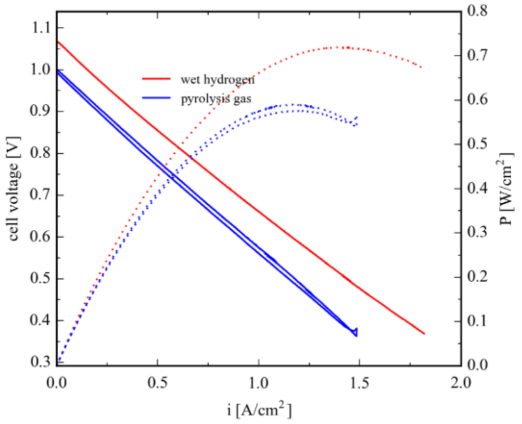
- A **fuel-flexible SOFC platform** based on **Ni-CGO infiltrated LSCM electrodes** has been developed
- The electrode exhibits:
  - **Low charge transfer resistance and high catalytic activity**
  - **Enhanced coking tolerance compared to conventional Ni-YSZ**
  - Robust performance under multiple fuel environments
- Across different fuels:
  - **Methanol:**
    - High performance (**~540 mW·cm⁻² at 900 °C**)
    - Efficient internal reforming to syngas (CO + $H_2$)
  - **Ammonia / Aqueous ammonia:**
    - Demonstrates feasibility of **carbon-free operation**
    - Highlights system-level challenges (safety, storage, handling)
  - **Urea:**
    - Acts as a **safe and practical ammonia carrier**
    - Shows potential for onboard fuel generation despite decomposition complexity

Mechanistically:

- LSCM backbone provides **redox stability and carbon resistance**
- Ni-CGO enhances **electrocatalytic activity and ionic transport**
- Their synergy enables **multi-fuel adaptability**





# Clean hydrogen engine: A unique look into the high-efficiency low-NOx process

## Clean Maritime Assembly 2026

Cliff Dansoh

Advanced Engineering Centre,
University of Brighton

UK National Clean Maritime Research Hub

University of Brighton

UKRI Engineering and Physical Sciences Research Council

Department for Transport

# International Maritime Organisation (IMO) greenhouse gas (GHG) emissions targets

## 2030

- Reduce annual GHG emissions from international shipping by 20%
- Reduce CO2 emissions per transport work by 40%

Dual-Fuel H2-Diesel

## 2040

- Reduce annual GHG emissions from international shipping by 70%

H2-lean operation

## 2050

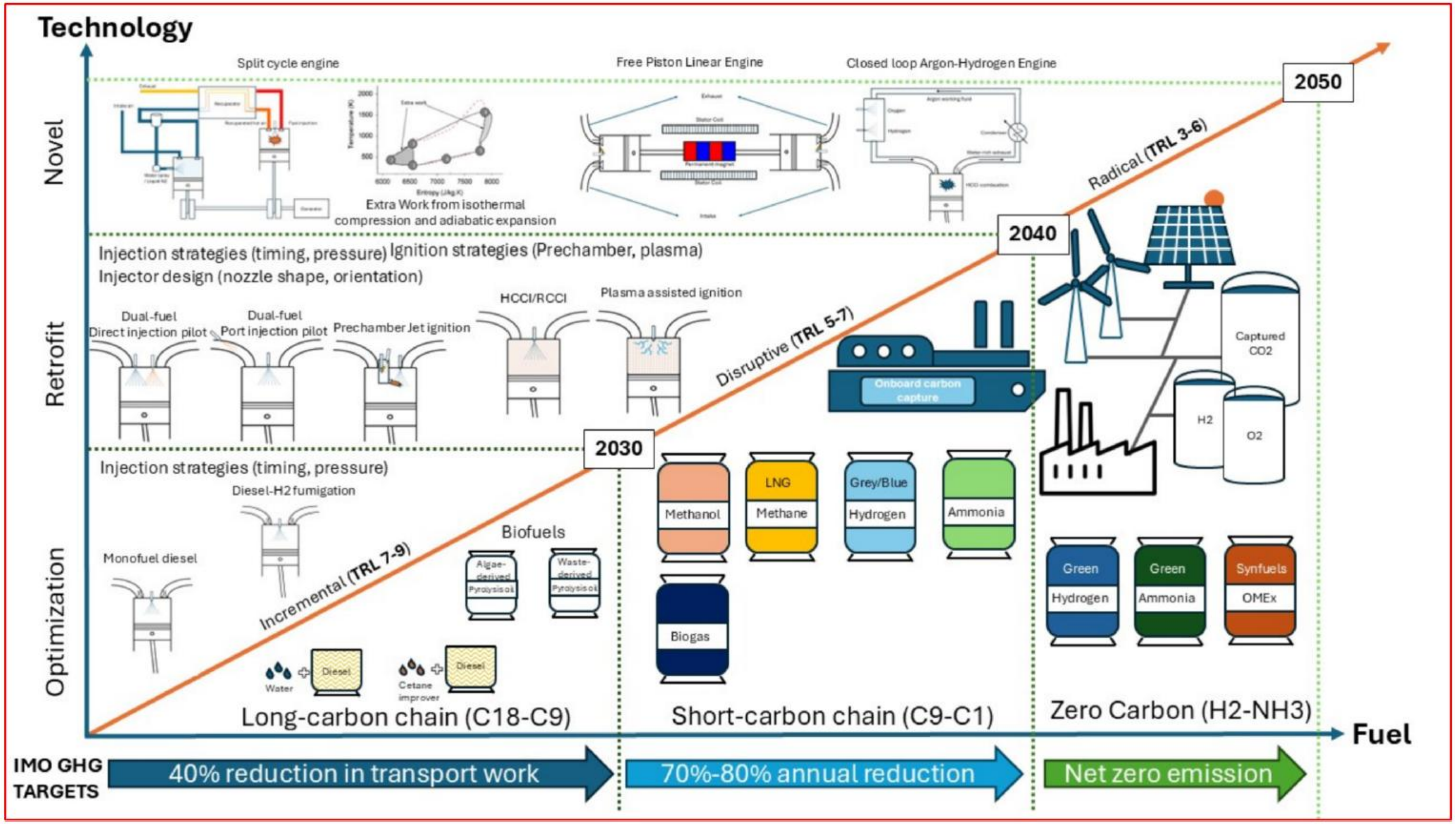
- Net-zero GHG emissions

H2 split cycle

# Overview and Scope of Activities at the UoB

UK National Clean Maritime Research Hub

University of Brighton




- Adoption of progressively more disruptive and novel technologies to reach net-zero 2050
- Moving away from long-carbon chain to zero carbon fuels

Mohd Tamam MQ., Dansoh C, Panesar A. The roadmap to carbon neutrality for the maritime industry: an insight into various routes to decarbonise ship engines, Energy Conversion and Management: X, Volume 27, 2025, 101184, ISSN 2590-1745, https://doi.org/10.1016/j.ecmx.2025.101184.

UKRI Engineering and Physical Sciences Research Council

Department for Transport

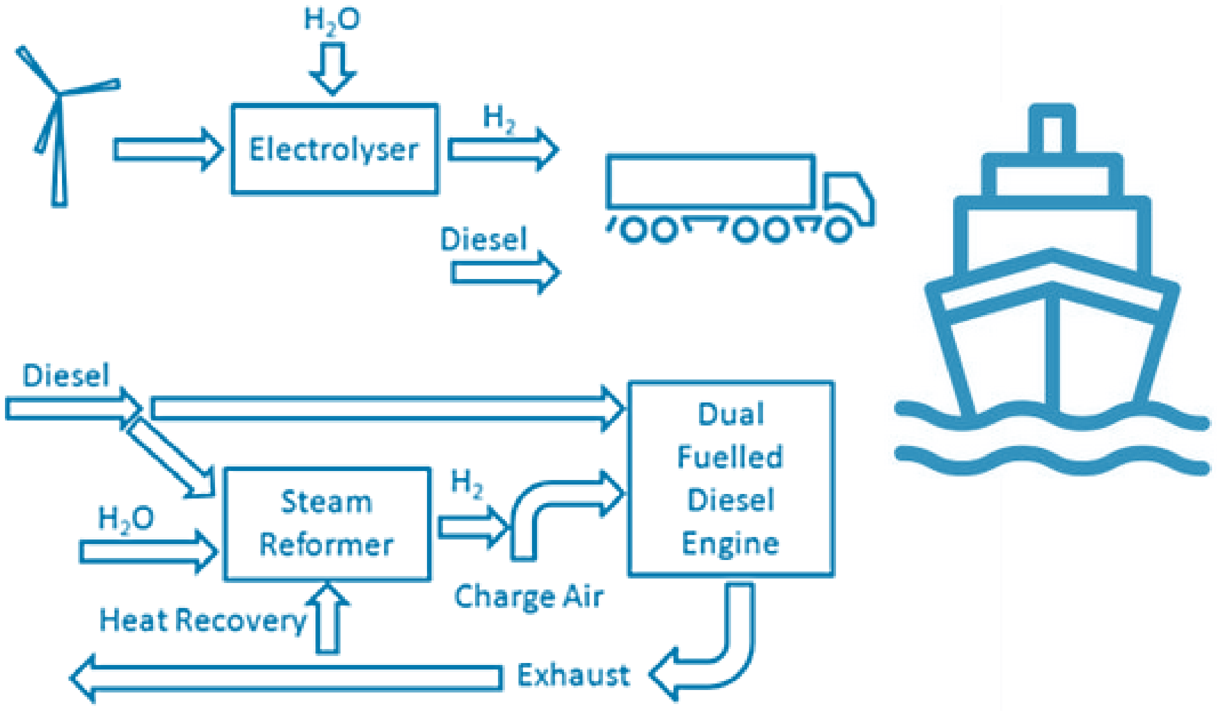
UK National Clean Maritime Research Hub

# A potential route for beyond **2030** via least disruption: Diesel-H2 fumigation onboard dual fuelling

University of Brighton

## To achieve 2030 IMO targets - Retrofit adaptive strategy

- Dual-fuel H2 fumigation-Diesel to establish the maximum decarbonisation and efficiency potential which could be achieved either via onboard steam reforming or bunkering and storage of both fuels separately.
- Incorporation of EGR and injection timing control to enable NOx mitigation
- Syngas fumigation as a hydrogen-carrier pathway enabled by onboard fuel reforming.

