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Clean Maritime Assembly 2026

Collaboration | Innovation | Transformation



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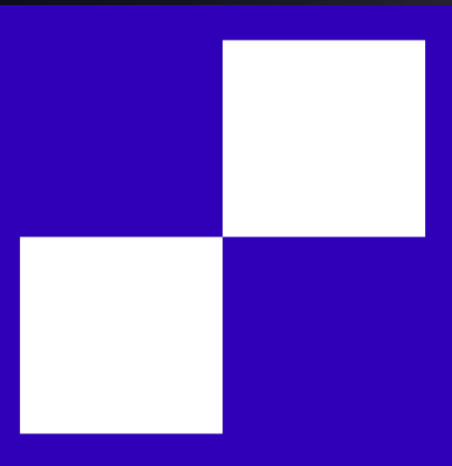
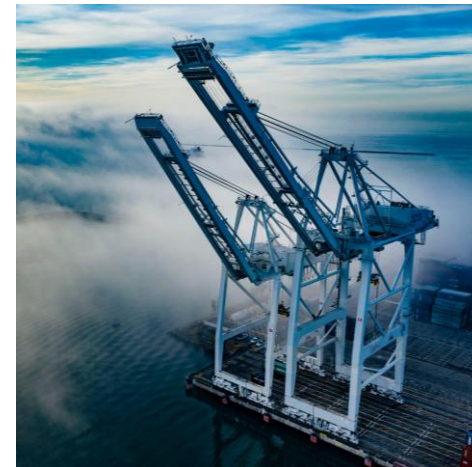
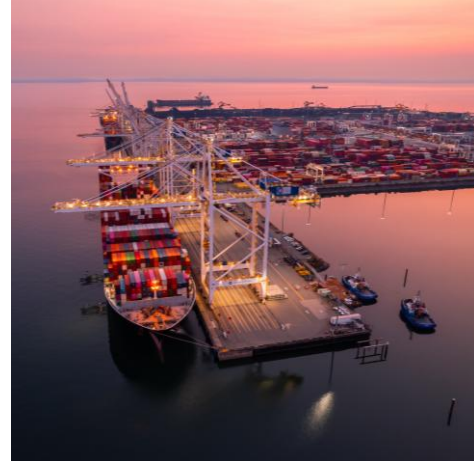
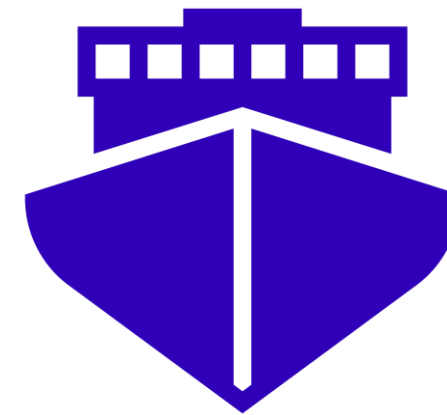
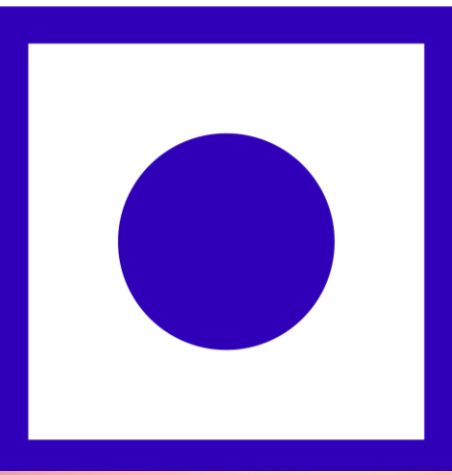
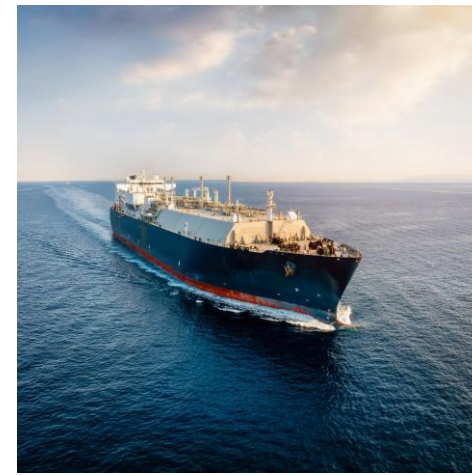


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Session 1

Integrated Maritime Power Systems

- Dr Tao Yang
- Dr Ebrahim Nadimi
- Prof Xinyan Wang





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From MW-level Electrical Propulsion to System Integration

Prof. Tao Yang
University of Nottingham
25.06.2026

www.clean-maritime-research-hub.org



Engineering and
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Department
for Transport



- Electric Propulsion for Marine
- Electrical Power System for Hybrid Electric Vessels
- MW-level Electric Propulsion Development
- System Level Integration and Validation Platform
- Conclusion

- (a) DFDS
- (b) MAHLE Powertrain
- (c) Midlands Innovation
- (d) Clean Air Power
- (e) ZISO
- (f) Sustainable Maritime Solutions
- (g) Dover Harbour Board
- (h) Suttons
- (i) Cummins
- (j) ULEMCo
- (k) Freeport East
- (l) Liverpool City Region – Freeport
- (m) Auriga Energy
- (n) Infineum
- (o) COSCO Shipping
- (p) Carisbrooke Shipping
- (q) Peel Ports Group
- (r) Hadland Maritime Limited
- (s) Calculus Energy Limited
- (t) Soil Machine Dynamics Limited
- (u) Stellar Systems
- (v) Teignbridge Propellers International Limited
- (w) Mersey Maritime
- (x) ABL Group London
- (y) Spot Ship
- (z) PD Ports
- (aa) Tees Valley Combined Authority
- (bb) Cox Powertrain
- (cc) Sustainable Shipping Initiative
- (dd) Kellas Midstream
- (ee) MOL (Europe Africa) Group
- (ff) Johnson Matthey
- (gg) Cowes Harbour Commission
- (hh) Portsmouth International Port
- (ii) Rux Energy
- (jj) Anemoi Marine
- (kk) Shell Global Solutions
- (ll) Midlands Engine
- (mm) Ceres Power
- (nn) BMT
- (oo) GSL-Technomar Shipping, Inc.
- (pp) ZEM Fuel Systems Ltd.
- (qq) Port of Felixstowe
- (rr) Network for EDI in the Energy Community
- (ss) IMarEST
- (tt) Caledonian Maritime Asset Ltd.
- (uu) Innospec Ltd.
- (vv) Teesside Freeport

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- 13 UK universities
- 70+ industrial, national & international partners
- £7.4 million
- 2023-2028

WP1: Marine fuel scale up and safety

WP2: Power & propulsion systems

WP3: Port infrastructure & vessel support

WP4: Vessel design and efficiency

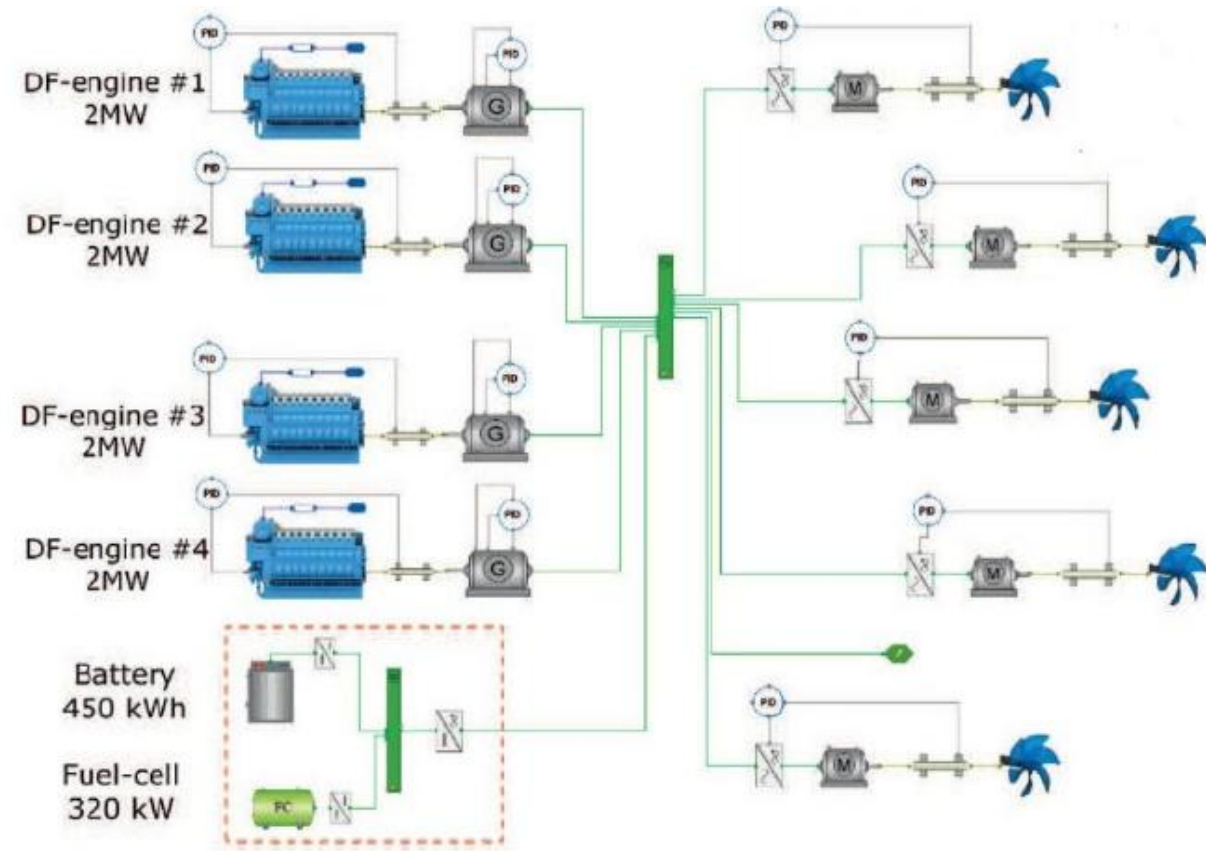
WP5: Digitalisation, maritime operations & finance

❑ Example of AC-bus electric propulsion system - **Viking Lady**

Project from DNV GL, Eidesvik and Wärtsilä, which is aim to explore the use of fuel cells, hybrid and battery technology in the shipping industry.



The offshore supply vessel, Viking Lady



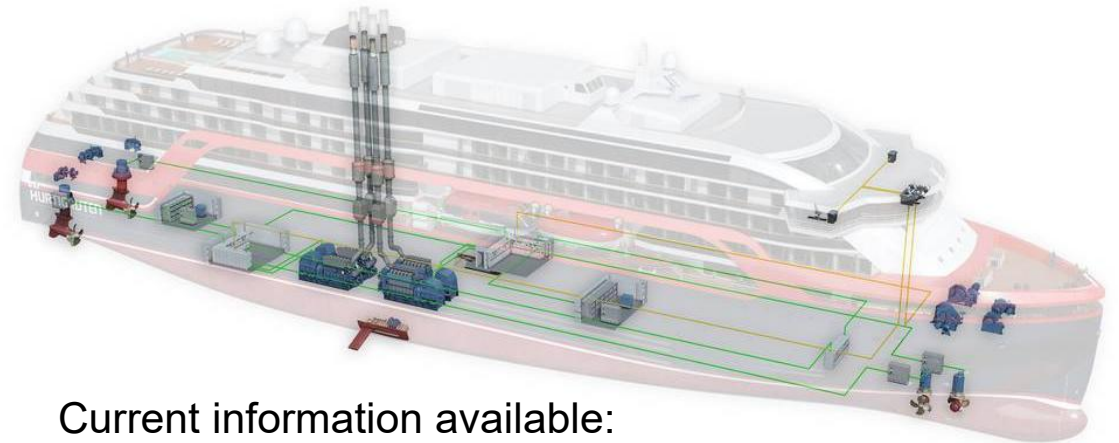
Source:

1. Kołodziejcki M. Review of hydrogen-based propulsion systems in the maritime sector[J]. Archives of Thermodynamics, 2023, 44(4).
2. Viking Lady. <https://corvusenergy.com/projects/viking-lady/> (accessed 22 Apr.2023).



Maritime Electric Propulsion Systems

❑ Example of DC-bus electric - **Hurtigruten Roald Amundsen in Norway**



Current information available:

Prime mover:

- (1) Four Bergen B33:45 engines (each has 3.6-5.4MW)
- (2) Batteries (1356kWh)

Propulsors

Hybrid Diesel-electric

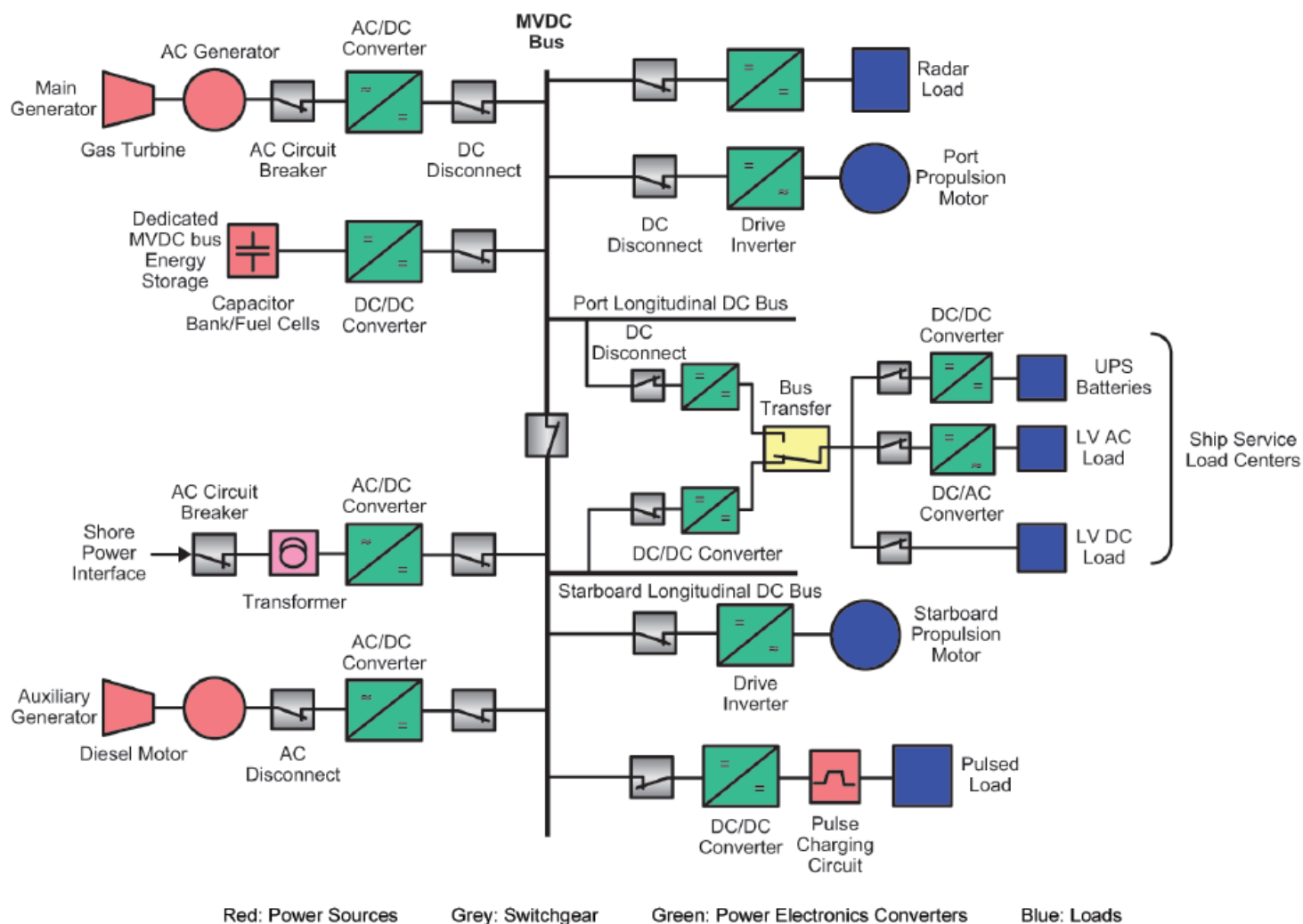
- **2 × Azipull azimuth thrusters** with integrated permanent-magnet (PM) motors (main propulsion)
- **2 × tunnel thrusters** for manoeuvring and DP

Source:

1. https://en.wikipedia.org/wiki/MS_Roald_Amundsen
2. <https://www.ship-technology.com/projects/ms-roald-amundsen-polar-cruise-ship/?cf-view>
3. <https://corvusenergy.com/projects/roald-amundsen/>

Electrical System for Hybrid Electric Vessels

Radial distribution Electrical Distribution System

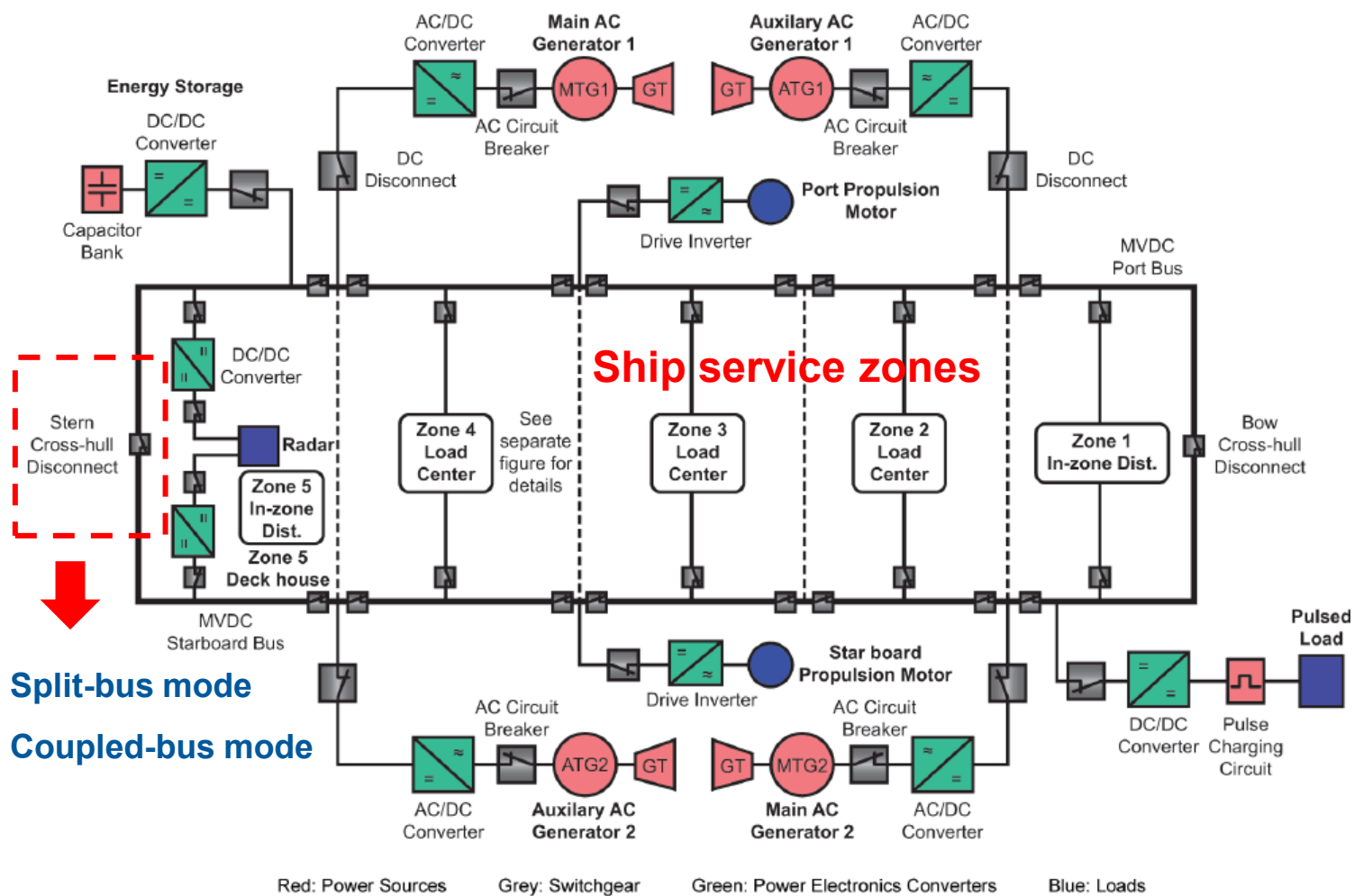


Features:

- Colour coded of power sources, switches, power converters and loads.
- Redundancy: two dc buses running on the port and starboard sides
- Simple structure
- Lower cost
- Not flexible when occurs faults on dc bus

Electrical System for Hybrid Electric Vessels

□ Zonal Electrical Distribution System



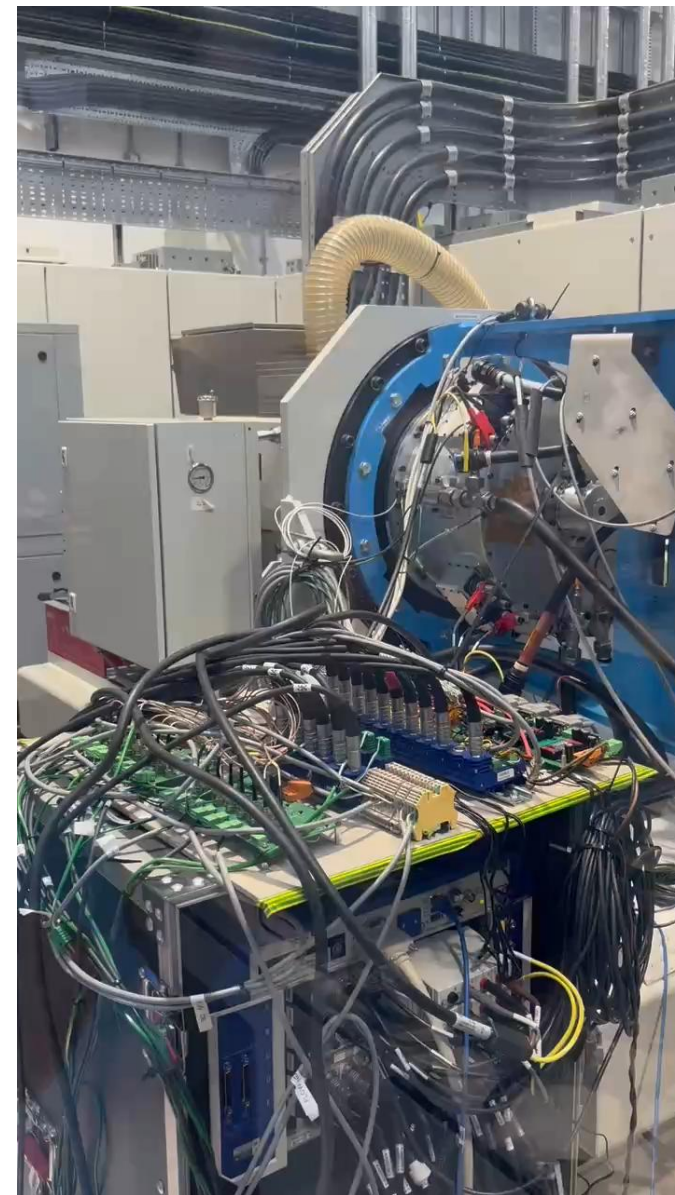
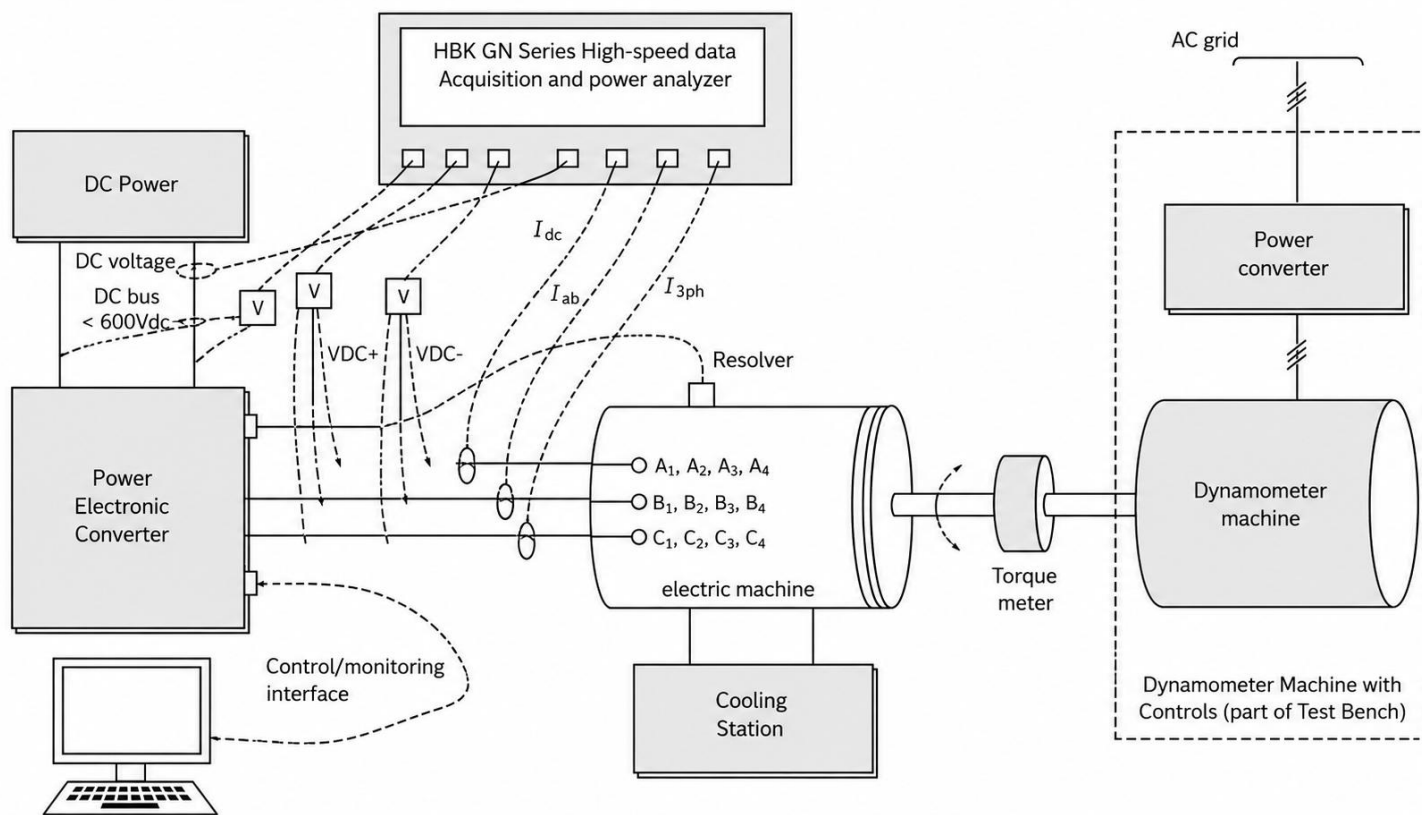
IEEE 1709 MVDC zonal shipboard power system

Features:

- Compatibility with the maritime cabin structure well and cable needs reduced
- High redundancy: each load center is powered by port and starboard buses
- Better survivability, redundancy, and fault isolation
- Flexible power routing
- Higher cost, design burden, less efficient
- Complicated control and coordination strategies

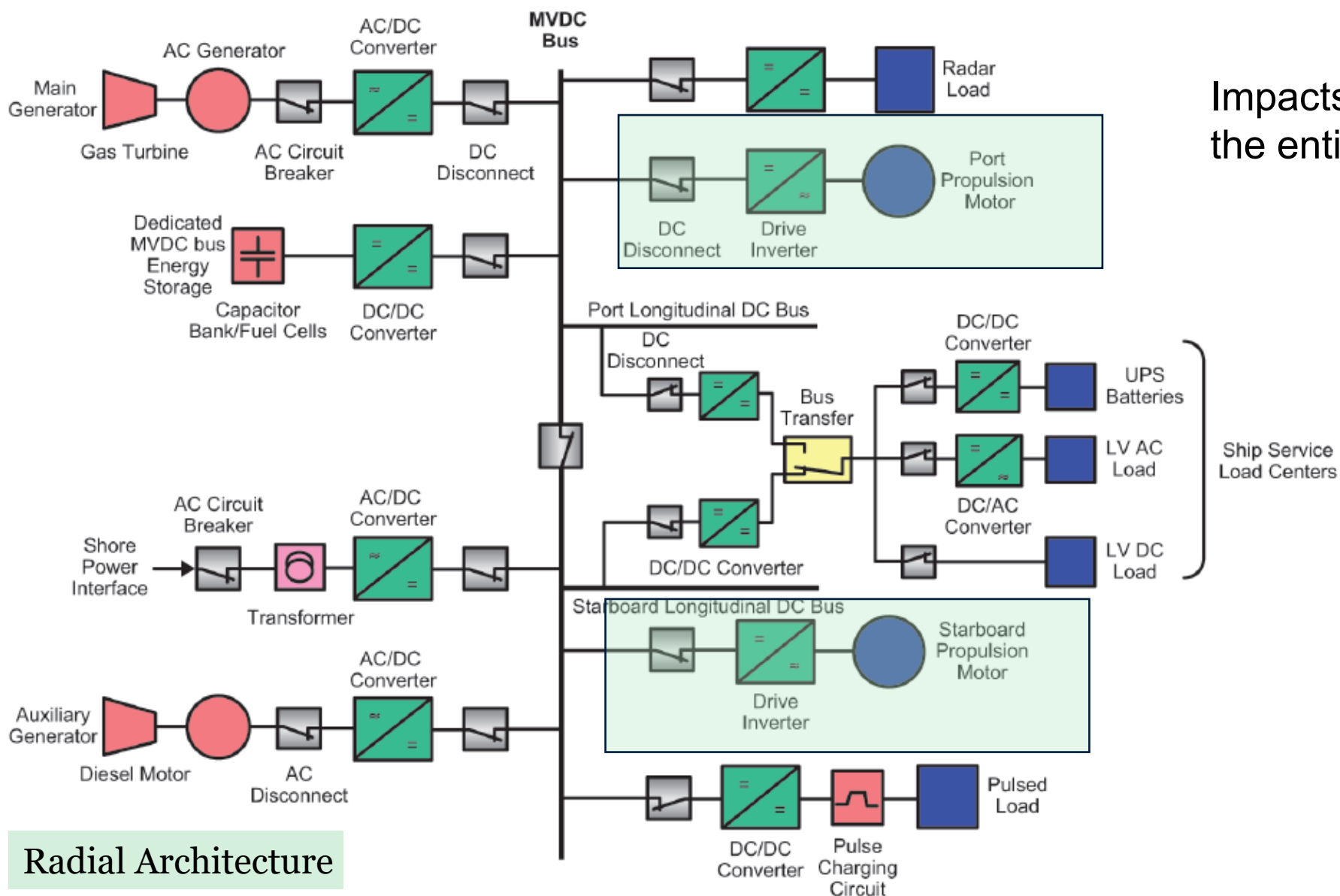


MW-level Electric Propulsion System in Nottingham



But what is the impact if we integrated such a new electric propulsion motor to existing maritime grid?