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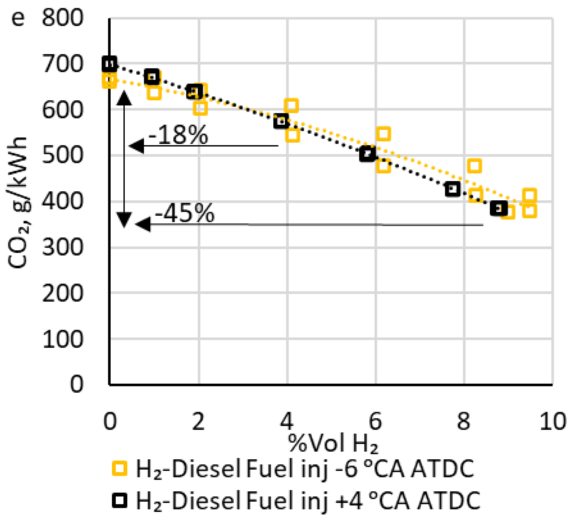
# A potential route for beyond **2030** via least disruption: Diesel-H2 fumigation onboard dual fuelling

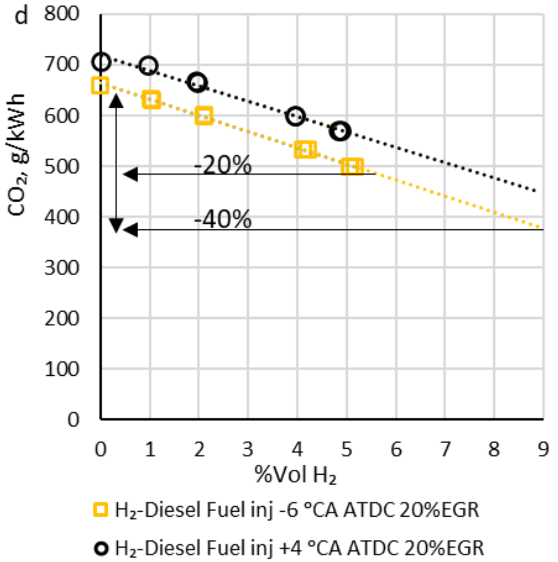
University of Brighton

## Diesel injection timing strategies

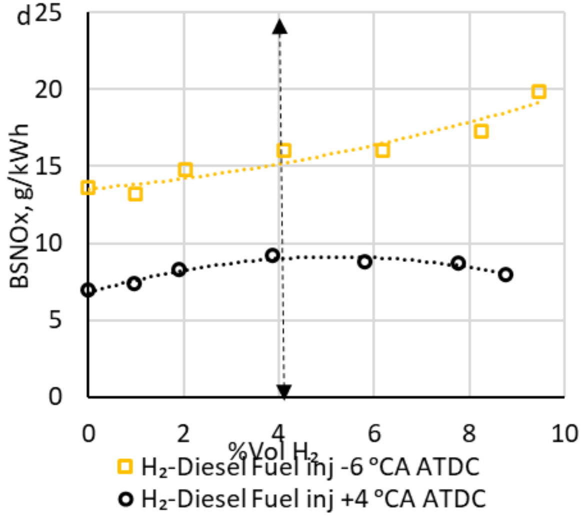
No EGR



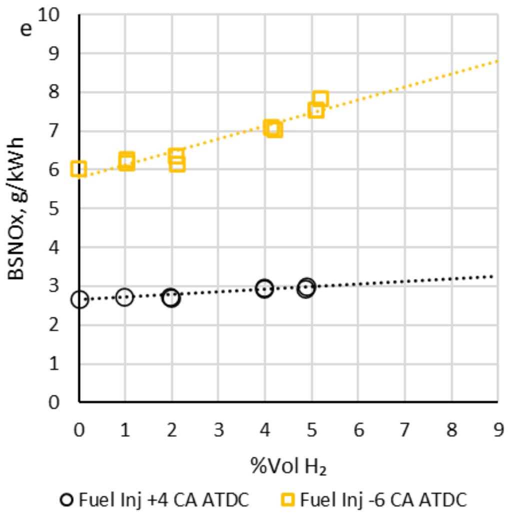

20% EGR




No EGR




20% EGR




With no EGR, at the highest substitution level of 9%vol of H2 fumigation, it is projected that **reductions of up to 45% $CO_2$**

With 20% EGR, up to **40% $CO_2$ reduction**

By comparing advanced no EGR baseline case −6 °CA ATDC early injection case, 20% EGR condition at projected ~8–9 vol% $H_2$ reduces $NO_x$ from 13.6 g/kWh to ~3.1 g/kWh. This indicates **~75–80% reduction in $NO_x$**

- Both EGR and No EGR operating conditions shows that IMO target for 2030 can be achieved by ~9% vol H2. Significant reductions of NOx achieved with retarded injection and EGR

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# A potential route for beyond **2040:** Lean H2 monofuel engine



## To achieve 2030 IMO targets – Lean monofuel H2 engine

Achieving ultra-low NOx emissions with stable combustion and minimal slip through lean operation of H2 engine

### NOx emissions

- Predominantly formed under high combustion temperatures above 1800 K
- Short-term exposure causes respiratory inflammations and increases chances of infections
- Catalyst for acid rain and ground-level O3 formation

### H2 slip

- H2 release decreases tropospheric concentration of OH radicals, atmospheric lifetime of methane.
- It is estimated that its 100-year GWP is 11 ± 5
- H2 warming potency can be at least 3 times more potent in the near term than in the long term.

# A potential route for beyond **2040:** Lean H2 monofuel engine



## Strategies:

- Improving air-fuel mixing by establishing the relationship between turbulent kinetic energy (TKE), in-cylinder fuel mass distribution and combustion characteristics
- Focus on optimisation of injection timing of direct H2 injection and spark timing to pivot from 2030 dual-fuel applications to 2040 monofuel H2 adoption through 3D CFD simulations.
- Experimental work will be conducted to validate the optimal case and expand the datasets by increasing the engine load operating point
- This work shall bridge the gap to 2050 split-cycle by understanding and quantifying the role that TKE plays in H2-air conditions as engine load increases.

# A potential route for beyond **2040:** Lean H2 monofuel engine

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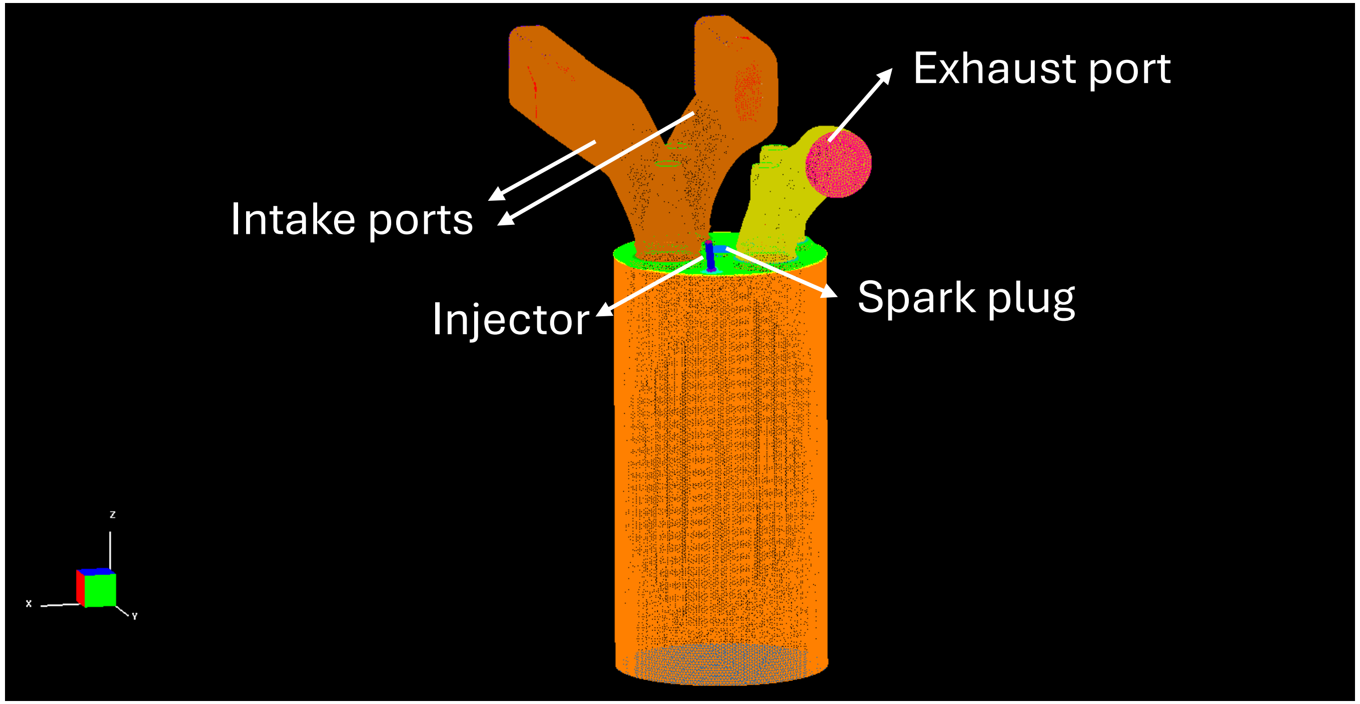
## 3D Model of single cylinder H2 engine




Based on Proteus P300 engine

1. Modelled and Simulated using Realis VECTIS
2. Operating conditions:
   - Intake pressure = 1.8 bar
   - Intake temperature = 40 ˚C
   - Engine speed = 1400 rpm
   - Lambda = 3

Engine specifications

- 131mm Bore
- 158mm Stroke
- 2130cc Swept Volume
- 17.4:1 Compression Ratio

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# A potential route for beyond **2040:** Lean H2 monofuel engine

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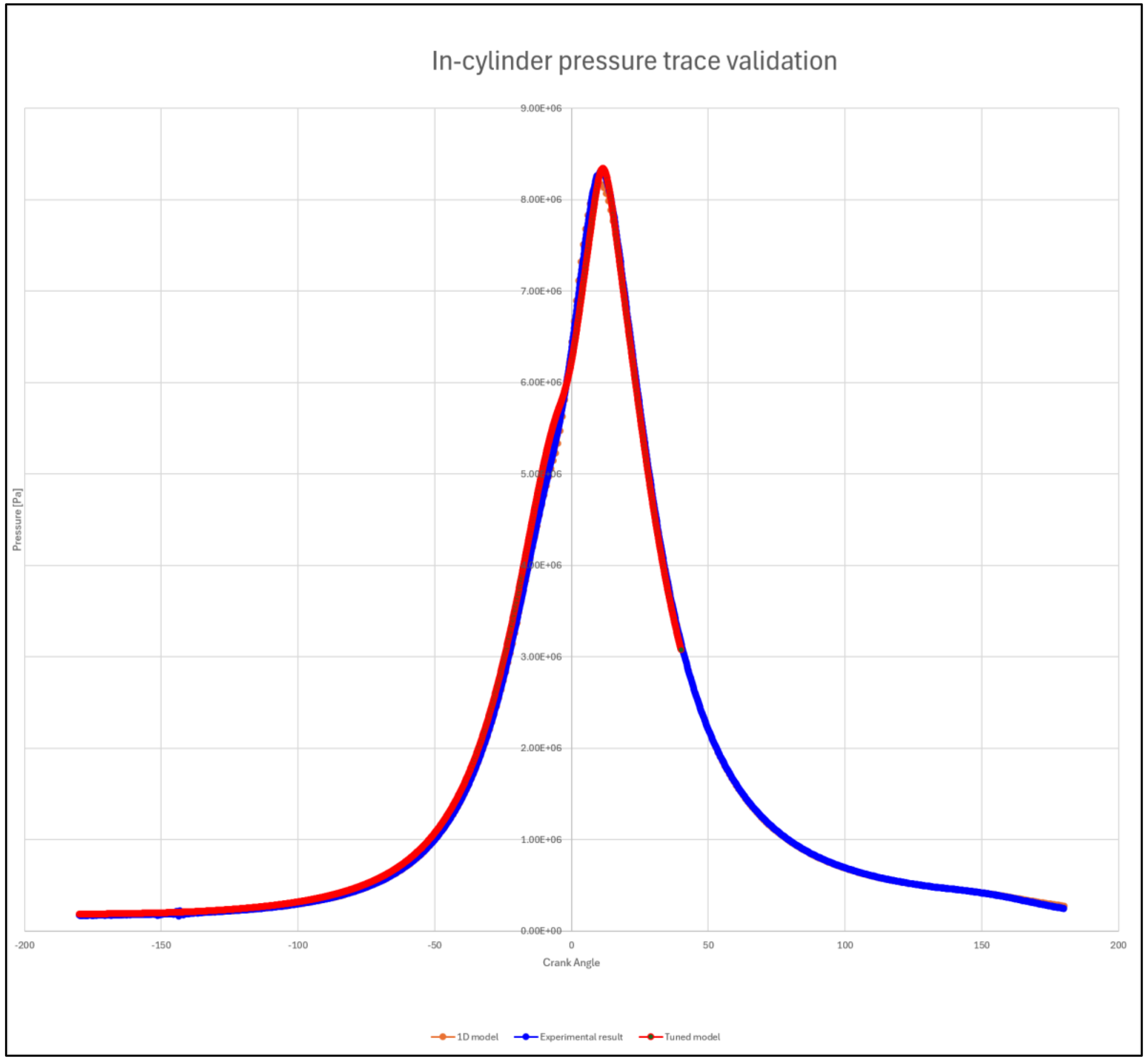
## Model Validation exercise