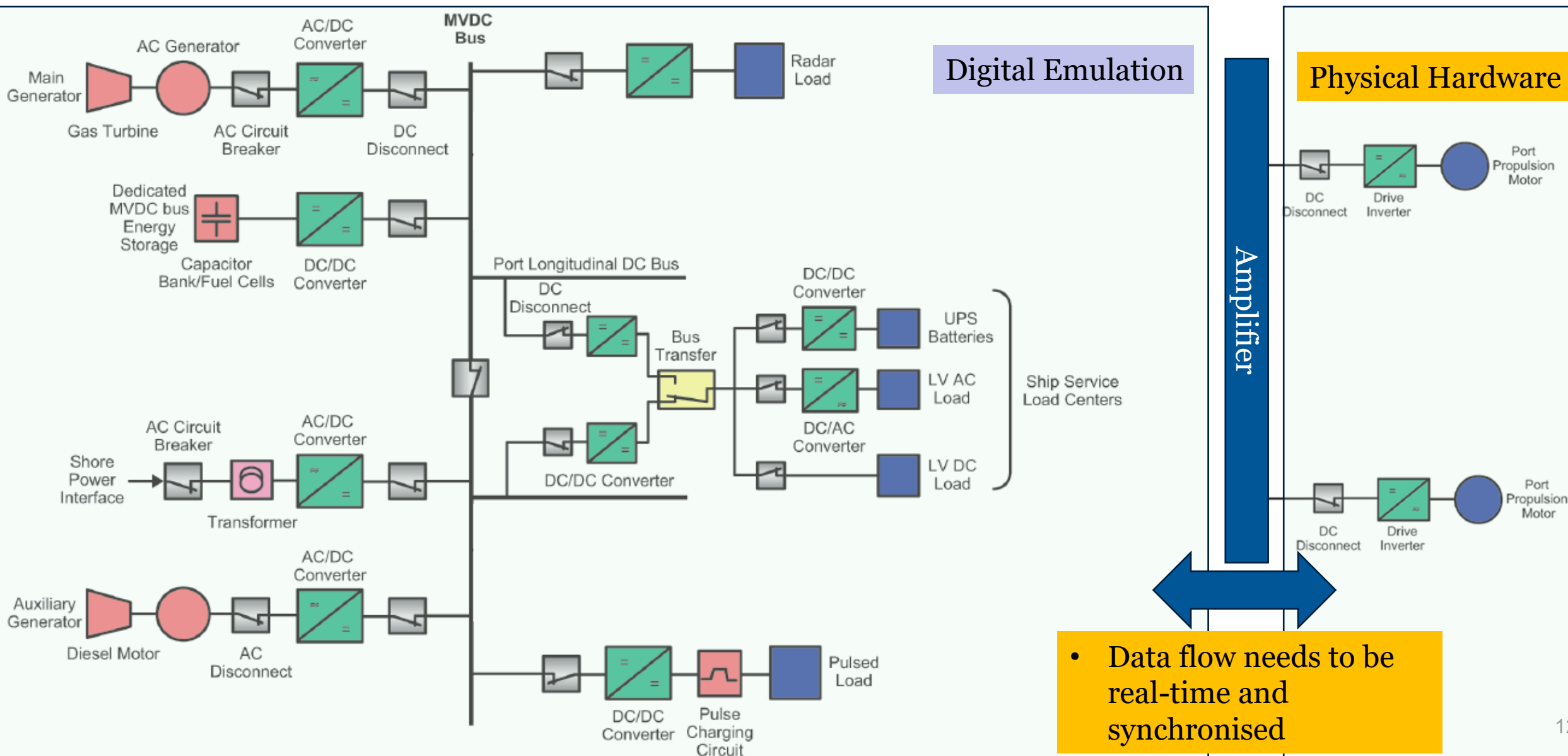
Electrical System for Hybrid Electric Vessels



Impacts of electrical propulsion to the entire electrical system

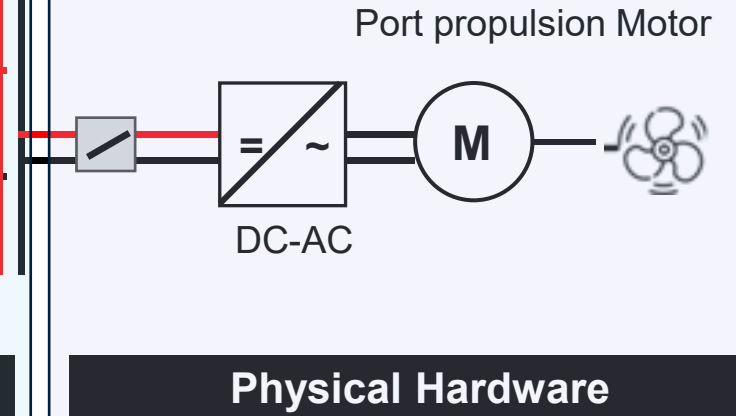
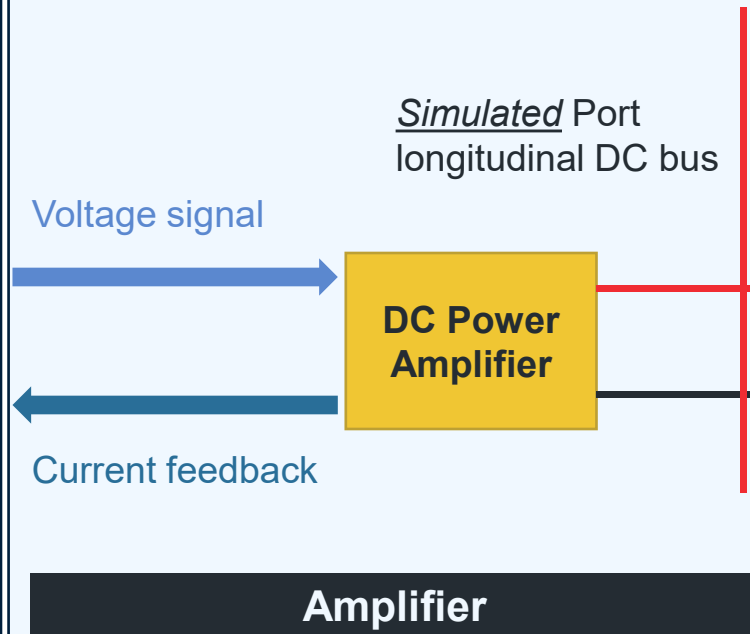
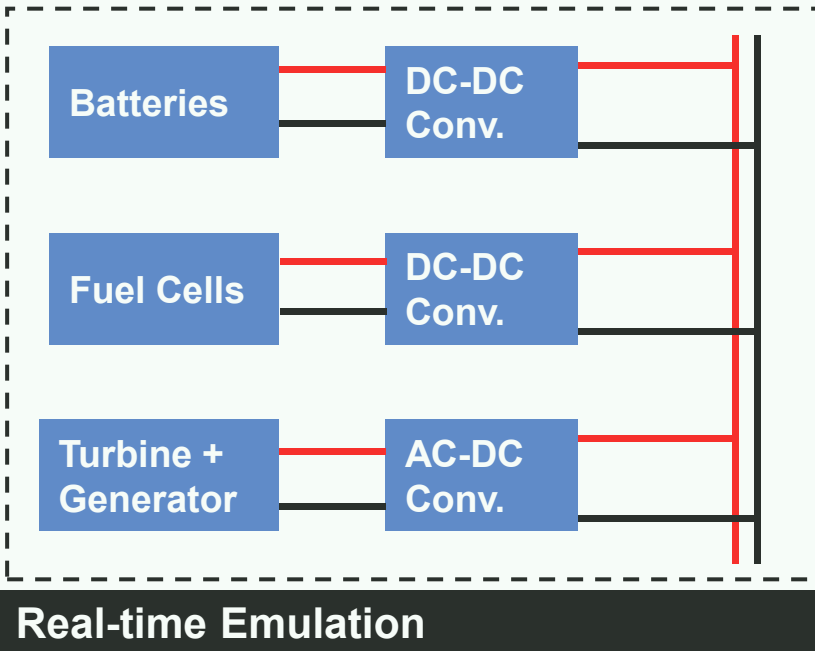
- Stability
- Power quality
- Energy management

Electrical System for Hybrid Electric Vessels



❑ Maritime EPS Real-time Emulation Platform (Power Hardware-in-the-loop, PHIL)

Typhoon + dSPACE Real-Time Simulator

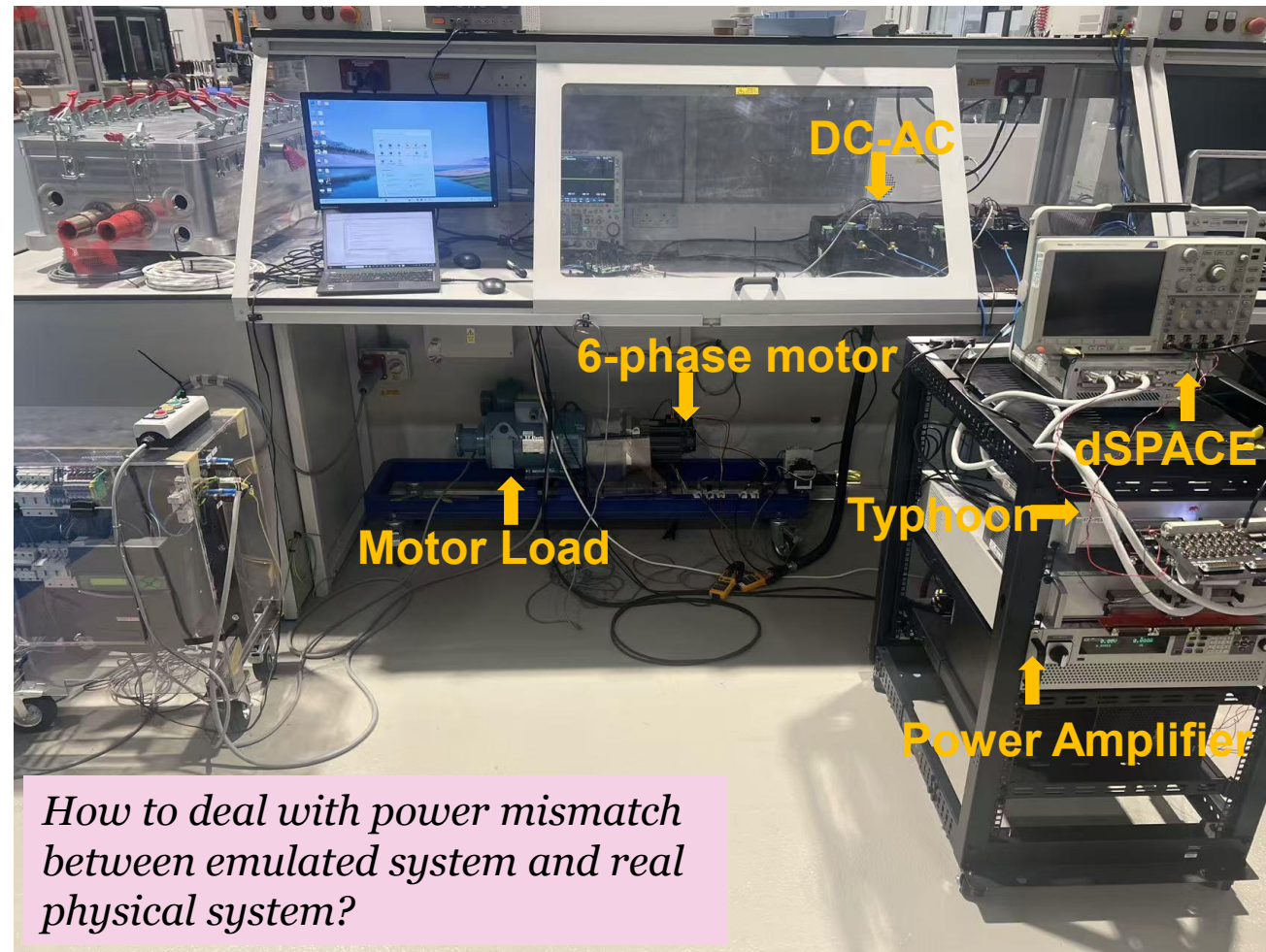
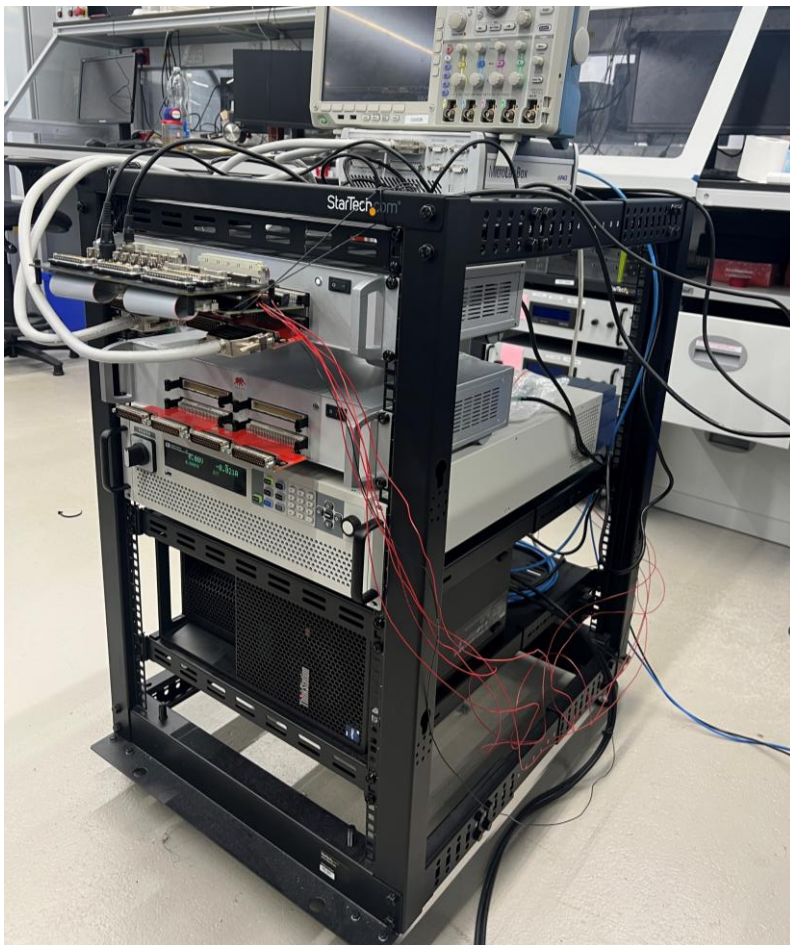




Electrical Power System Integration Platform in Nottingham

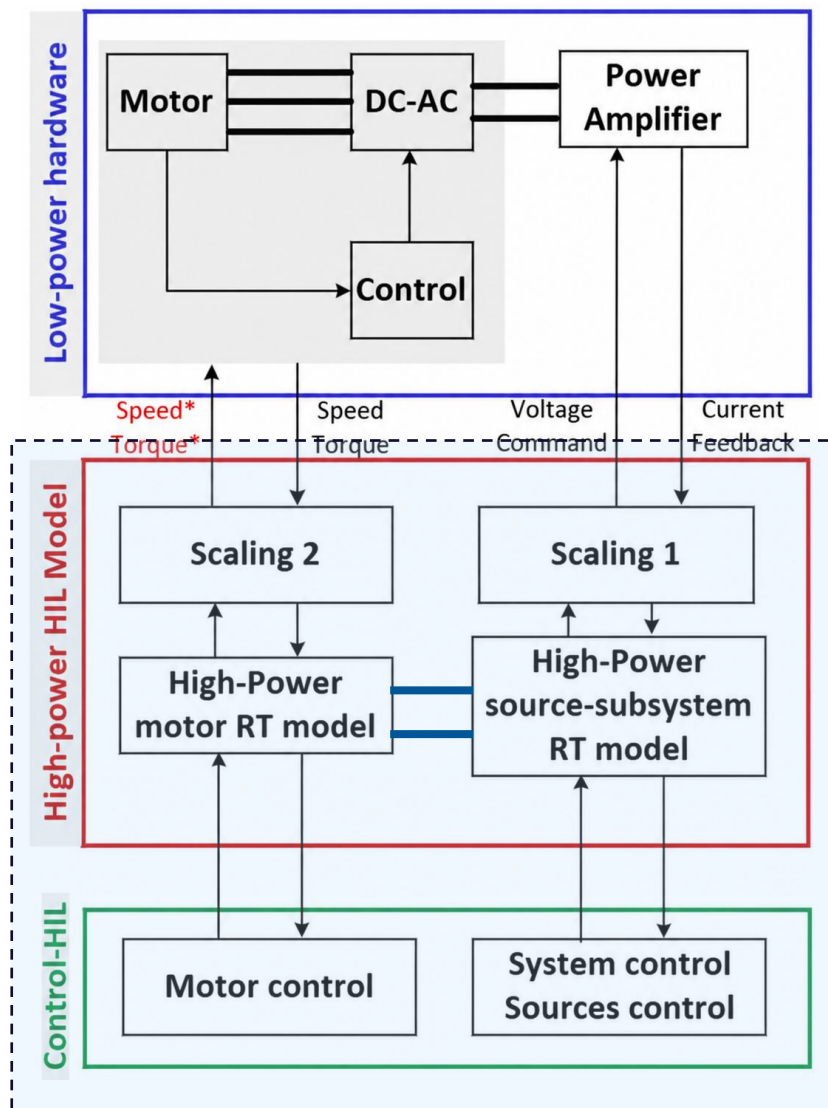
❑ UoN P-HIL testing platform

dSPACE →
Typhoon#1 →
Typhoon#2 →
DC Power Amplifier →
Host PC →



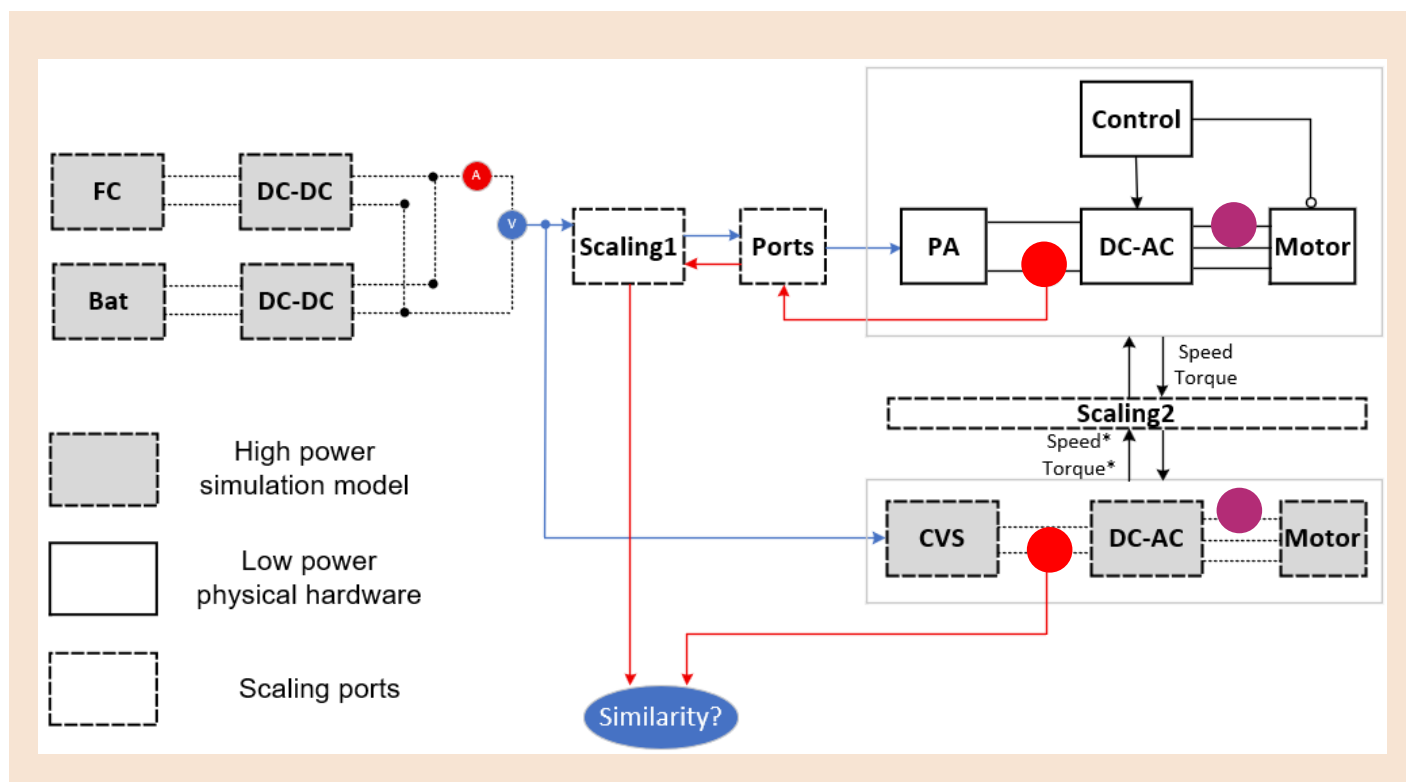


- Scaling up from 2kW to 85kW Level

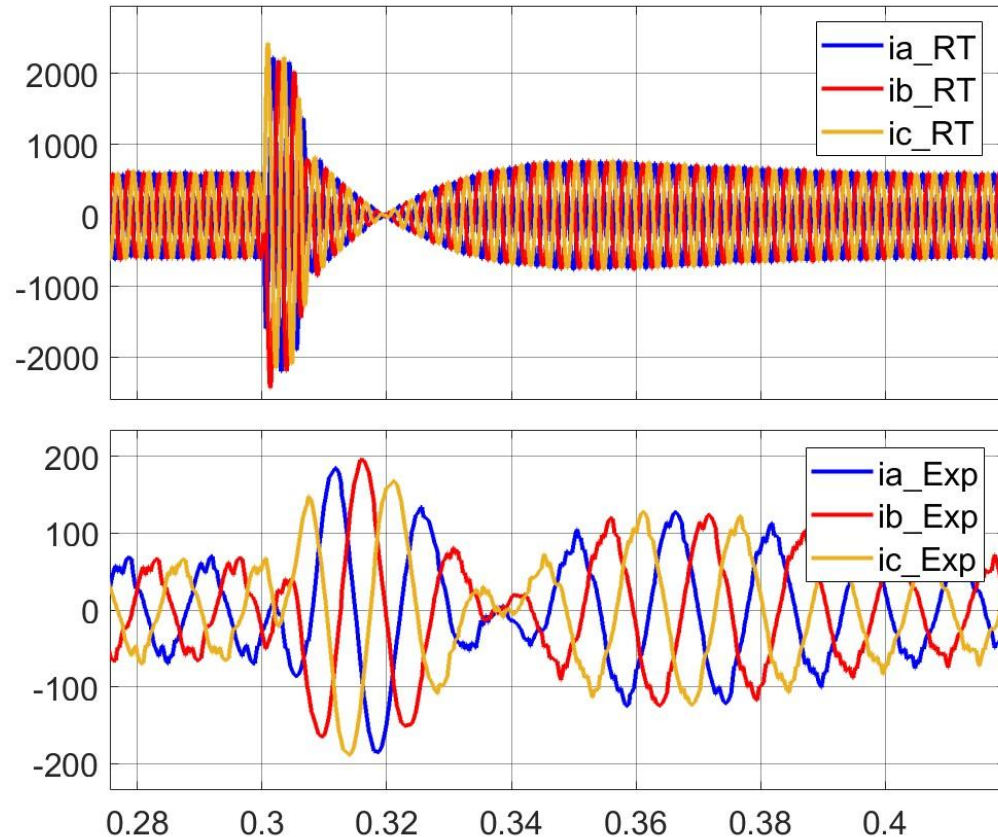


Scaling factors

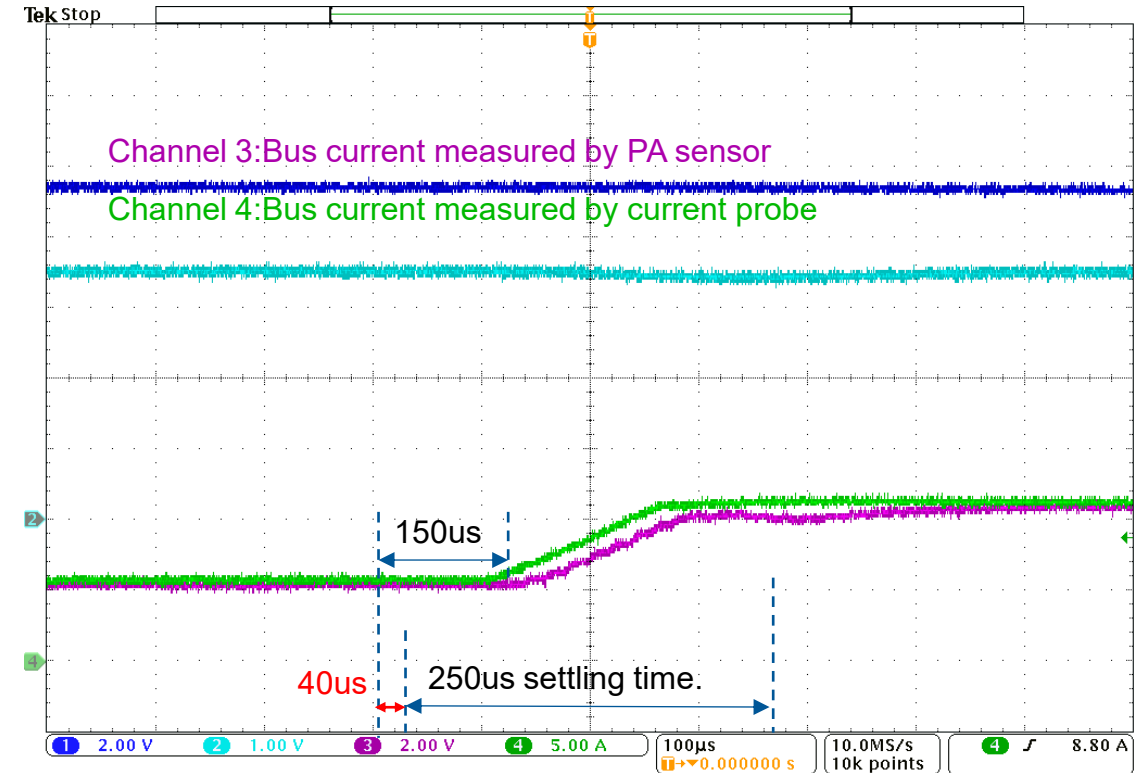
- 1: DC bus voltages
- 2: Motor and its drives



- Scaling up from 2kW to 85kW Level

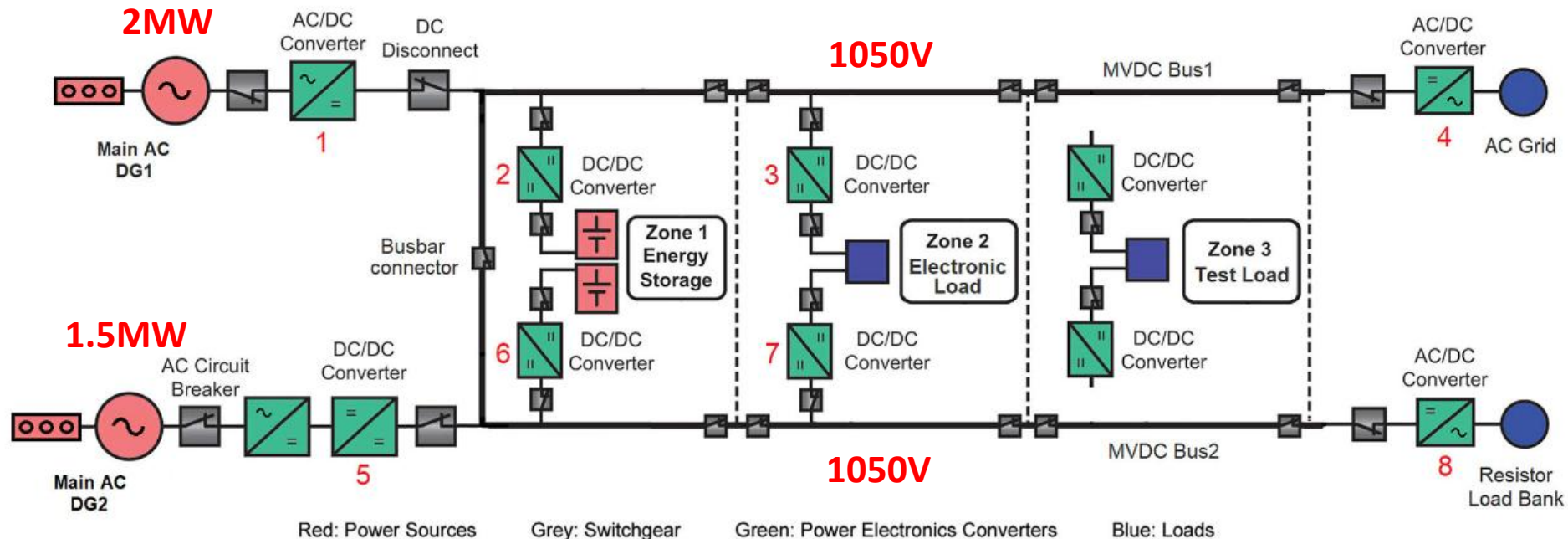


Motor current comparison between emulated high-power motor and low-power physical motor



DC Link current comparison between emulated high-power motor and low-power physical motor

□ Zonal Electrical Distribution System



Main AC DG
DG1 2 MW
DG2 1.5MW

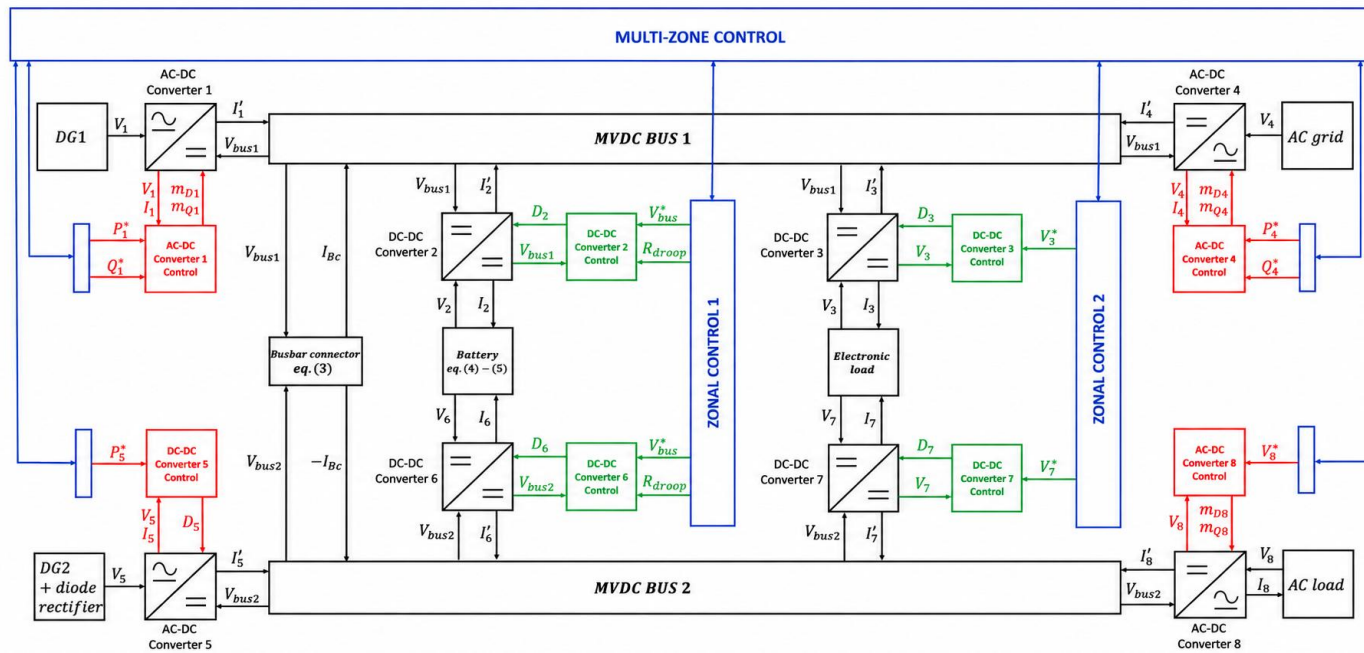
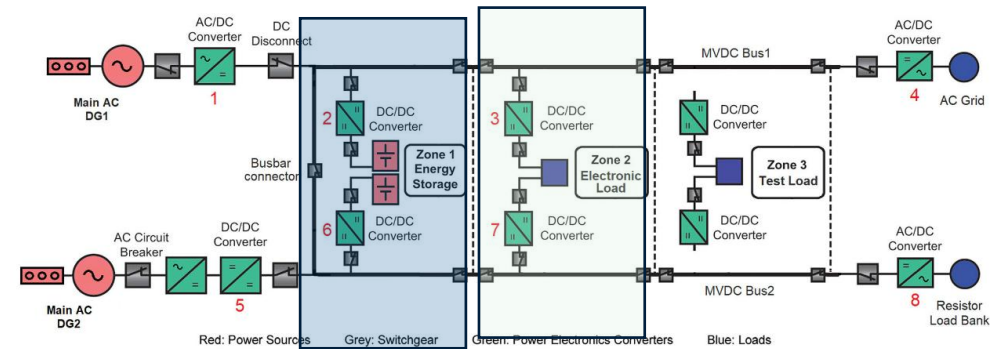
Dual DC Bus
1050 V × 2

Zone 1 ESS
452 kWh BESS

Zone 2 Electrical Load
2.5 MW Load step

Ref: High-Performance Megawatt-Scale MVDC Zonal Electrical Distribution System Based on Power Electronics Open System Interfaces

□ Zonal Electrical Distribution System Modelling and next steps



- MVDC bus protection strategy
- Zonal Reconfiguration
- Pulsed-load management
- Propulsion load prioritisation
- Energy storage coordination
- System stability
- Power quality
- Converter interactions



Conclusion

- Electric Propulsion plays a key role in Clean maritime
- MW-level electric propulsion system for maritime is in need
- Hardware-in-the-loop (HIL) Technology is essential to validate system level performance, especially for integration of new electrical equipment
- Power HIL **platform is now ready** for maritime EPS studies in Nottingham
- **The Zonal Architecture** provides good redundancy and higher survivability while Radial Architecture



University of
Nottingham

UK | CHINA | MALAYSIA

Thank you!