Operating conditions:

- Intake pressure = 1.8 bar
- Intake temperature = 40˚C
- Engine speed = 1400 rpm
- Lambda = 3
- Spark timing = -12.5 ˚ATDC

## Combustion phasing validation

| Parameter | Simulated Value | Experimental Value | Difference |
|---|---|---|---|
| Peak pressure | 83.42 bar | 83.12 bar | **0.3 bar** |
| Peak pressure crank angle | 11.45 CA ATDC | 10.68 CA ATDC | **0.77 CA** |
| 10% mass fraction burnt crank angle | 1.25 CA ATDC | -0.6 CA ATDC | **1.85 CA** |
| 50% mass fraction burnt crank angle | 8.26 CA ATDC | 7.49 CA ATDC | **0.77 CA** |
| 90% mass fraction burnt crank angle | 19.15 CA ATDC | 19.66 CA ATDC | **0.51 CA** |

# A potential route for beyond **2040:** Lean H2 monofuel engine

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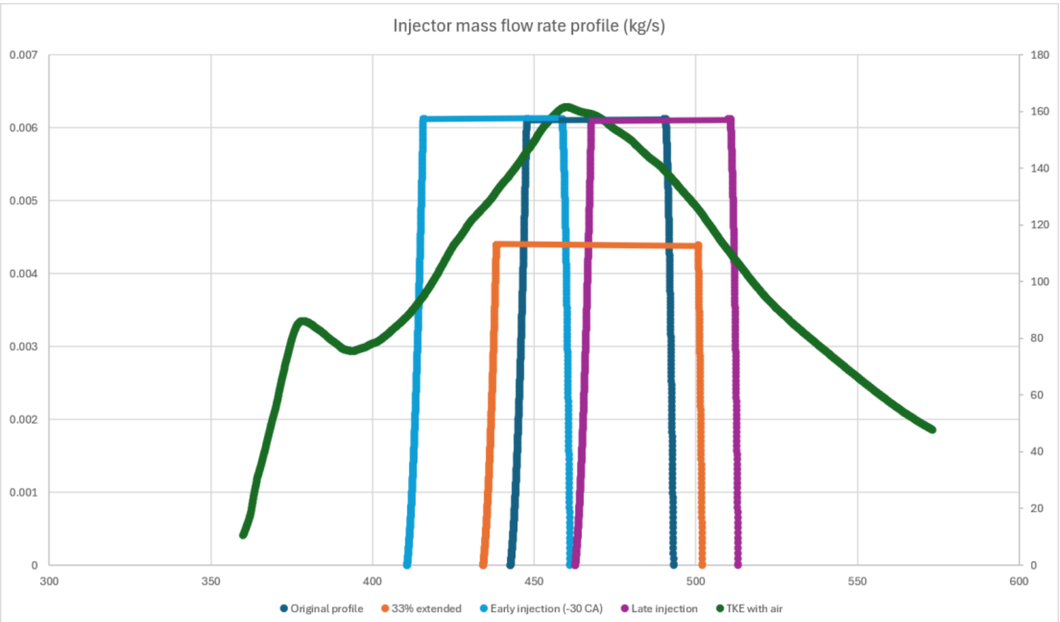
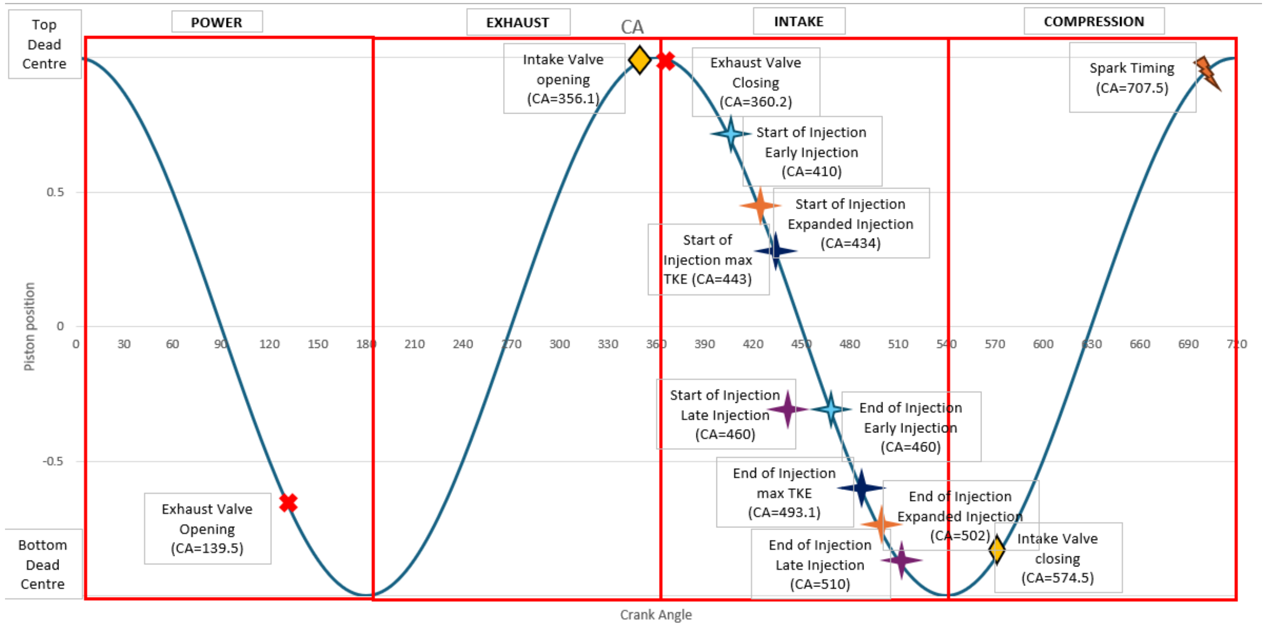
## Injection profiles under examination




## Crank angle convention




Global crank angle convention used in this presentation. 720˚ is Top Dead Centre at the beginning of power stroke

- Motoring run suggests peak turbulent kinetic energy (TKE) was achieved at 480˚ global crank angle (green curve)
- To maintain lean lambda = 3, mass of $H_2$ injected per cycle was maintained constant at 3.383E-05 kg
- 4 different injection regimes were examined:
  1. Early injection (injection ends at peak TKE) - start of injection at 410˚ to 460˚
  2. Injection at peak TKE (peak TKE during injection) - start of injection at 442˚ to 492˚
  3. Late injection (injection starts at peak TKE) - start of injection at 460˚ to 510˚
  4. Expanded injection (injection duration extended 33%) to start of injection at 434˚ to 502˚

### Engine parameters

| | |
|---|---|
| Spark timing | 707.5 CA |
| Intake valve opening | 356 CA |
| Intake valve closing | 574.5 CA |
| Exhaust valve opening | 139.5 CA |
| Exhaust valve closing | 360.2 CA |

# A potential route for beyond **2040:** Lean H2 monofuel engine

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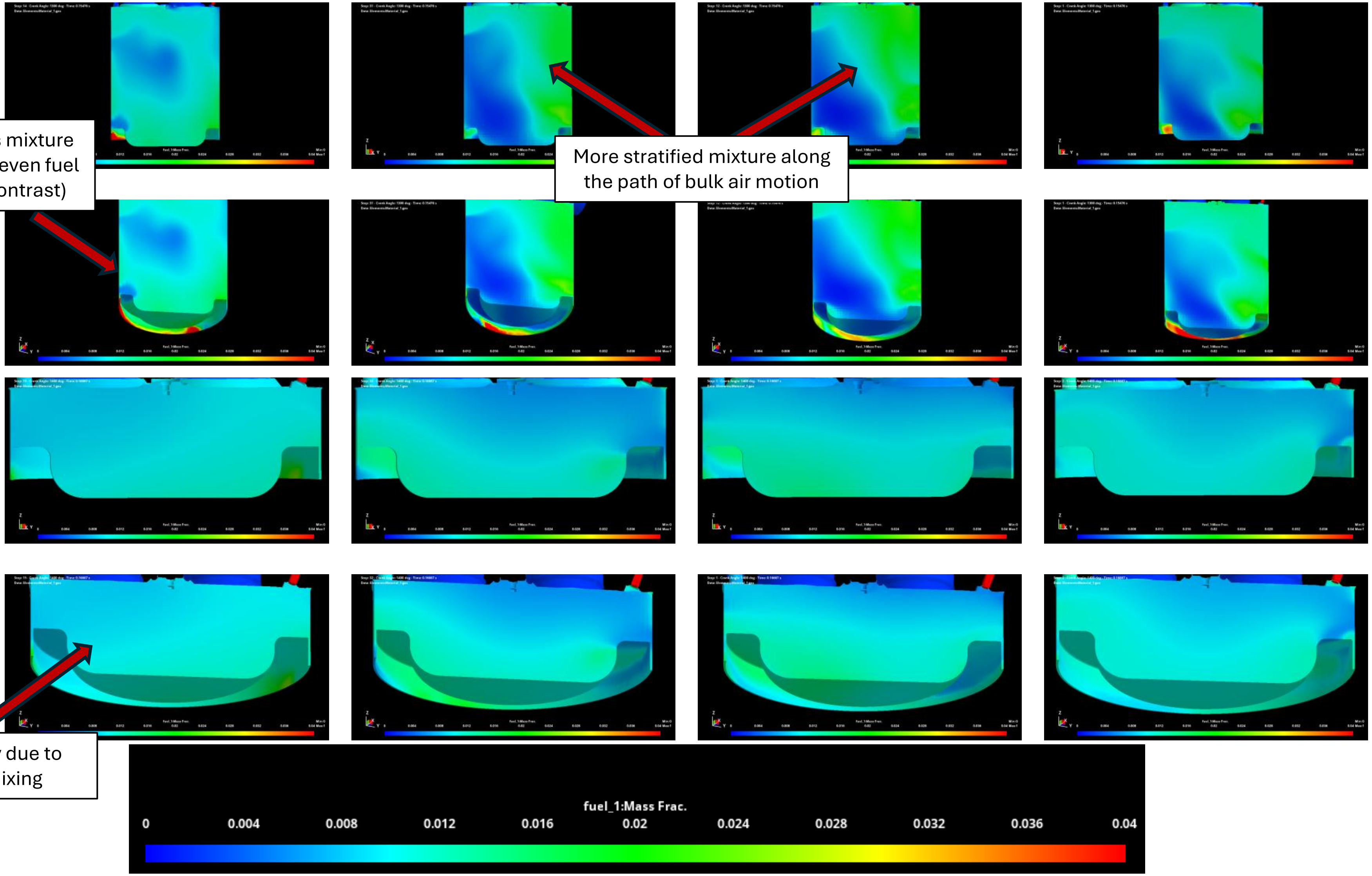
Crank angle | Early injection | Injection at max TKE | Late injection | Expanded injection

580˚ (-140˚ATDC)

680˚ (-40˚ATDC)



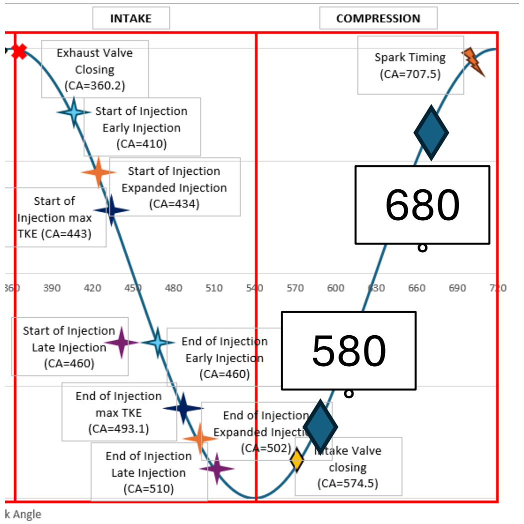

More homogeneous mixture indicated by a more even fuel distribution (less contrast)

More stratified mixture along the path of bulk air motion

High homogeneity due to more time for mixing

- Early injection results in more homogeneity in the cylinder but higher concentration along the crevices
- Delaying injection would increase stratification with less hydrogen trapped in the crevices

- Progressively more homogeneous mixture as the piston gets nearer to TDC
- Early injection has more time for mixing, resulting in overall highest homogeneity compared to others



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# A potential route for beyond **2040:** Lean H2 monofuel engine

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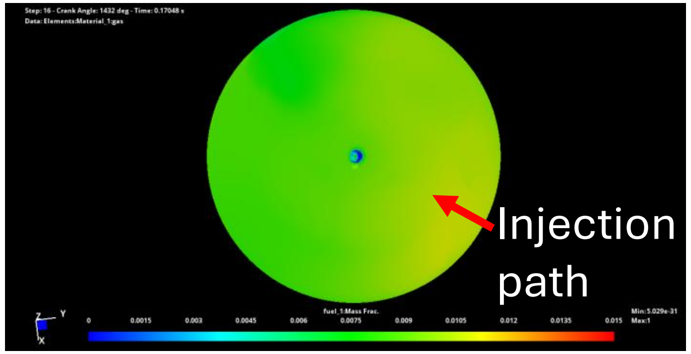
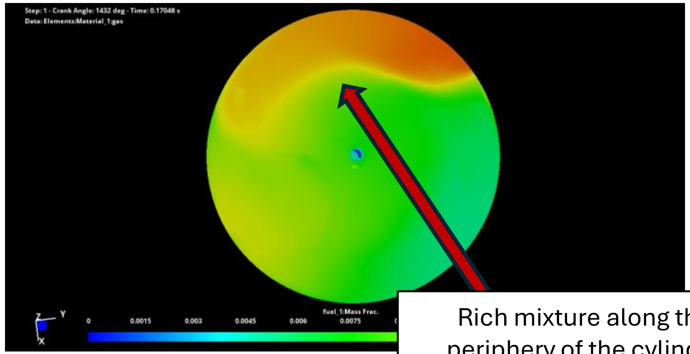
## At crank angle 712˚ (-8˚ ATDC)

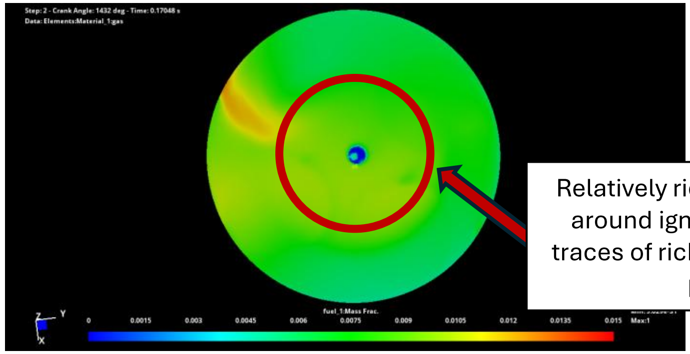
### Early injection



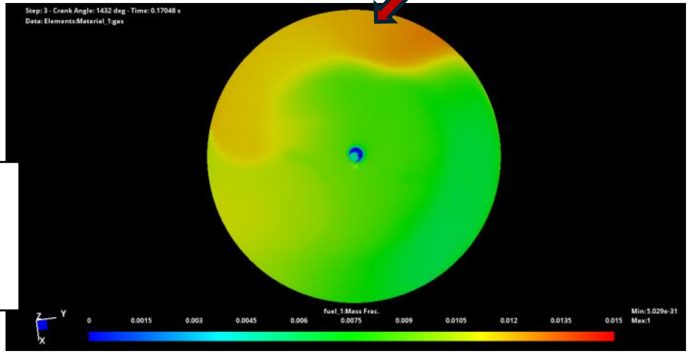

### Injection at max TKE



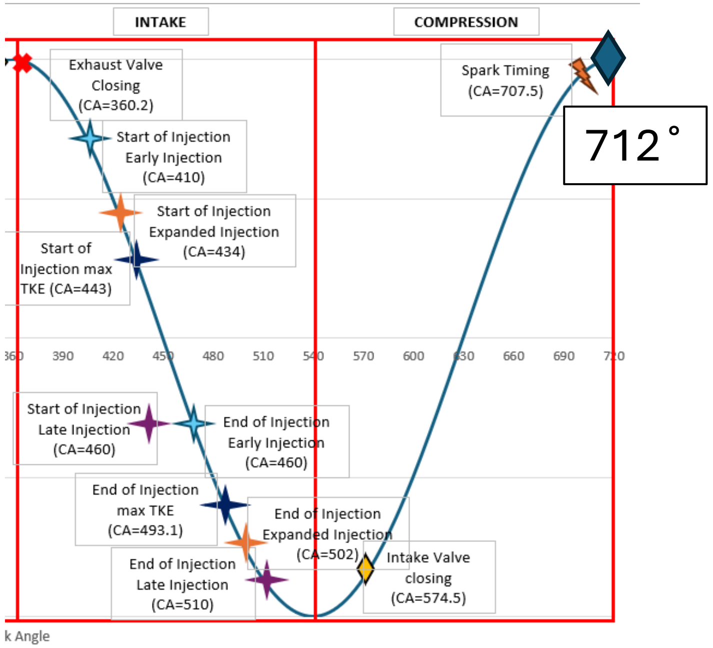

### Late injection




### Expanded injection



- Late injection showed most stratified concentration around spark region.
- Injection regimes that capitalises on peak TKE showed richer region in the direction of injection; this shows the effect bulk air motion has on spreading air-fuel mix to the piston peripheries





*The spectrum range is amplified to accentuate different mass fraction distribution

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# A potential route for beyond **2040:** Lean H2 monofuel engine

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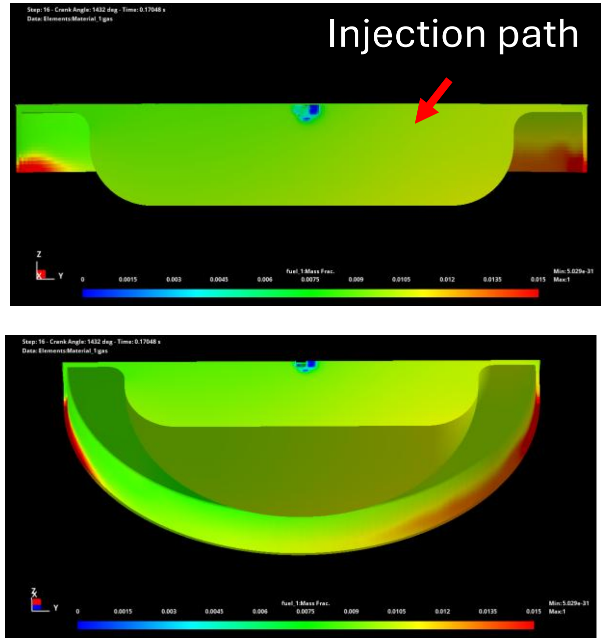
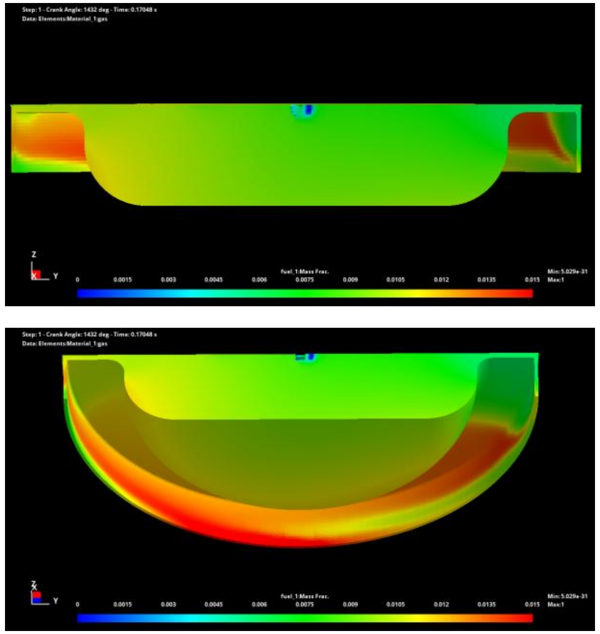
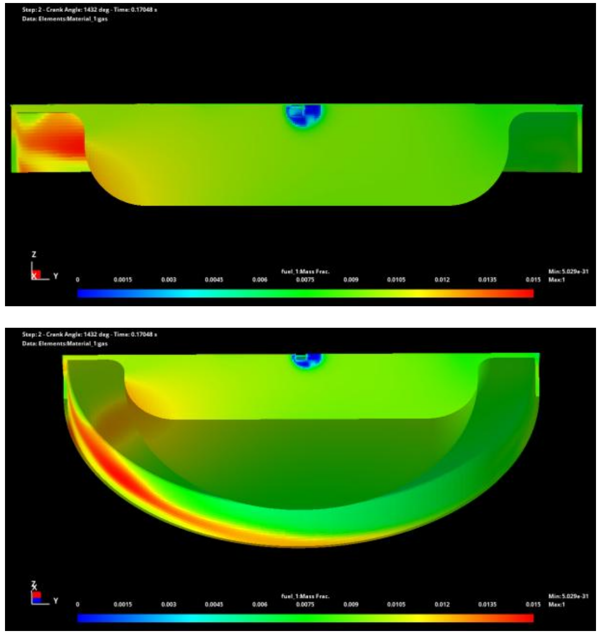
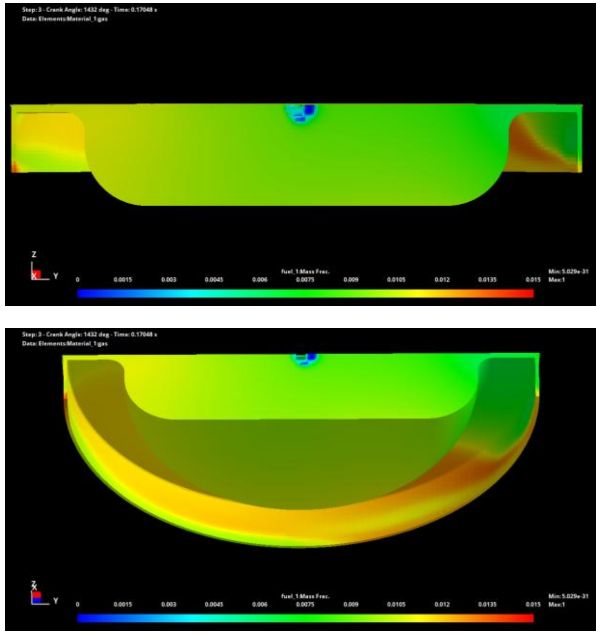
## At crank angle 712° (-8° ATDC)

| Early injection | Injection at max TKE | Late injection | Expanded injection |
|---|---|---|---|
|   |  |  |  |