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University

Multi-objective Optimisation of Hydrogen and Methanol-based Hybrid Power Systems for Service Operation Vessels (SOV): A Techno-economic and Environmental Analysis

Jiacheng Yu
Yuqi Zhang
Dr Salman Farrukh
Dr Ebrahim Nadimi
Prof Dawei Wu





Scope

- Maritime decarbonisation and SOV motivation
- SOV hybrid powertrain design under real mission operation
- Powertrain pathways: DFME, MRFC and PEMFC
- Solve a tri-objective problem: CAPEX–OPEX–CII over 25 years
- Life-cycle cost, CII reduction and integration trade-offs
- Fuel-price and carbon-price sensitivity
- Summary

Shipping decarbonisation

99%

world fleet fossil-powered

Alternative fuels must scale from demonstration to fleet-level deployment.

1,076 MtCO₂e

shipping GHG in 2018

2.89% share of global anthropogenic GHG

5–10%

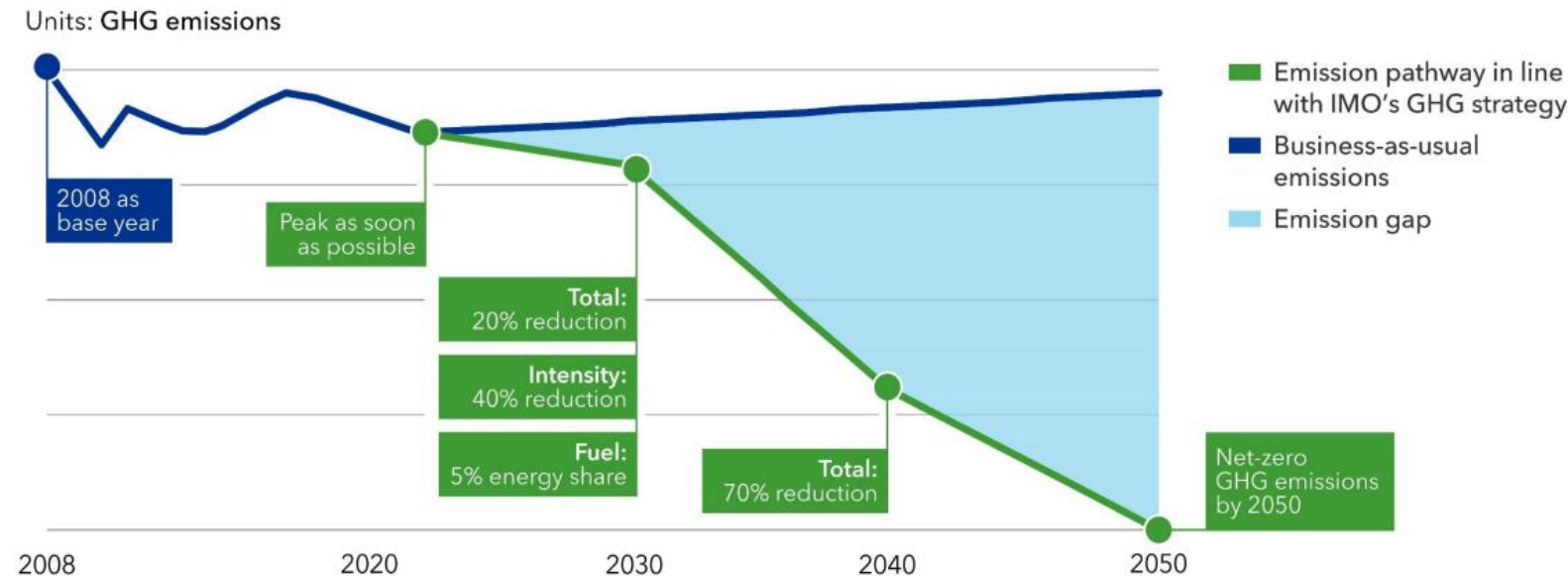
zero/near-zero fuels

IMO ambition for zero/near-zero fuels and energy sources by 2030.

2050

IMO net-zero target

Net-zero GHG emissions by or around 2050, with 2030/2040 checkpoints.

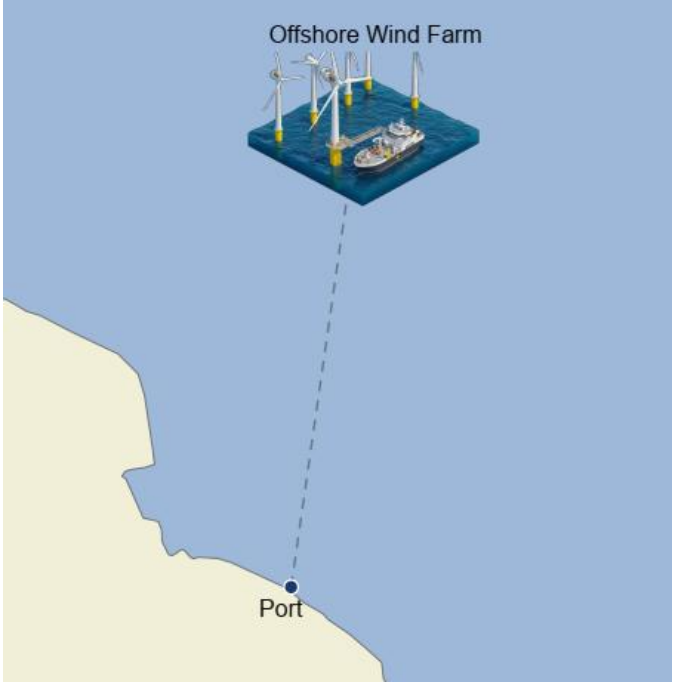


Design implication for SOVs

- SOVs support offshore wind, but still rely heavily on diesel powertrains.
- Long endurance, DP loads, and high hotel demand make battery-only solutions unrealistic.
- Hydrogen, methanol and hybridisation must be assessed together with cost, storage and CII.

Total: Well-to-wake GHG emissions; Intensity: CO₂ emitted per transport work; Fuel: Uptake of zero or near-zero GHG technologies, fuels and/or energy sources

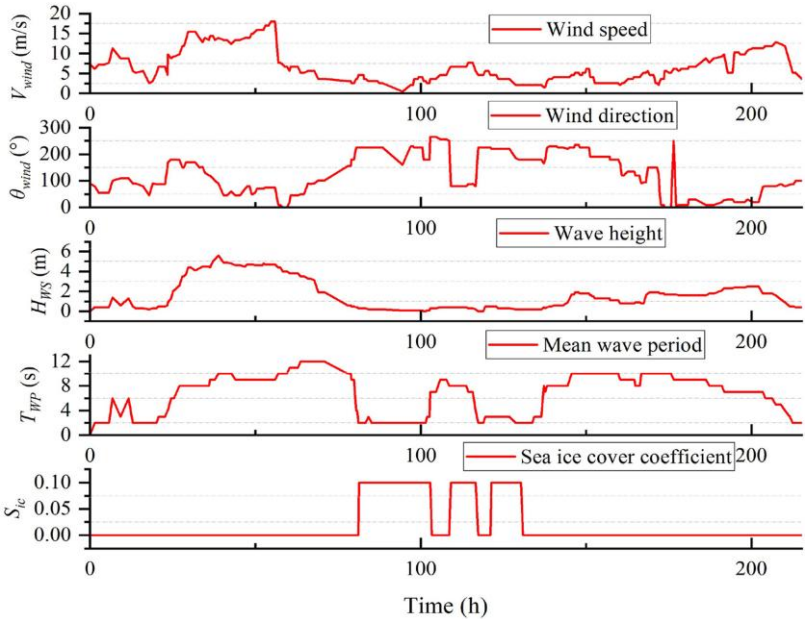
©DNV



Cruising route of the reference SOV during the representative 14-day voyage

Table 1: Reference vessel specifications.

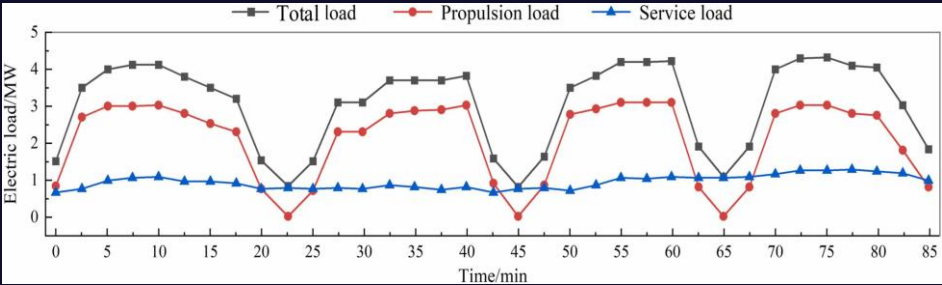
Parameter	Value	Unit
Ship type	Service Operation Vessel (SOV)	
Length overall	85	m
Gross tonnage	5 000	GT
Power system	Diesel-electric	
Service speed	12	kn
Installed power	6 000	kW
Voyage duration	14	days



The sea conditions profiles along the typical real-world navigation case

Case study vessel and 14-day mission profile

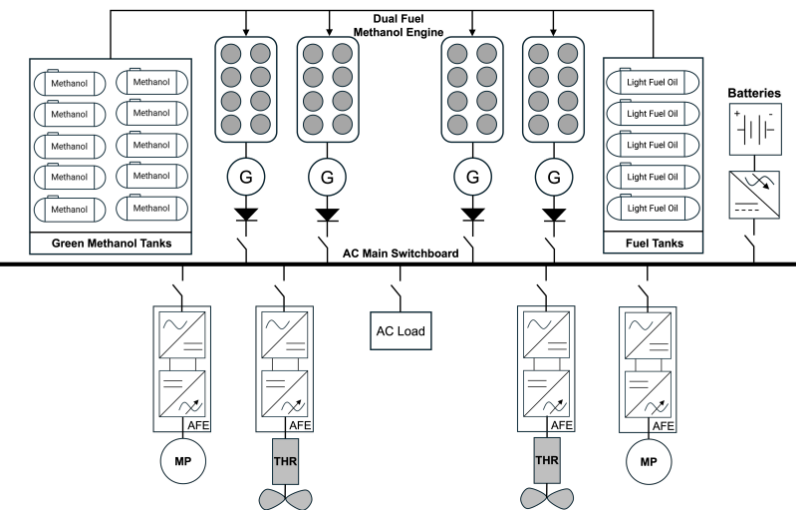
- **Operational phases:** departing, sailing, approaching, harbour/shore
- **Operation states:** Docking ≈ 340 kW; sailing power ≈ 1650 kW; working power ≈ 295 kW
- Mission profile resolved at high temporal resolution to capture Dynamic Positioning transients



The speed profile of the typical real-world navigation case

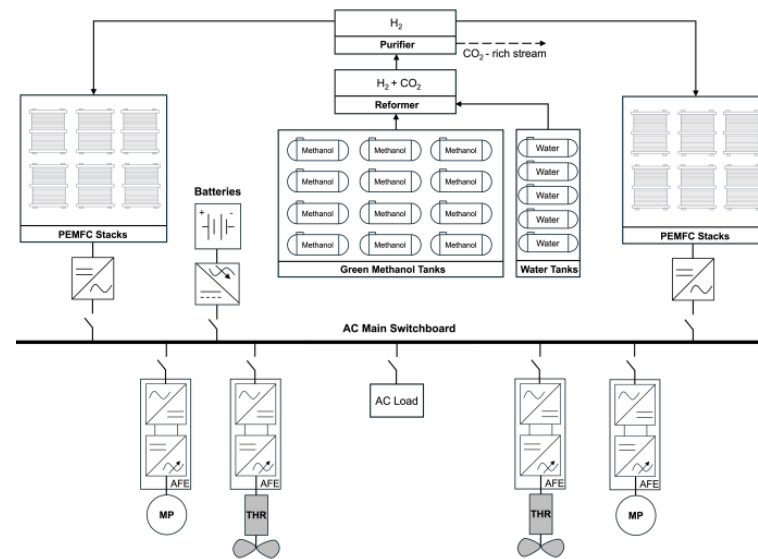
Powertrain architectures assessed

A. Methanol-LFO engine + battery (DFME)



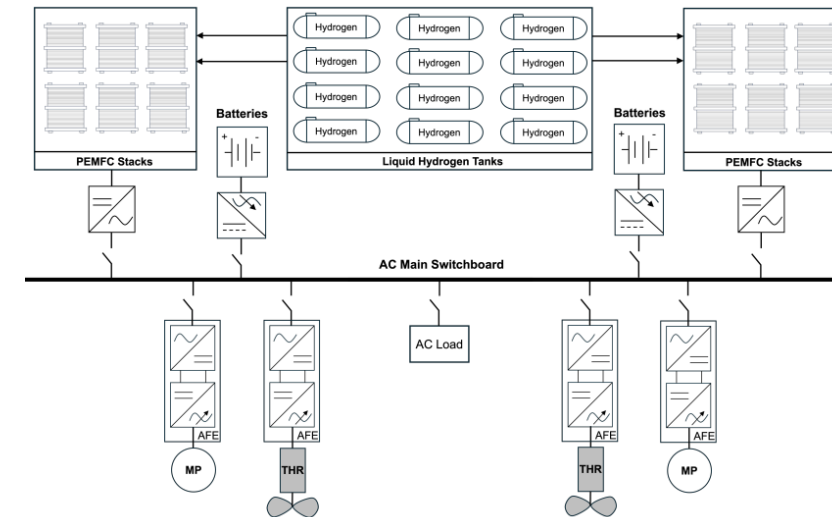
- Higher readiness and easier storage; LFO pilot and methanol price affect OPEX and CII.

B. Methanol reformer + PEMFC + battery



- Liquid fuel logistics; onboard H_2 production; reformer complexity and WTW carbon depend on methanol route.

C. Liquid H_2 + PEMFC + battery



- Zero local emissions; high FC efficiency; storage and H_2 price dominate feasibility.