- Between injection at max TKE and expanded injection regimes, the latter showed less pronounced H2 concentration inside the piston crevice
- Due to less time for mixing, late injection displayed a clear trace of injection residuals along injection path (inside piston bowl and crevice area in the path of injection)

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# A potential route for beyond **2040:** Lean H2 monofuel engine

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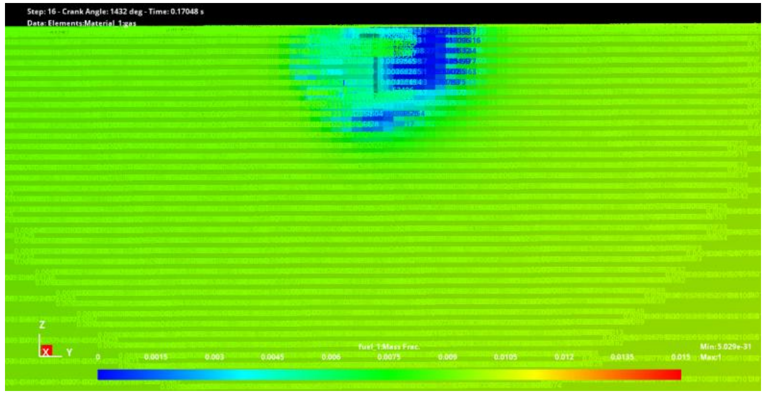
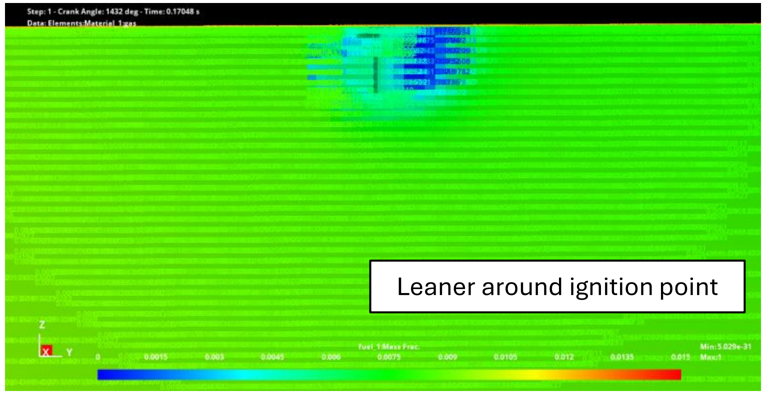
## At crank angle 712° (-8° ATDC)

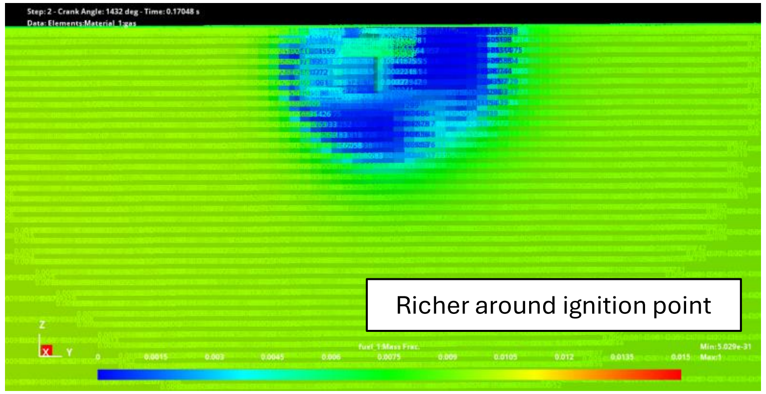
### Early injection



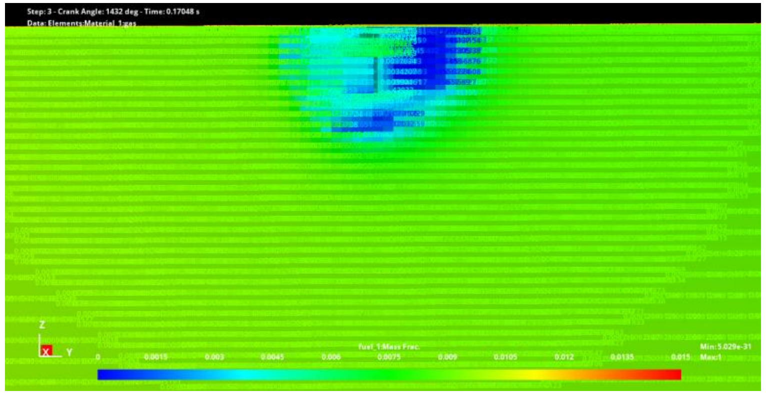
### Injection at max TKE

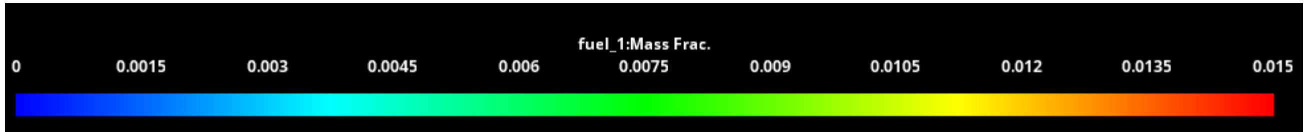



### Late injection

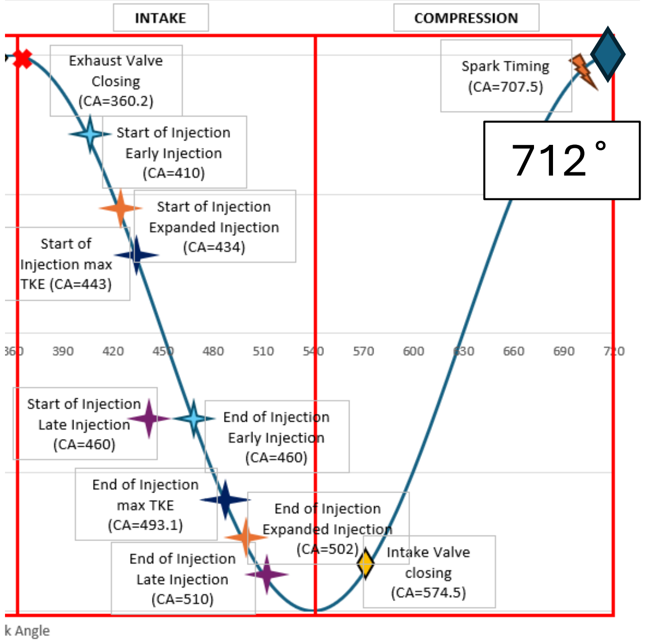



### Expanded injection





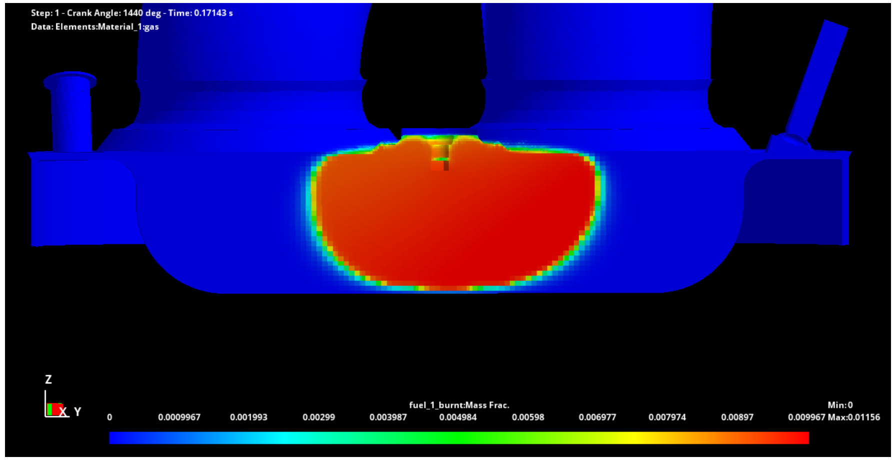

- Closing in on the spark region, late injection showed much richer and stratified mixture.
- This caused faster propagation of flame front and initial kernel growth
- Although overall early injection showed much higher mixing, around the spark region Injection at max TKE shown a more even mixing.



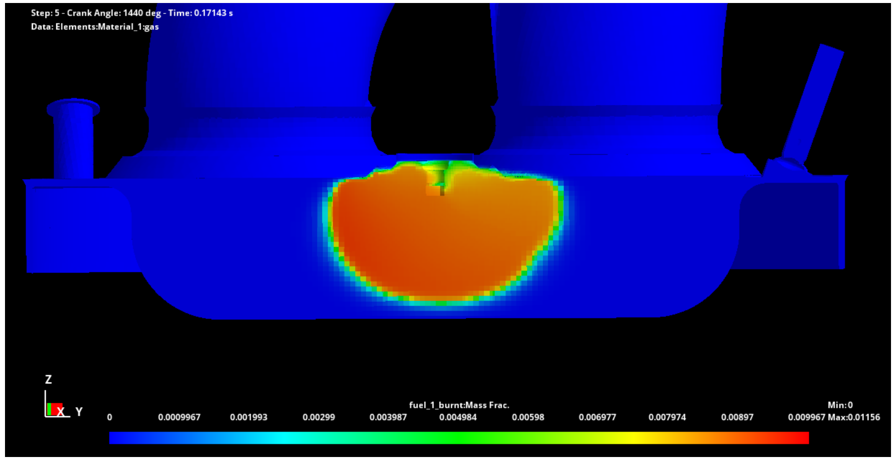
# A potential route for beyond **2040:** Lean H2 monofuel engine

## At TDC

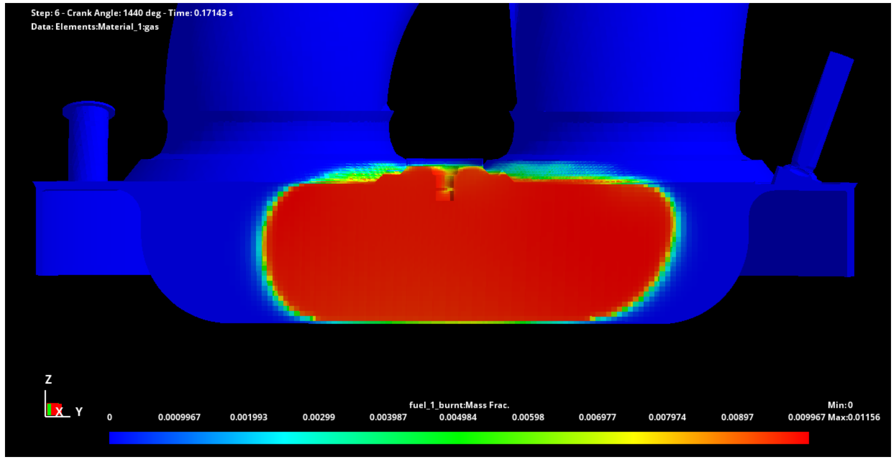
### Early injection



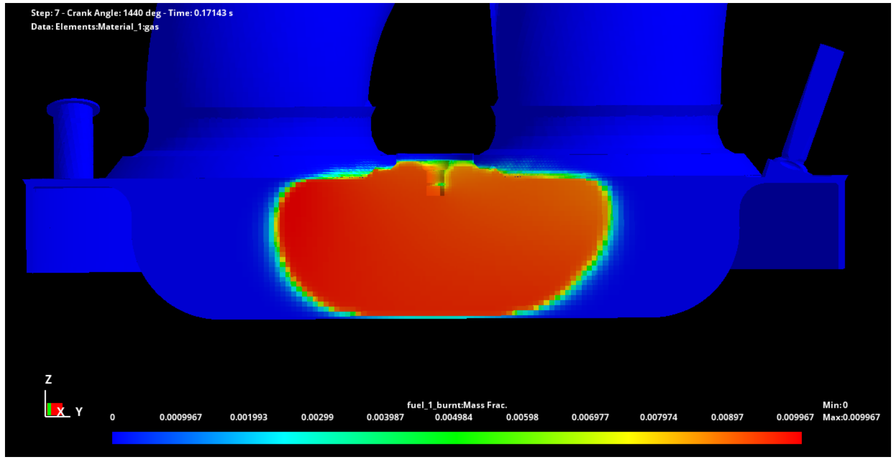

### Injection at max TKE



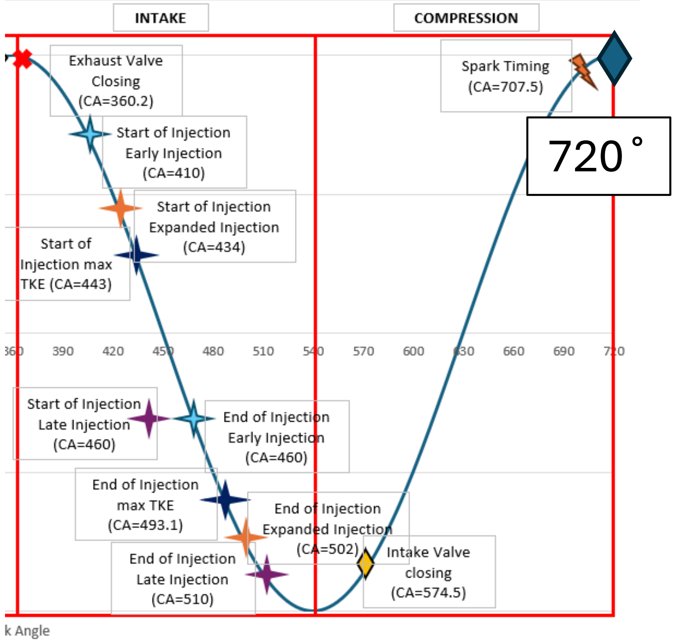

### Late injection




### Expanded injection




- A clear relationship can be established between stratification and flame growth, with late injection showing fastest flame growth



# A potential route for beyond **2040:** Lean H2 monofuel engine

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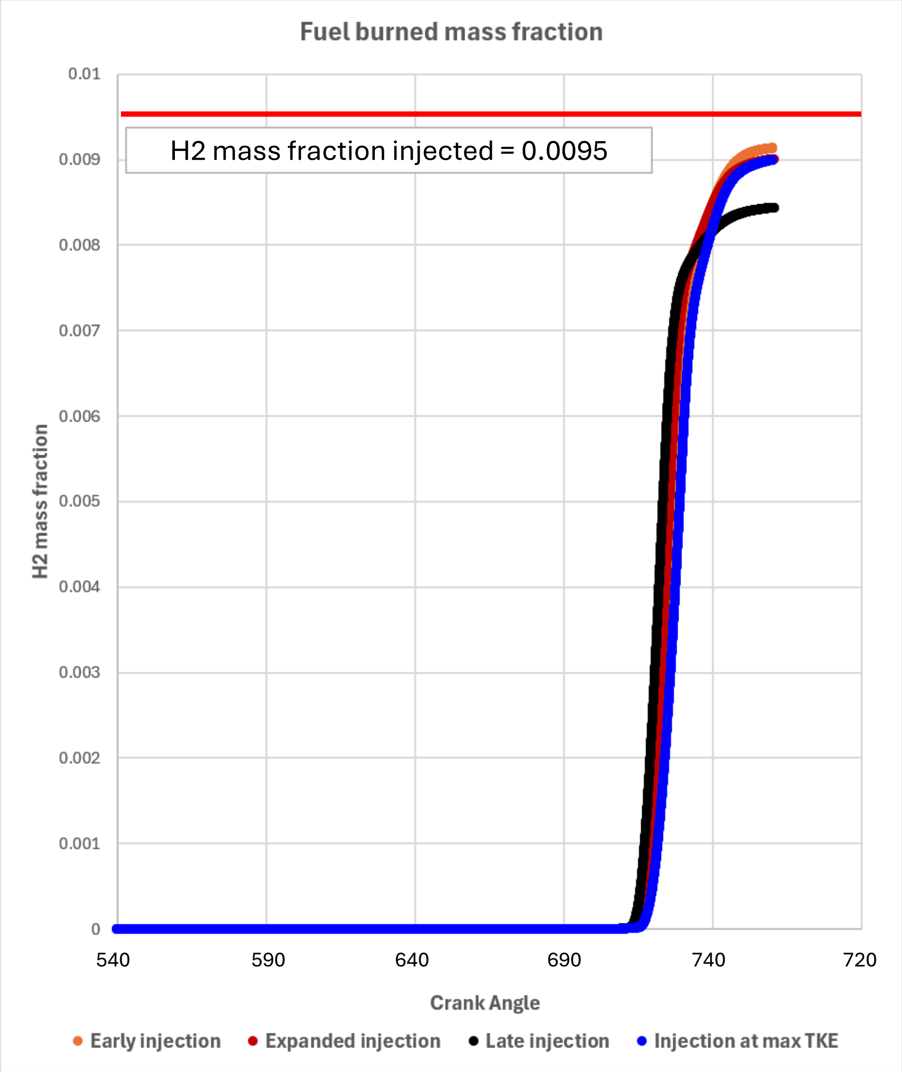


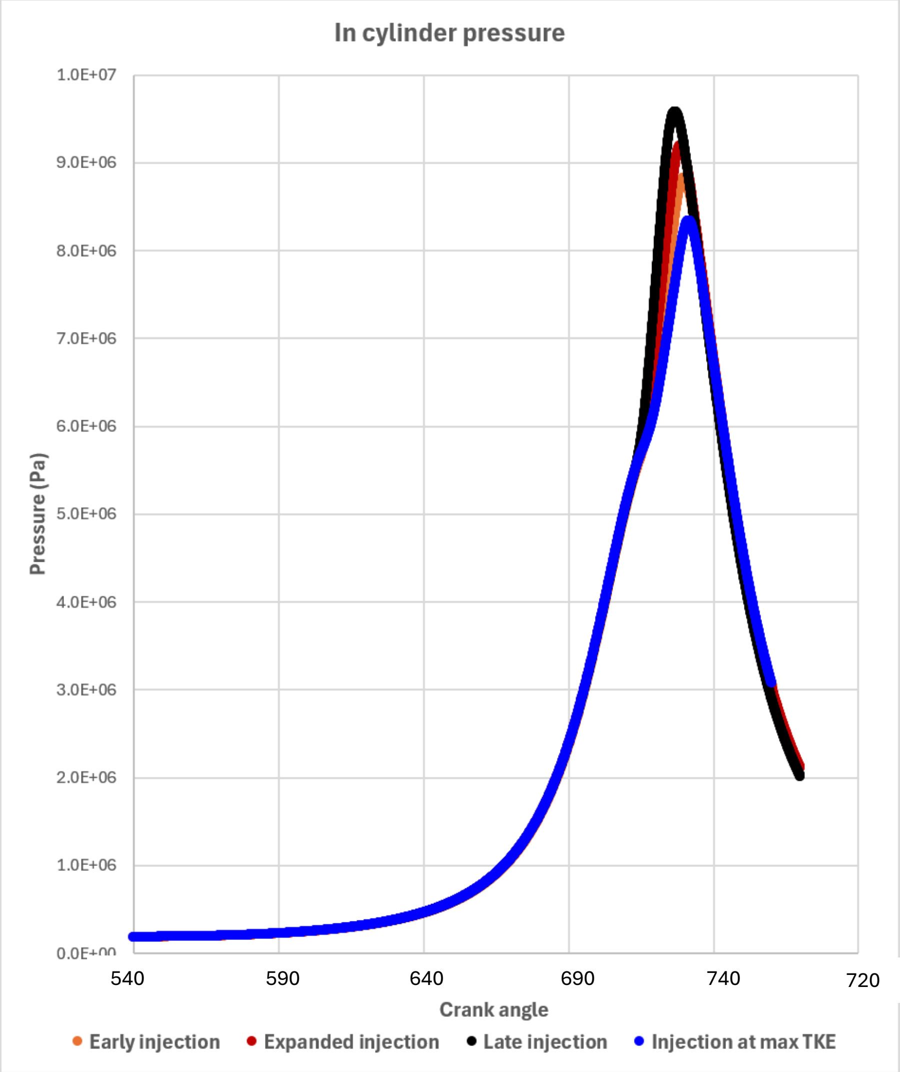


- Faster flame growth observed from late injection resulted in significantly faster combustion phasing compared to other regimes but tails off quite early and resulted in lower combustion efficiency (higher slip).
- This has also resulted in highest peak pressure of 9.57 MPa achieved at 6.85˚ ATDC.
- On the other hand, early injection showed highest combustion efficiency at 0.00915 mass fraction burned at 40˚ ATDC followed by the two TKE bound injection regimes.
- Expanded injection struck a good balance between combustion efficiency and peak pressure

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# A potential route for beyond **2040:** Lean H2 monofuel engine