Method: bi-level optimisation (NSGA-II + mission-based EMS)

- Design variables: Number of fuel-cell platforms/stacks, battery modules, engines and cylinders
- Constraints: space & weight, power balance, SOC bounds, component ramp limits
- EMS ensures operational realism → only feasible designs appear on the Pareto front
- Only technically feasible designs are retained in the Pareto front

A: LH₂ PEMFC + Battery
B: Methanol-LFO Engine + Battery
C: Methanol Reformer + PEMFC + Battery

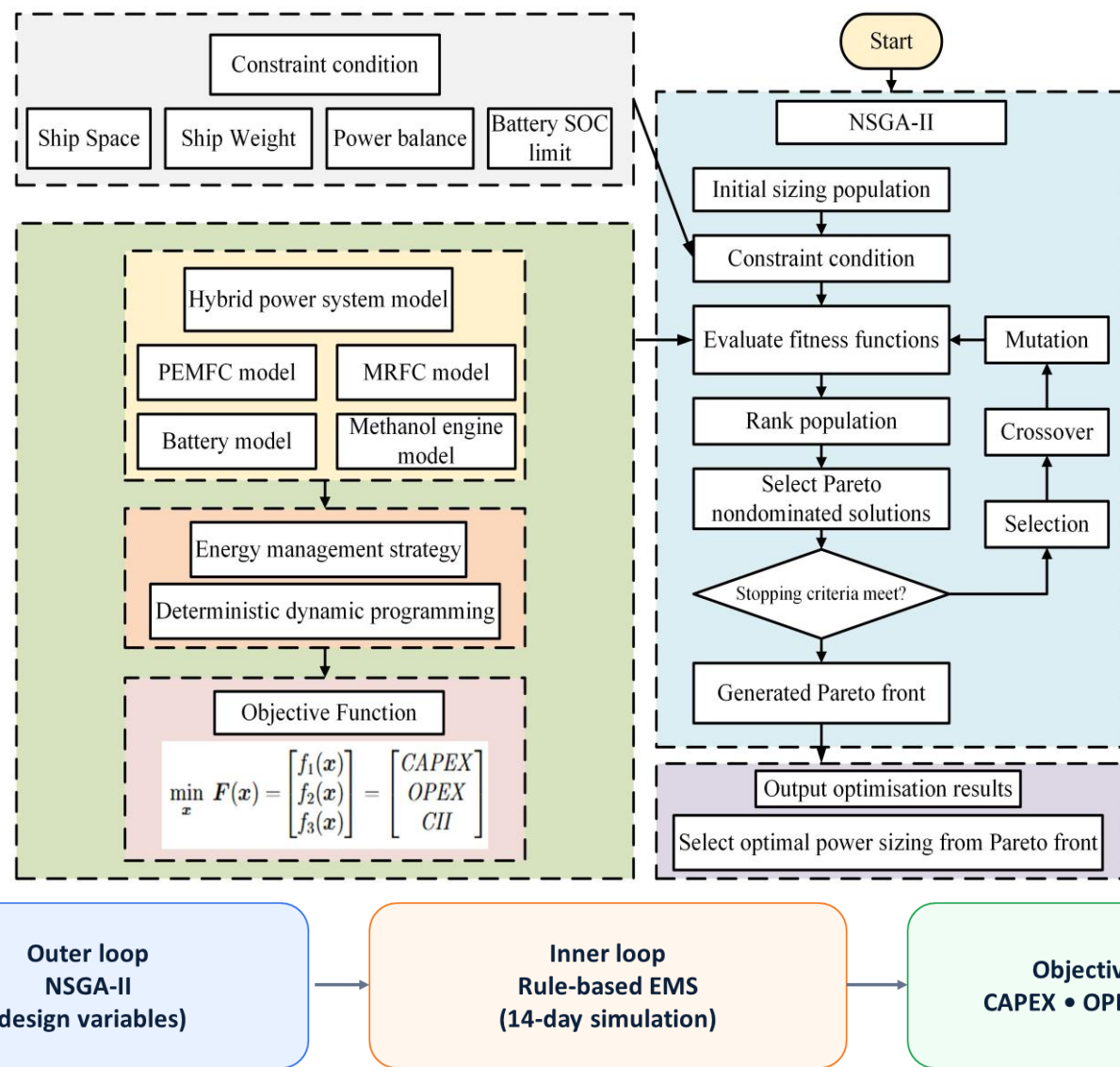


Diagram of the optimisation process

Economic and emission parameters

Parameter	Value	Unit
<i>Fuel prices</i>		
Green hydrogen	8.59	\$/kg
E-methanol	1.44	\$/kg
LFO	0.67	\$/kg
Shore power	0.26	\$/kWh
<i>Emission factors (well-to-wake)</i>		
Green hydrogen	0.80	kgCO ₂ e/kg
E-methanol	0.318	kgCO ₂ e/kg
LFO	3.151	kgCO ₂ /kg
Shore power	0.177	kgCO ₂ e/kWh

Decision variables and ranges for each pathway

Description	PEMFC	MRFC	DFME
Number of fuel cell platforms	1–10	–	–
Number of PEM fuel cell stacks	1–20	1–30	–
Number of methanol reformers	–	1–30	–
Number of methanol engines	–	–	1–3
Cylinders per engine	–	–	{6, 7, 8, 9}
Number of battery modules	0–150	0–150	0–150

Optimisation objectives: CAPEX, OPEX, and Carbon Intensity Indicator (CII)

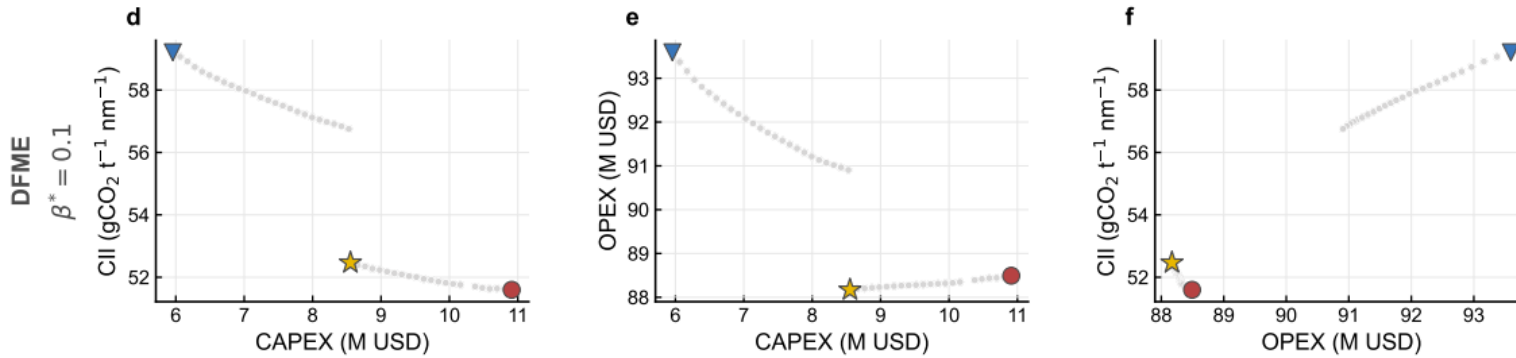
- **CAPEX:** fuel cell platform/stacks, engines, batteries, tanks + replacements over 25-year life cycle
- **OPEX:** fuel cost + carbon tax + fixed O&M
- **CII:** Well-to-Wake CO₂e per transport work (gCO₂e / t·nm), aligned with IMO-style intensity metrics

$$CII = \frac{\text{Total CO}_2 \text{ emitted in a year}}{\text{Ship capacity} \times \text{Distance sailed}}$$



A. DFME Pareto Results: Cost-effective Near-term Transition Pathway

● Pareto-optimal solutions ★ TOPSIS (= Min-OPEX for MRFC, DFME) ▼ Min-CAPEX ■ Min-OPEX (PEMFC only) ● Min-CII

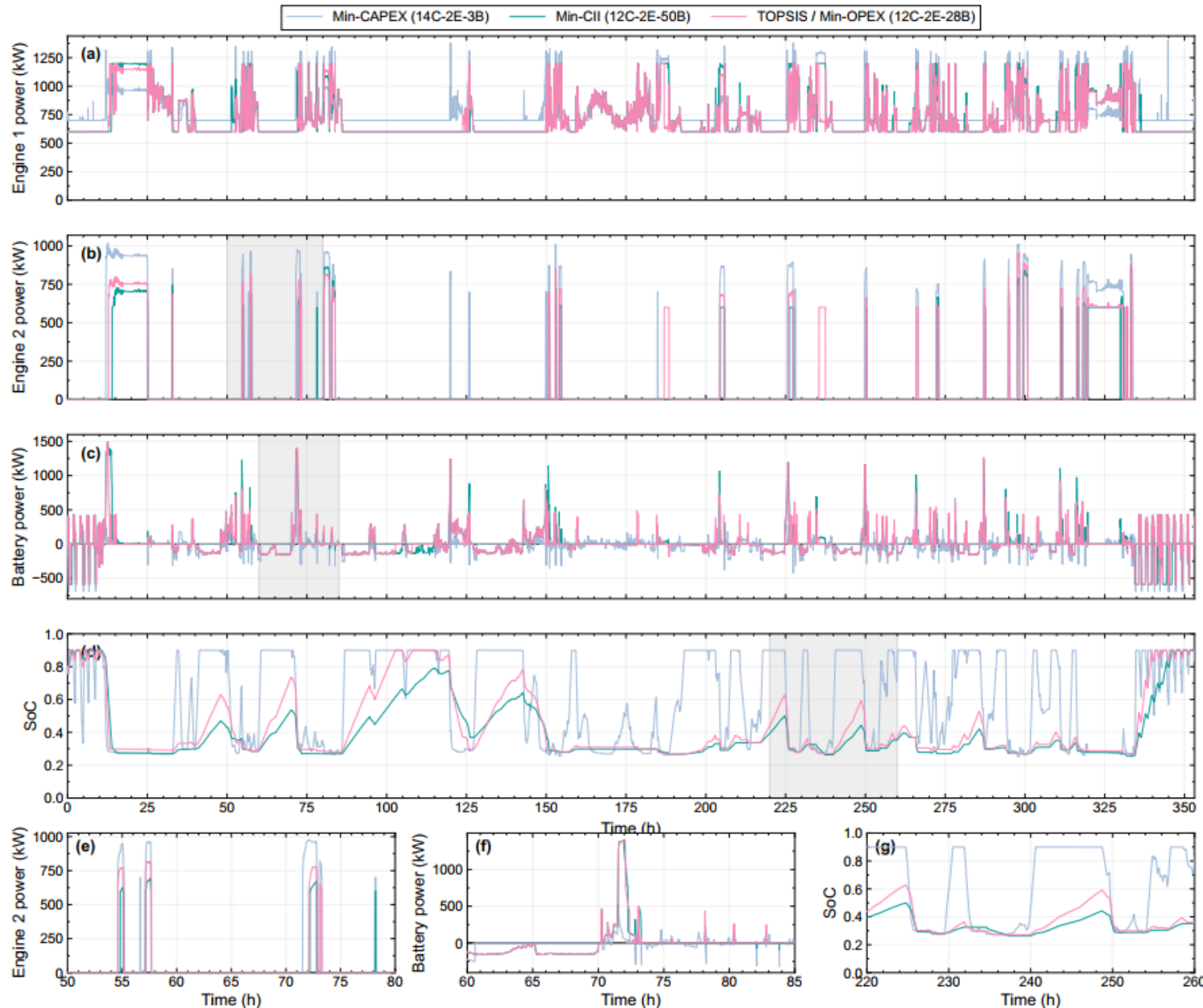


- DFME reduces CII by 66.4% compared with diesel.
- Min-CAPEX option is cheaper, but gives higher OPEX and weaker CII reduction.
- Min-CII gives only a small extra CII benefit, but requires higher CAPEX and more batteries.
- DFME is therefore a cost-effective near-term transition pathway.

Representative Pareto-optimal solutions for DFME

Pathway	Solution	Config.	Batt.	CAPEX (MUSD)	OPEX (MUSD)	CII (gCO ₂ /t·nm)	TOPSIS rank
DFME	TOPSIS	12C-2E	28	8.55	88.17	52.47	1
	Min-CAPEX	14C-2E	3	5.96	93.59	59.21	47
	Min-OPEX	12C-2E	28	8.55	88.17	52.47	1
	Min-CII	12C-2E	50	10.91	88.49	51.60	22





A. DFME Operation: Battery Sizing Reduces Engine Cycling

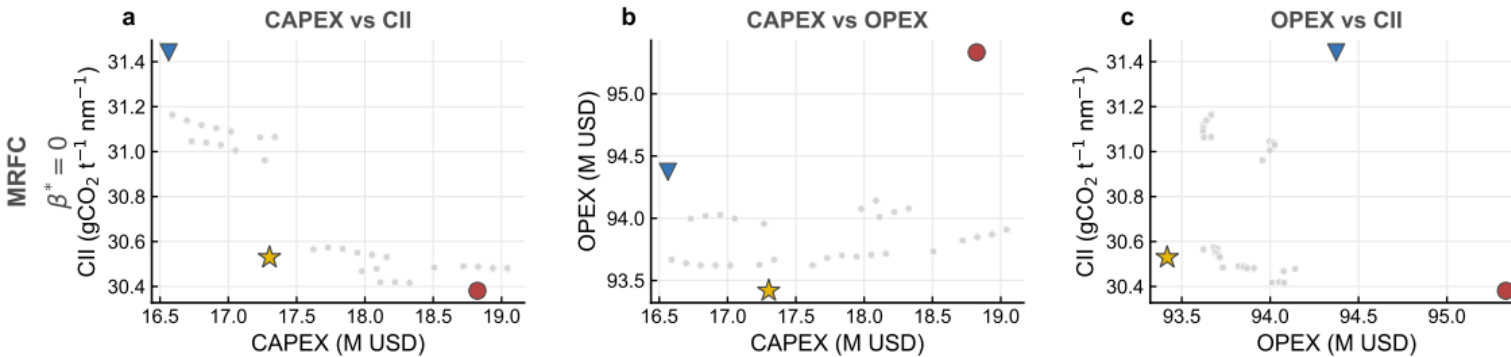
- Engine 1 provides the main continuous power; Engine 2 supports high-load periods.
- Min-CAPEX uses larger engine capacity: 14C-2E-3B, 2800 kW installed.
- Larger batteries absorb load peaks and reduce engine cycling.
- TOPSIS balances engine sizing and battery support without excessive battery oversizing.
- DFME performance is mainly improved by avoiding low-efficiency engine operation.





B. MRFC Pareto Results: Retrofit-friendly Deep Decarbonisation Pathway

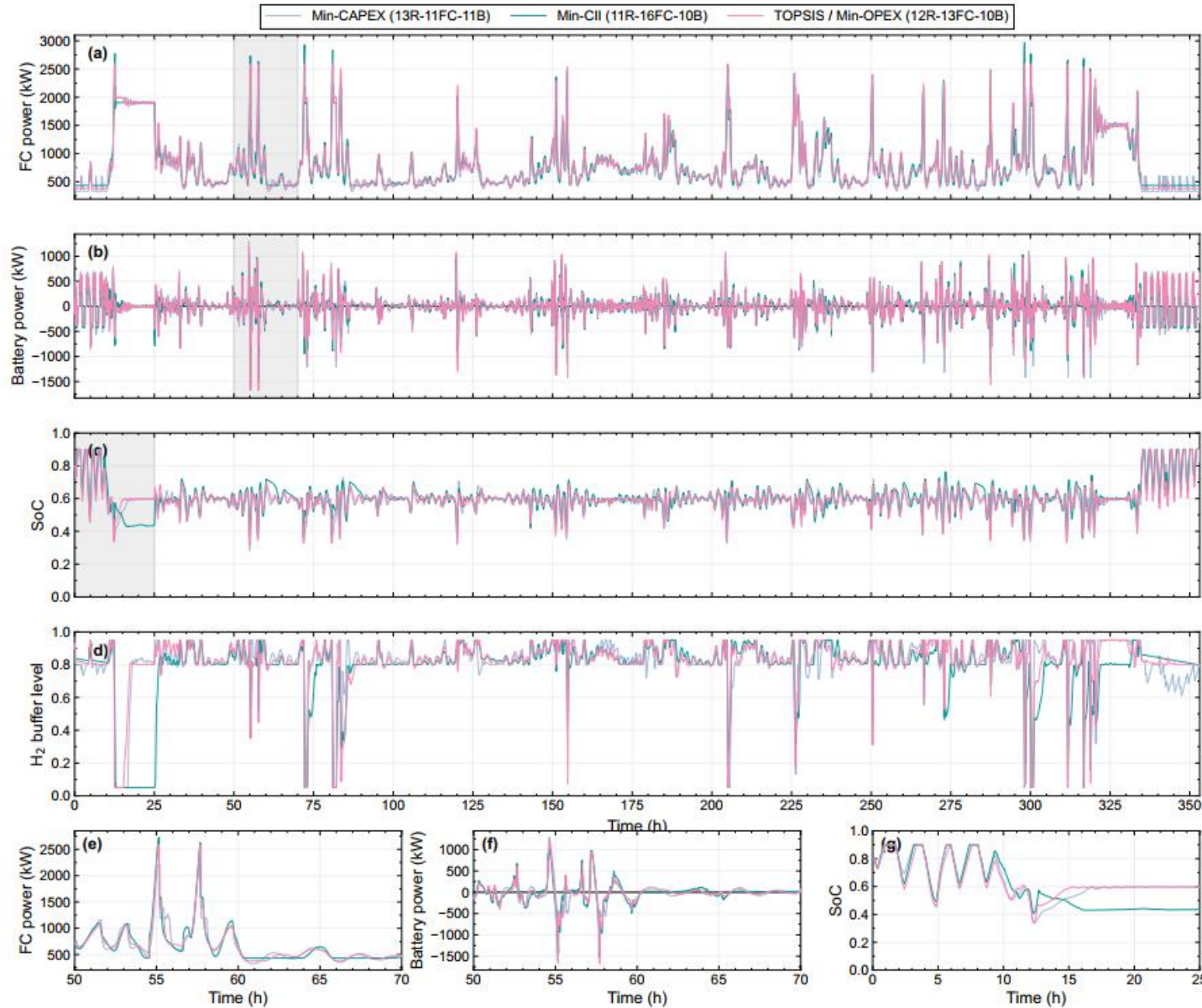
● Pareto-optimal solutions ★ TOPSIS (= Min-OPEX for MRFC, DFME) ▼ Min-CAPEX ■ Min-OPEX (PEMFC only) ● Min-CII



- MRFC reduces CII by 80.5% vs diesel: $156.26 \rightarrow 30.53 \text{ gCO}_2/\text{t}\cdot\text{nm}$.
- Min-CAPEX is slightly cheaper, but gives higher CII and OPEX.
- Min-CII gives only marginal extra CII reduction: $30.53 \rightarrow 30.38 \text{ gCO}_2/\text{t}\cdot\text{nm}$
- MRFC is the best retrofit-fit option, with $\beta^* = 0$ and no major reallocation need.

Representative Pareto-optimal solutions for MRFC

Pathway	Solution	Config.	Batt.	CAPEX (MUSD)	OPEX (MUSD)	CII ($\text{gCO}_2/\text{t}\cdot\text{nm}$)	TOPSIS rank
MRFC	TOPSIS	12R-13FC	10	17.30	93.42	30.53	1
	Min-CAPEX	13R-11FC	11	16.56	94.37	31.44	30
	Min-OPEX	12R-13FC	10	17.30	93.42	30.53	1
	Min-CII	11R-16FC	10	18.82	95.33	30.38	31



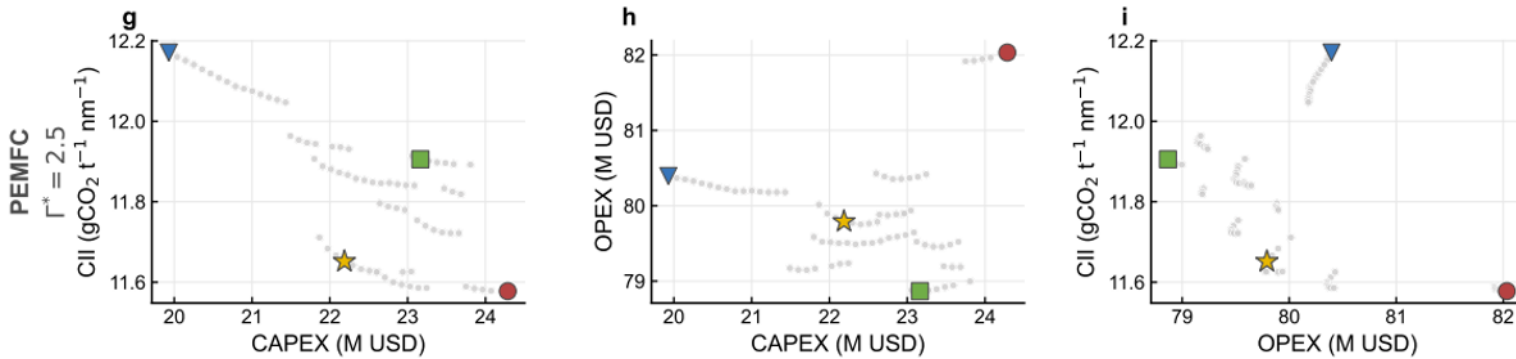
B. MRFC Operation: Reformer–FC Sizing Controls Battery Stress

- MRFC operation depends mainly on reformer count, FC capacity and battery buffering.
- Larger FC capacity reduces H₂ use: 0.0597 → 0.0579 kg/kWh.
- Min-CII reaches highest FC peaks, up to ~2.7–3.0 MW, reducing battery peak-shaving.
- Min-CAPEX hits the 2.2 MW FC ceiling and needs stronger battery discharge.
- TOPSIS gives the balanced operation: 12R–13FC–10B, CII = 30.53 gCO₂/t·nm.



B. PEMFC Pareto Results: Maximum Carbon Reduction, Higher Integration Cost

● Pareto-optimal solutions ★ TOPSIS (= Min-OPEX for MRFC, DFME) ▼ Min-CAPEX ■ Min-OPEX (PEMFC only) ● Min-CII



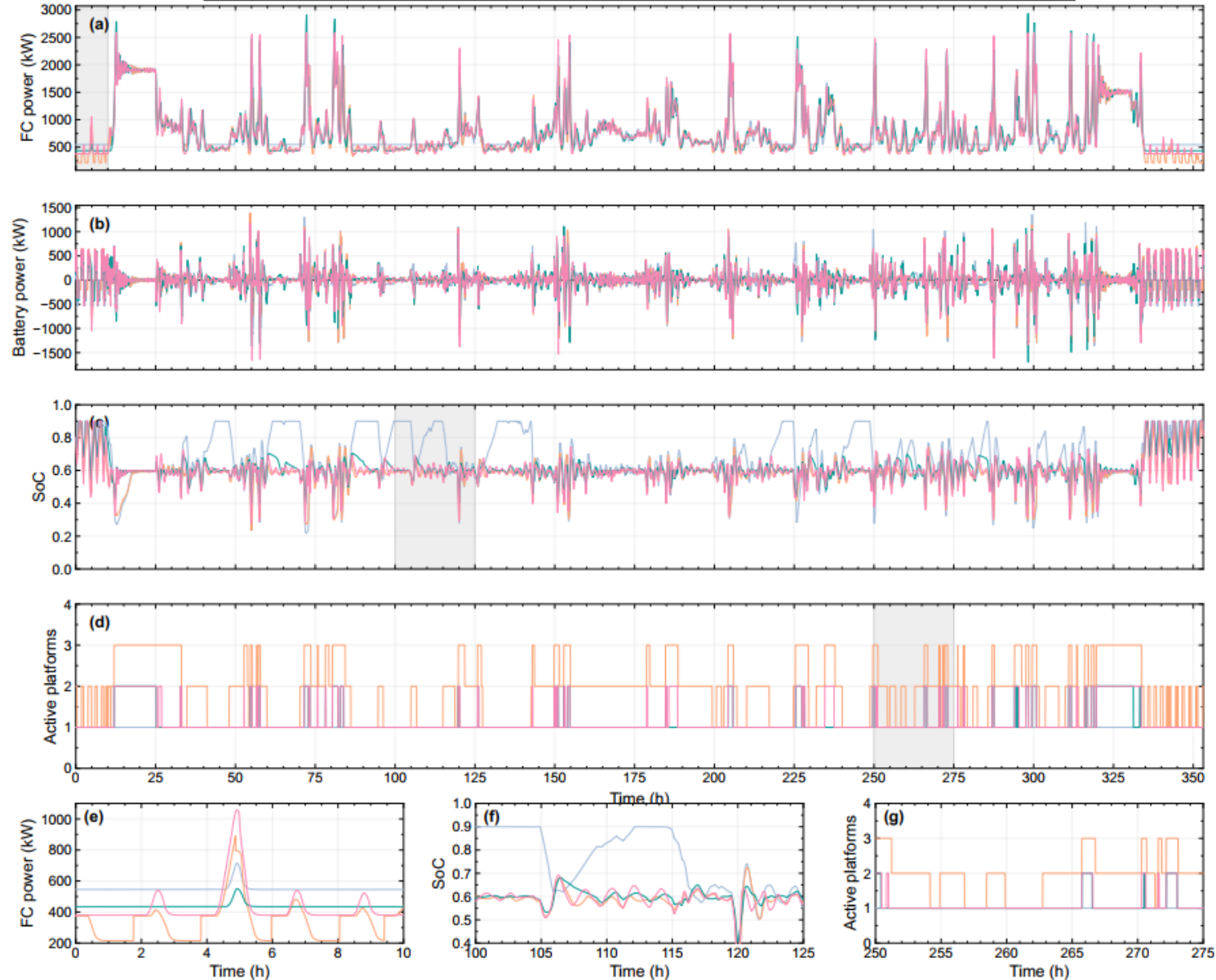
Representative Pareto-optimal solutions for PEMFC

Pathway	Solution	Config.	Batt.	CAPEX (MUSD)	OPEX (MUSD)	CII (gCO ₂ /t·nm)	TOPSIS rank
PEMFC	TOPSIS	2P-13FC	8	22.19	79.79	11.65	1
	Min-CAPEX	1P-10FC	9	19.93	80.39	12.17	64
	Min-OPEX	3P-10FC	10	23.16	78.87	11.91	43
	Min-CII	2P-16FC	13	24.29	82.03	11.58	77

- PEMFC achieves the deepest CII reduction: 156.26 → 11.65 gCO₂/t·nm.
- TOPSIS selects 2P-13FC-8B as the best compromise design.
- Min-CAPEX is cheaper, but gives higher CII: 12.17 gCO₂/t·nm.
- Min-CII gives only marginal improvement: 11.65 → 11.58 gCO₂/t·nm.
- Higher investment reduces CII, but with diminishing carbon benefit



Min-CAPEX (1P-10FC-9B) Min-OPEX (3P-10FC-10B) Min-CII (2P-16FC-13B) TOPSIS (2P-13FC-8B)



C. PEMFC Operation: Platform Partitioning Reduces H₂ Use

- PEMFC performance depends on both fuel-cell capacity and platform partitioning.
- Platform shutdown reduces H₂ use during low-load operation
- Larger fuel-cell capacity supplies more peak demand directly.
- Smaller fuel-cell systems rely more on battery peak-shaving.
- Higher fuel-cell capacity reduces battery stress and narrows SoC fluctuation.



Cross-technology comparison of TOPSIS-selected decarbonisation solutions against the diesel baseline for the reference SOV

	Diesel baseline	DFME	PEMFC	MRFC
Configuration	–	12C–2E–28B	2P–13FC–8B	12R–13FC–10B
Operating condition	–	$\beta^* = 0.10$	$\Gamma^* = 2.5$	$\beta^* = 0.0$
CAPEX (MUSD)	1.83	8.55	22.19	17.30
OPEX (MUSD)	26.37	88.17	79.79	93.42
LCC (MUSD)	28.20	96.72	101.98	110.72
CII (gCO ₂ /t·nm)	156.26	52.47	11.65	30.53
CII reduction (%)	–	66.4	92.5	80.5
Green premium, GP (MUSD)	–	68.52	73.78	82.52
AAC (USD/tCO ₂)	–	1,180	912	1,173
Integration requirement	Baseline	Fuel reallocation (46.5 t of 465 t)	Volume expansion (+425 m ³ deck)	Drop-in ($\beta^* = 0.0$)

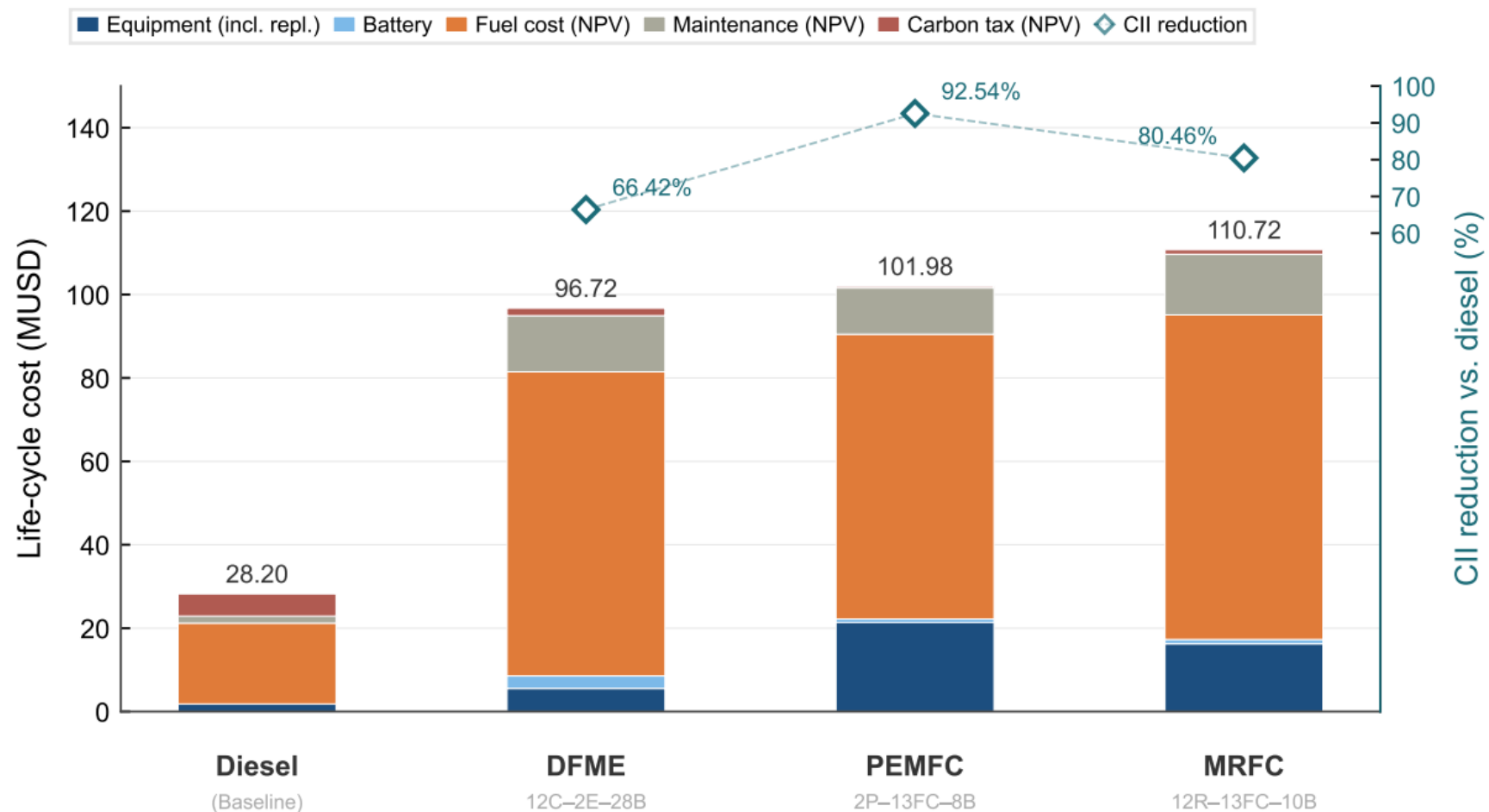
Cross-technology trade-offs and SOV-specific implications

- **DFME:** Lowest LCC: 96.72 MUSD; CII = 52.47 gCO₂/(t·nm)
- **MRFC:** Best retrofit fit: $\beta^* = 0$; CII = 30.53 gCO₂/(t·nm)
- **PEMFC:** Deepest CII cut: 11.65 gCO₂/(t·nm); $\Gamma^* = 2.5$

- *Baseline diesel CII: 156.26 gCO₂/(t·nm). All alternatives reduce CII substantially, but lifecycle cost rises from 28.20 MUSD to 96.72-110.72 MUSD.*

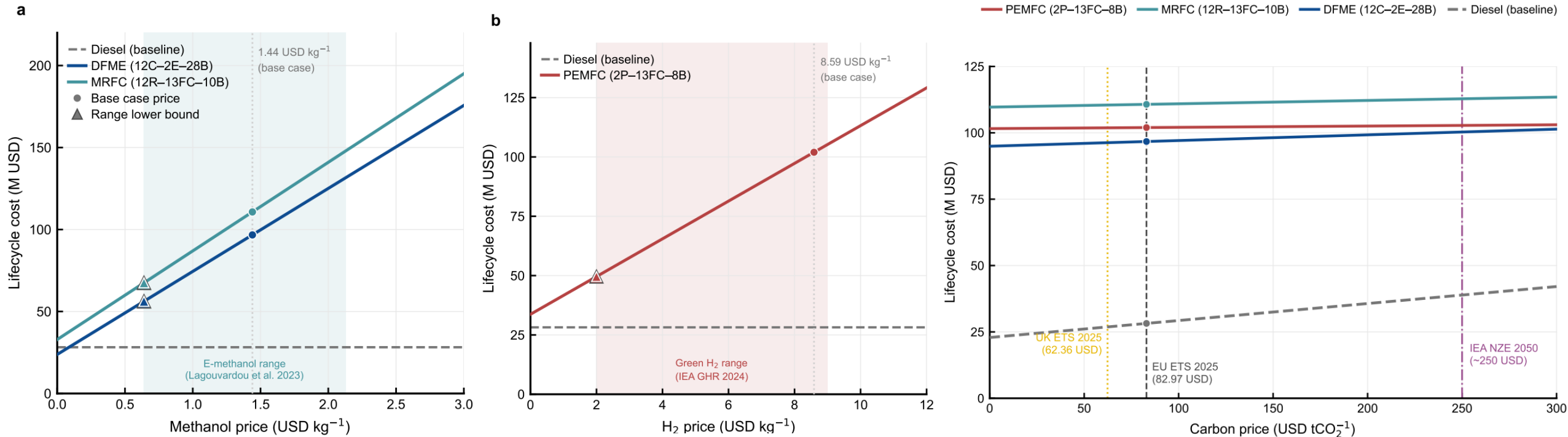
Life-cycle cost over 25 years

- Alternative pathways cut CII strongly, but at much higher life-cycle cost.
- Diesel remains cheapest: 28.2 MUSD over 25 years.
- PEMFC gives the highest CII reduction: 92.5%, but cost rises to 102.0 MUSD.
- DFME is the lowest-cost alternative; MRFC offers a balanced retrofit-friendly route.
- Fuel cost dominates the life-cycle cost, not equipment cost.