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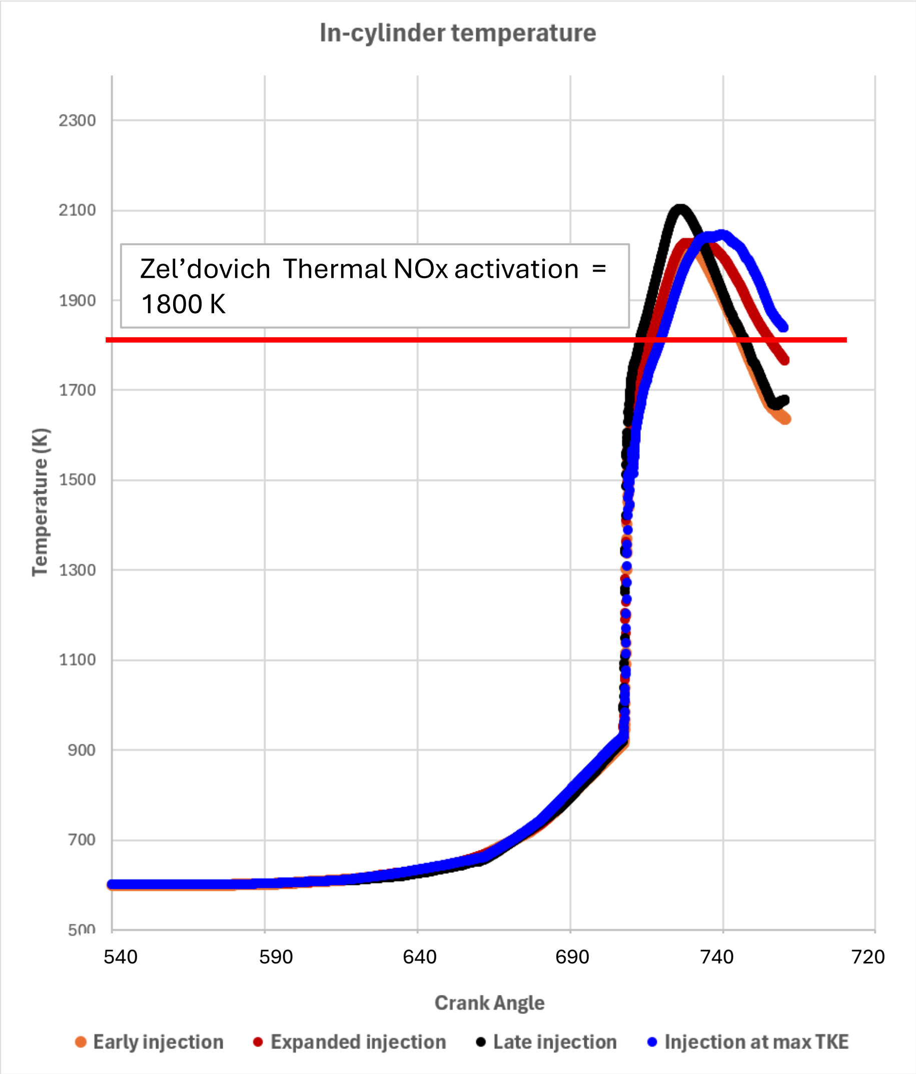


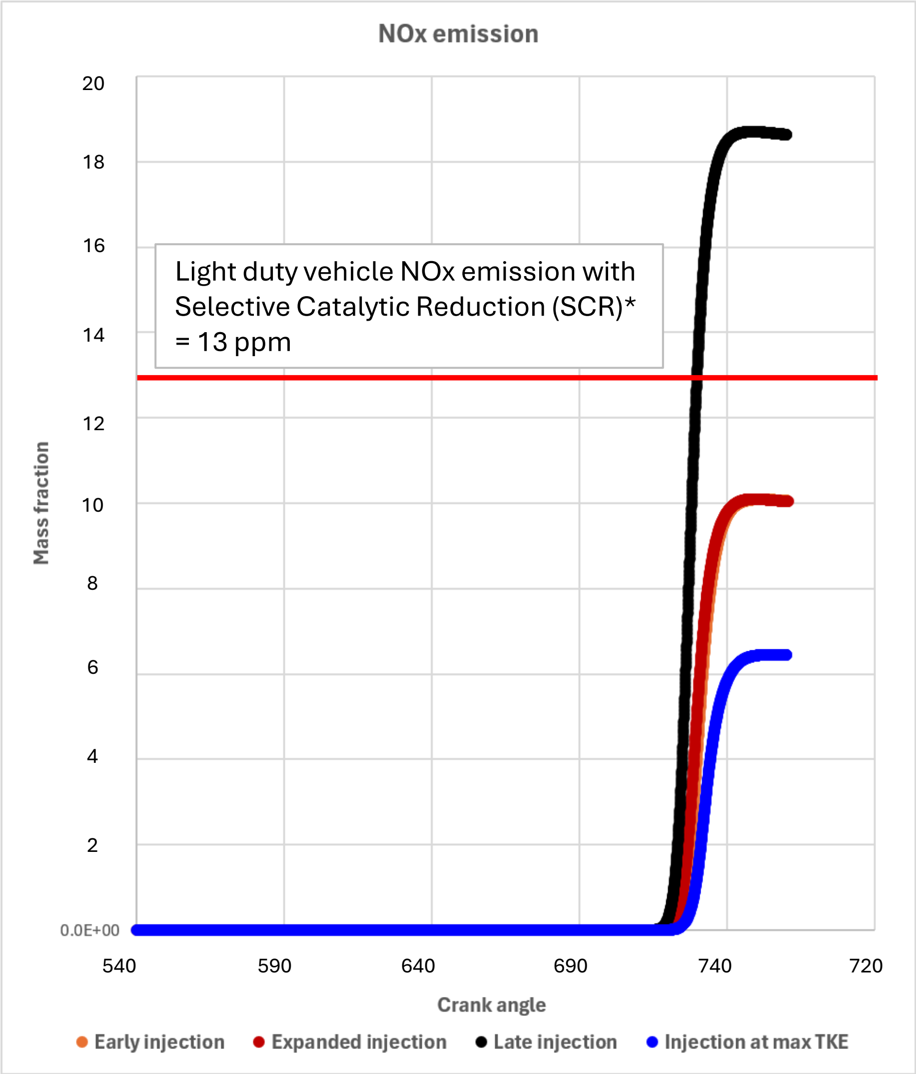


- Higher combustion temperatures for late injection significantly raises NOx emissions
- Start of injection earlier than peak TKE (expanded and early injection) and delaying injection has shown in a relatively richer concentration around spark region which also influences rise rate in temperature.
- This in turn causes NOx emissions to increase when compared to peak TKE injection regime.
- Nonetheless, despite emitting the highest NOx, late injection emitted 18.6 ppm

*Franzetti, J., Selleri, T., Fonseca-González, N. *et al.* Assessment of NOx concentration levels during periodic technical inspection idle test of SCR-equipped diesel vehicles. *Environ Sci Eur* **37**, 103 (2025). https://doi.org/10.1186/s12302-025-01155-0

# A potential route for beyond **2040:** Lean H2 monofuel engine



## Conclusions

- Advancing injection > more time for mixing > higher overall homogeneity in the cylinder.
- However, taking advantage of injection during peak TKE would result in a more homogeneous mix around point of ignition, slowing ignition flame kernel growth and rise of peak temperatures, suppressing NOx
- Late injection showed a more stratified mix around point of ignition, displaying fastest kernel growth, highest peak pressure and temperature compared to other regimes. Nonetheless, hydrogen slip is the highest.
- Peak TKE injection showed the best of trade-off between peak pressure and NOx emissions while having a relatively high combustion quality.

## Future plans

- Experimental works to validate the findings of the 3D CFD simulation results.
- Expanding the dataset to include low speed (800 rpm) and higher loads for marine relevant applications

*The UoB would like to acknowledge the support given by **Realis simulations** and **Ricardo Plc** in conducting the work presented in this section*

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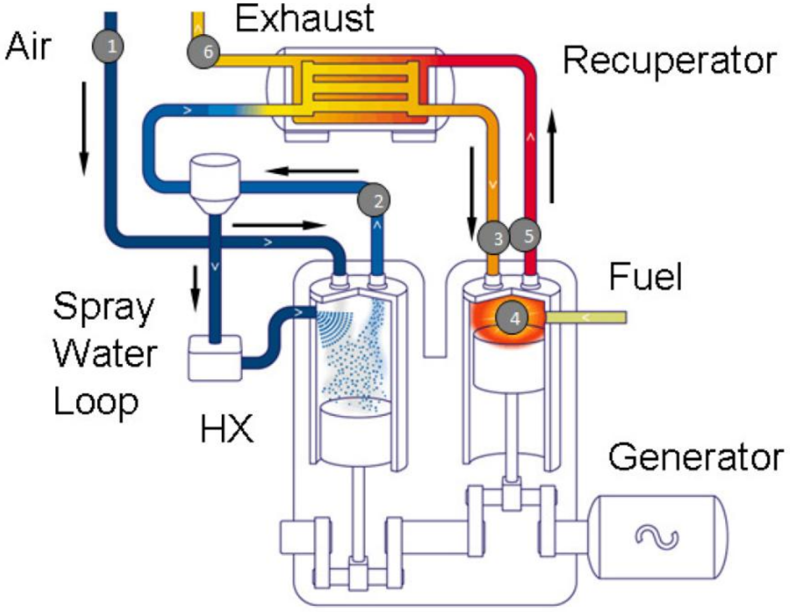
# A potential route for beyond **2050** is via Recuperated Split Cycle Engine

University of Brighton

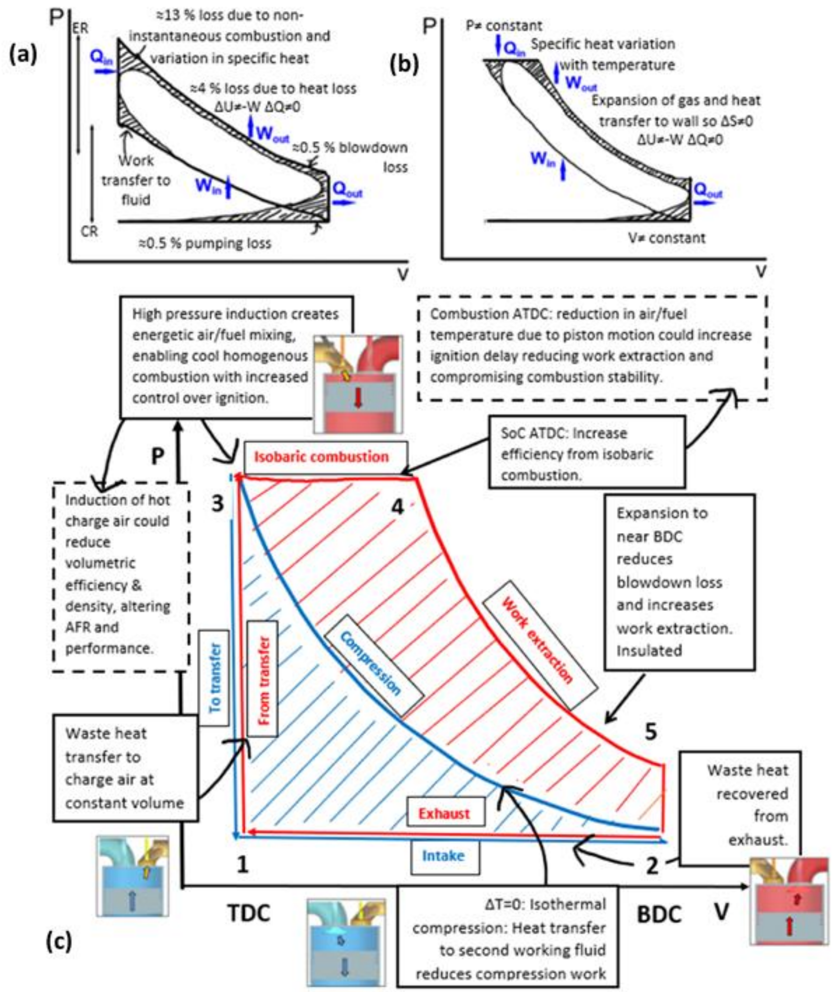
## Recuperated split cycle engine

- Split cycle engine uses two different cylinder (intake/compression and power/exhaust)
- A variant of the recuperated Brayton cycle with two main differences; the compression process is near isothermal and reciprocating compressors and expanders are used rather than the turbomachines more commonly used in gas turbine prime movers




| | |
|---|---|
| 1-2 | Induction of air into the compressor cylinder and isothermal compression. |
| 2-3 | Constant pressure heat transfer in a recuperator, recovering exhaust heat. |
| 3-4 | Induction into the combustor cylinder, (addition of fuel and heating through combustion.) |
| 4-5 | Expansion in the combustion cylinder. |
| 5-6 | Exhaust and heat recovery in the recuperator, recovering exhaust energy to the pre-combustion charge air. |


Morgan RE, Jackson N, Atkins A, Dong G, Heikal M, Lenartowicz C. The recuperated split cycle - experimental combustion data from a single cylinder test rig. SAE Int J Engines 2017;10(5):2596–605. https://doi.org/10.4271/2017-24- 0169.



Wylie E, Panesar A, Morgan R. Feasibility of hydrogen fuelled split cycle engine using multizone modelling. Int J Hydrogen Energy 2024;60:917–26. https://doi. org/10.1016/j.ijhydene.2024.02.112.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# A potential route for beyond **2050** is via Recuperated Split Cycle Engine

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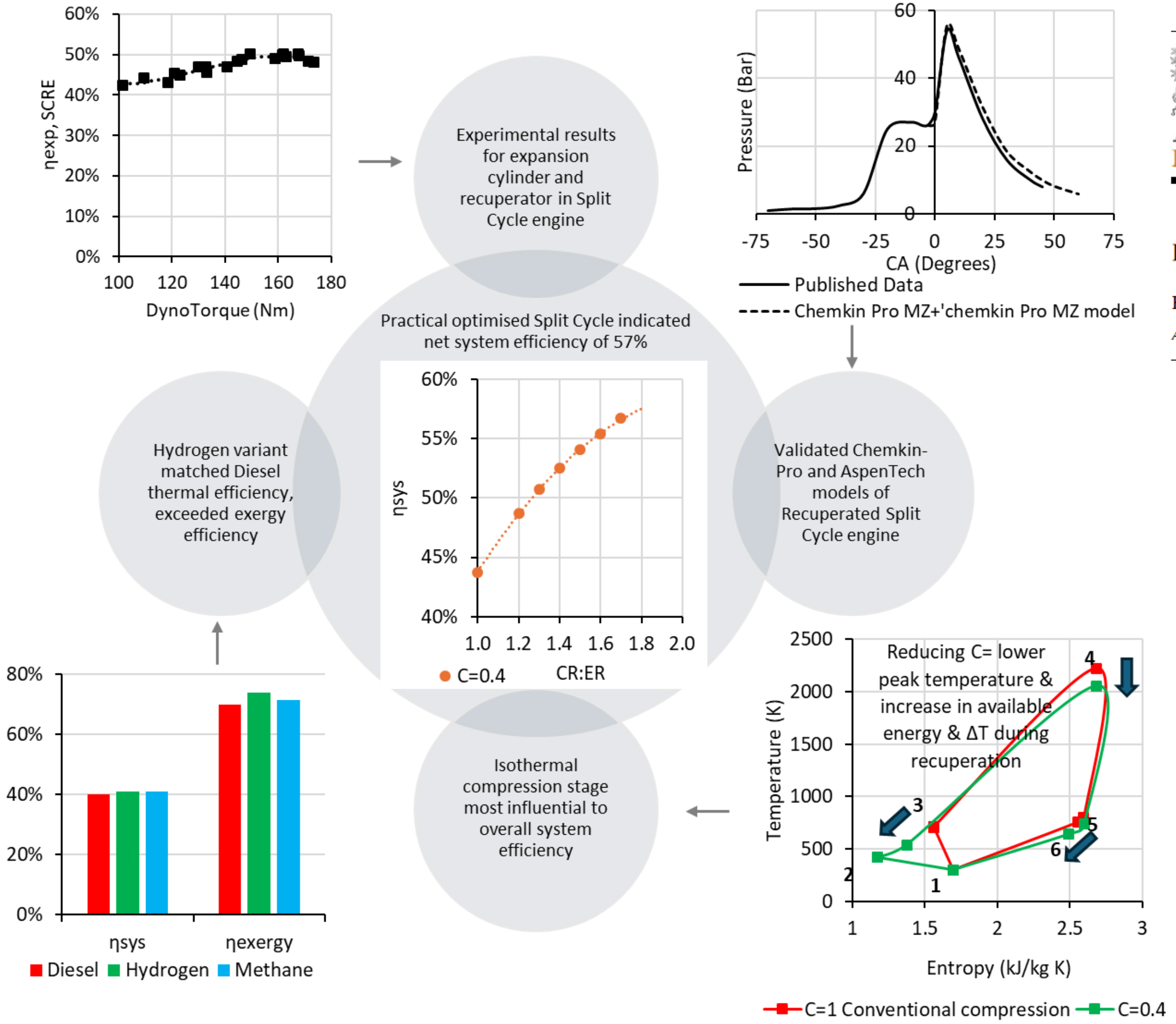


Energy 340 (2025) 139158

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## High efficiency fuel agnostic split cycle engine optimisation

Elisa Wylie, Angad Panesar *, Robert Morgan

*Advanced Engineering Centre, School of Architecture, Technology and Engineering, University of Brighton, UK*

Engineering and Physical Sciences Research Council

Department for Transport

# A potential route for beyond **2050** is via Recuperated Split Cycle Engine



## Drawing lessons from 2040 monofuel hydrogen engine and application to 2050 split cycle work

- In the previous work with the hydrogen Proteus P300, we have established that injection at peak TKE plays an important role in promoting homogeneity around the ignition point.
- However, a homogeneous mixture is achieved at -18 ˚ ATDC, about 120˚ from end of injection
- In a split cycle engine, air intake into the cylinder, fuel injection, and combustion occurs close to TDC with very little time for air-fuel mixing. Furthermore, air enters the combustion cylinder at high velocities (therefore high kinetic energy).
- Having known the importance of TKE, moving forward we are planning to further quantify the effect of high turbulence from under expanded jets of air moving through the valve and examine how it affects air-fuel mixing within the short time span between intake valve opening to start of ignition

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# Thank You, Discussions and Q&A

## Contact details:

Dr. Cliff Dansoh
C.Dansoh@brighton.ac.uk

Dr. Angad Panesar
A.S.panesar@brighton.ac.uk

Dr. Mohamad Tamam
M.Tamam@brighton.ac.uk

University of Brighton

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# Advanced Engineering Centre: our capabilities

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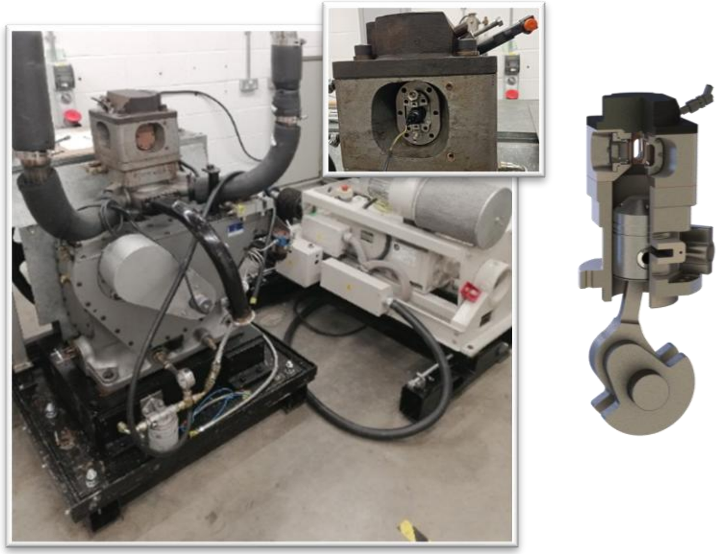
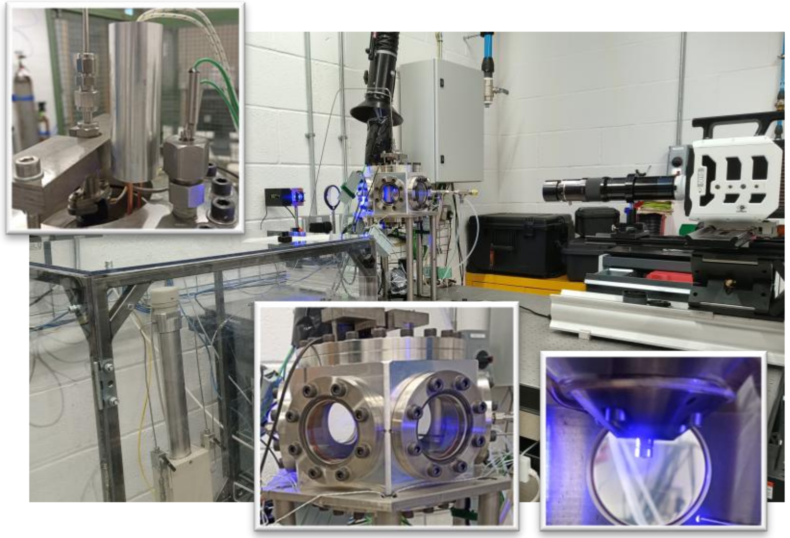
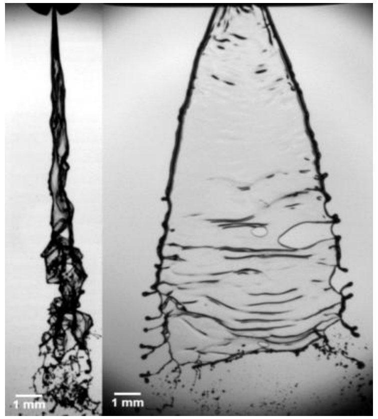


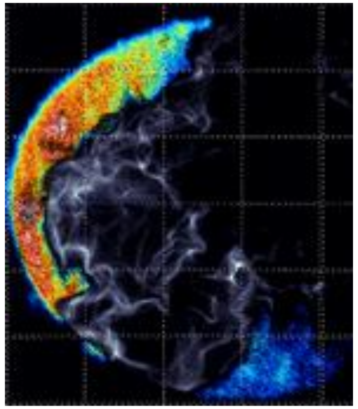
- Rapid compression expansion machine

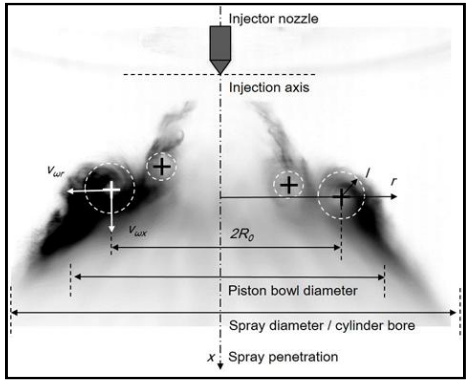


- Optical Low-Pressure Chamber

- Proteus P300 engine
- Horiba MEXA ONE & 7000 exhaust analyser






- High-speed infrared thermal imaging camera (Telops FAST M1k)
- Long range microscopy (K2 Infinity lens),
- High-speed image intensifier (max 10kHz LAvision)
- EdgeWave Innoslab DPSS Sirah Tunable HS-LIF system (max 10kHz)
- Schlieren and Shadowgraphy,
- Laser and Phase Doppler system, Dantec Classical 2-component optimised dense sprays
- Cavitar 1 MHz, CREE LEDs, Nd-YAG
- PLIF (HC, NO, OH), LII, LIP, MIE scattering, holography, combustion imaging, chemiluminescence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