Fuel price and Carbon price sensitivity

- Fuel price strongly controls (66–75% of lifecycle) alternative pathway LCC.
- PEMFC becomes more competitive only if delivered H₂ price falls sharply.
- PEMFC is highly H₂-price sensitive: 101.98 MUSD at 8.59 USD/kg H₂ → 49.6 MUSD at 2 USD/kg H₂.
- PEMFC becomes cheaper than DFME only when H₂ price falls below ~7.9 USD/kg.
- Carbon price up to 300 USD/tCO₂ is not enough for cost parity with diesel.





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Thank you for your attention

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Prof Dawei Wu

Email: dawei.wu@durham.ac.uk



Engineering and
Physical Sciences
Research Council



Funded by
UK Government



Department
for Transport

This work was supported by the Engineering and Physical Sciences Research Council, United Kingdom
Grant numbers: MaRes (EP/Y024605/1).

UK-MaRes Hub The UK-MaRes Hub logo, featuring three small icons: a green square, a white circle, and a white flag on a pole.



**Centre for Advanced
Powertrain and Fuels**



Advanced Propulsion Technologies for Maritime Decarbonisation Using Hydrogen and Derived Fuels

Prof Xinyan Wang

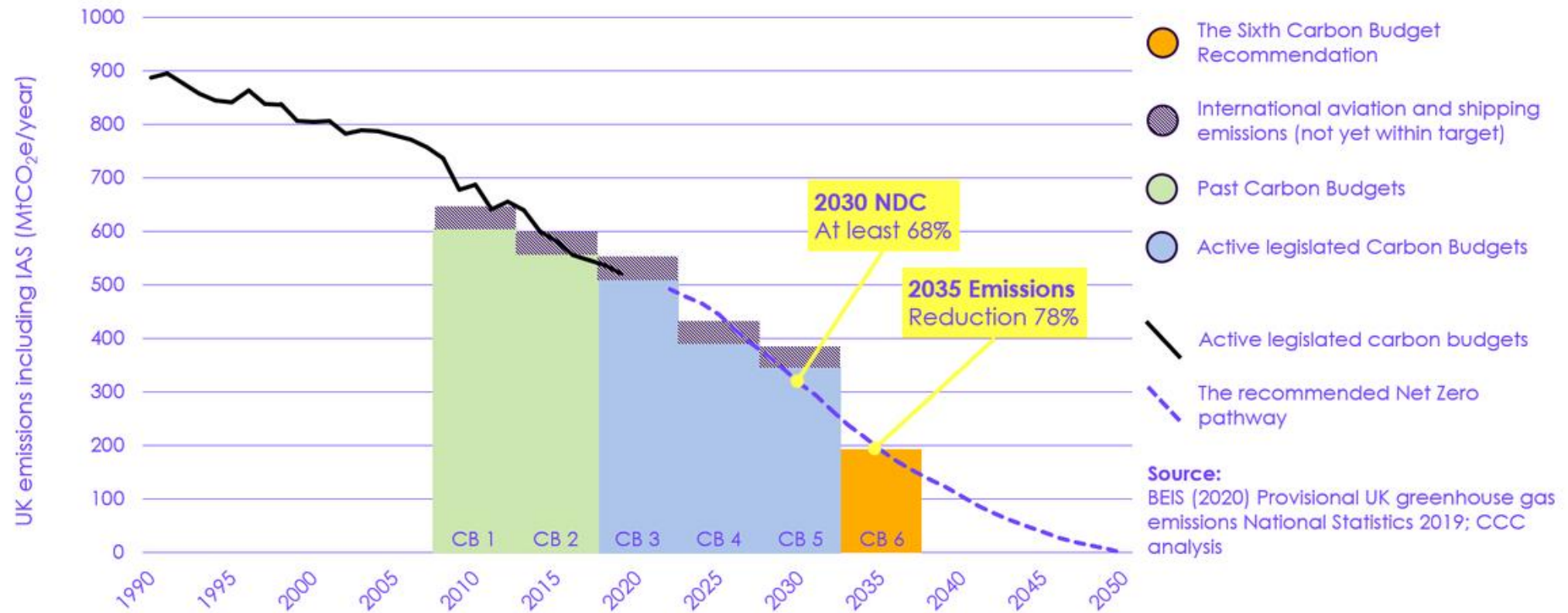
Co-Director, Centre for Advanced Powertrain and Fuels

Brunel University of London



Challenges of moving towards net zero

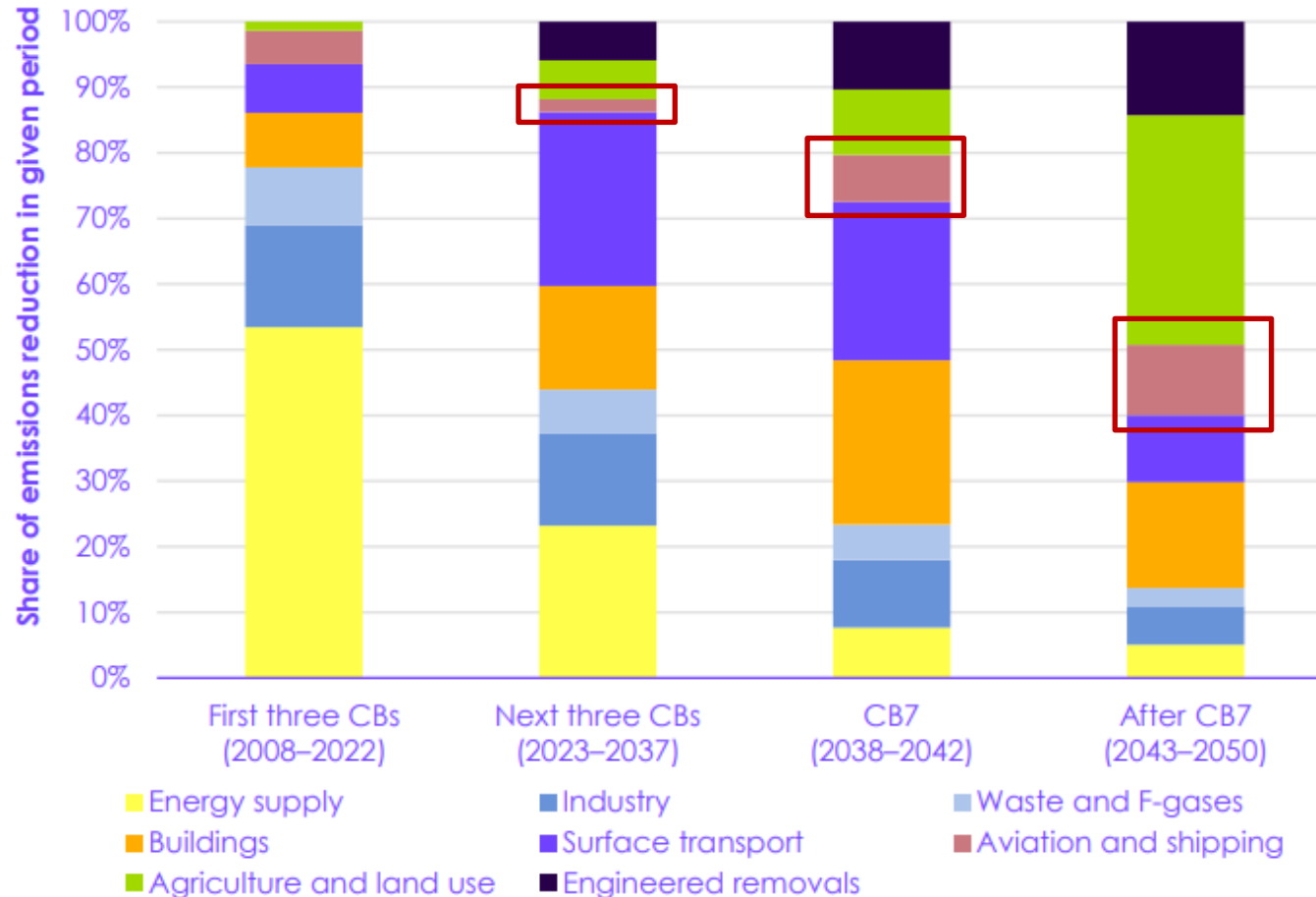
UK carbon budgets





Challenges of moving towards net zero

Figure 2 Distribution of emissions reductions during each carbon budget period



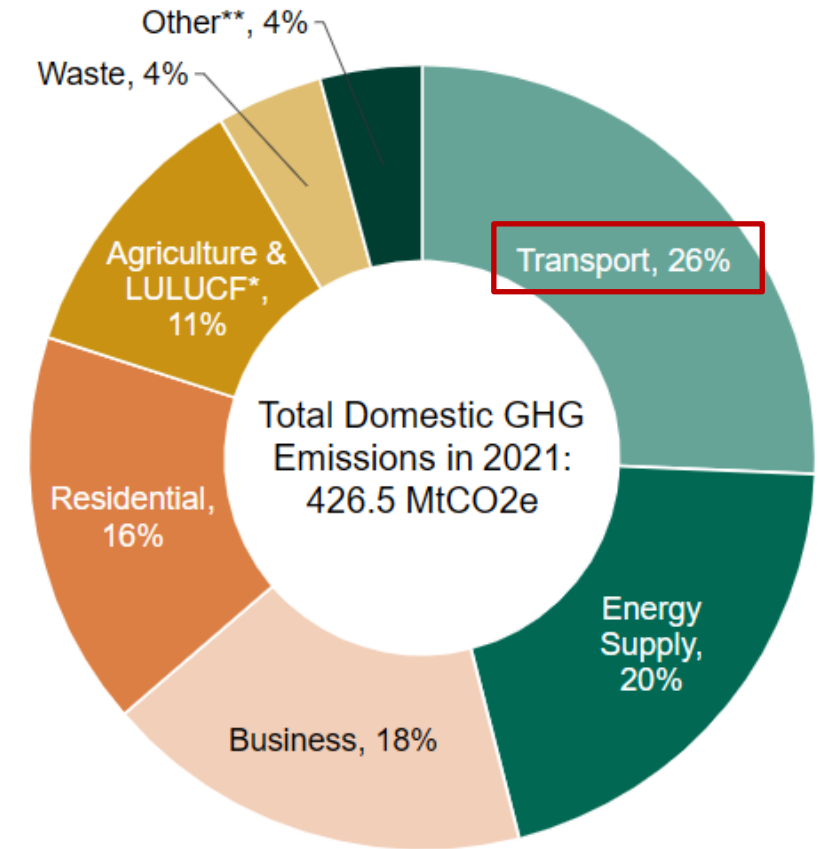
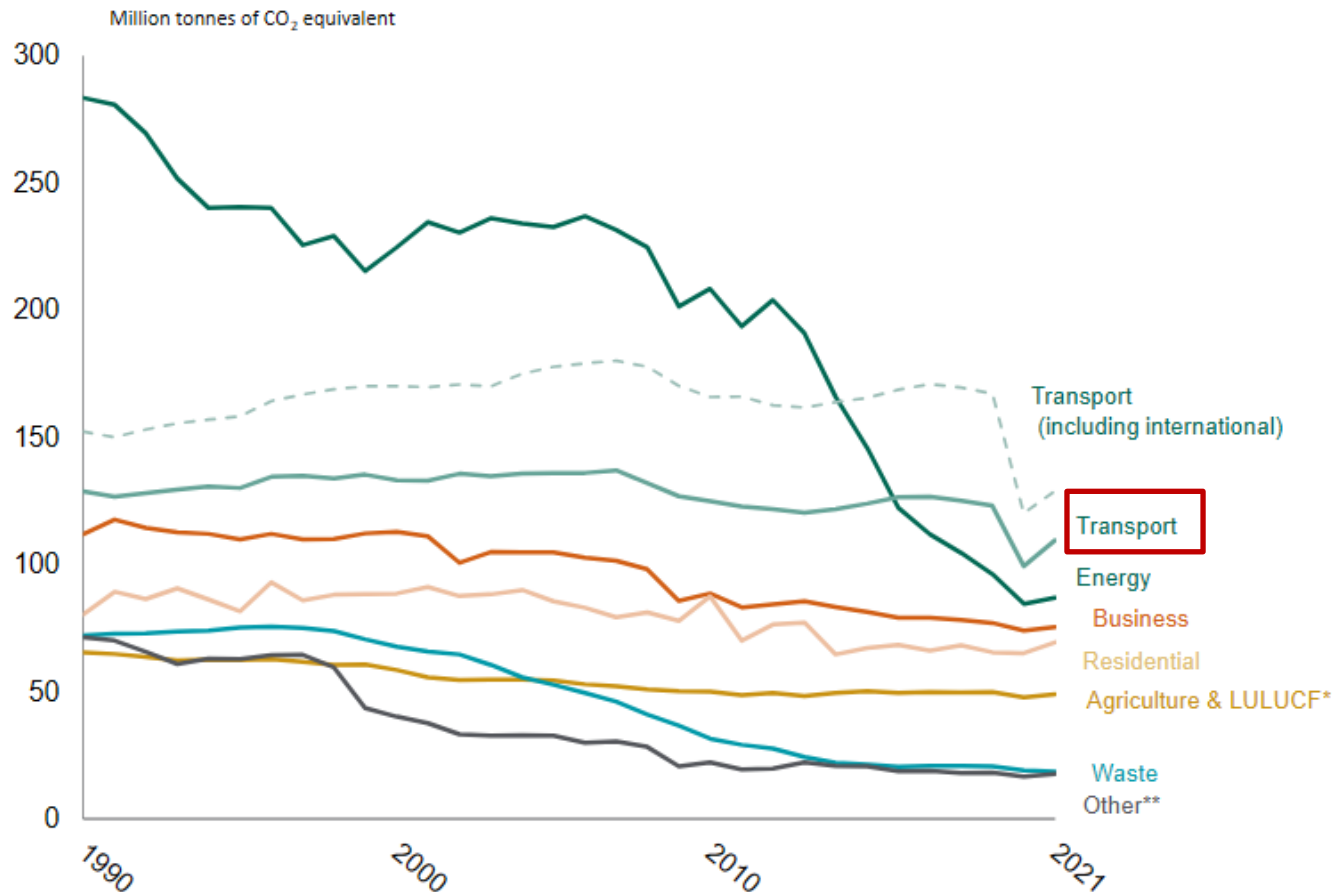
Aviation and shipping

Surface transport

Source: The Seventh Carbon Budget Advice for the UK Government

Challenges of moving towards net zero

Transport is an important but challenging area for decarbonisation





Challenges of moving towards net zero

What about aviation, marine, and non-road mobile machinery?

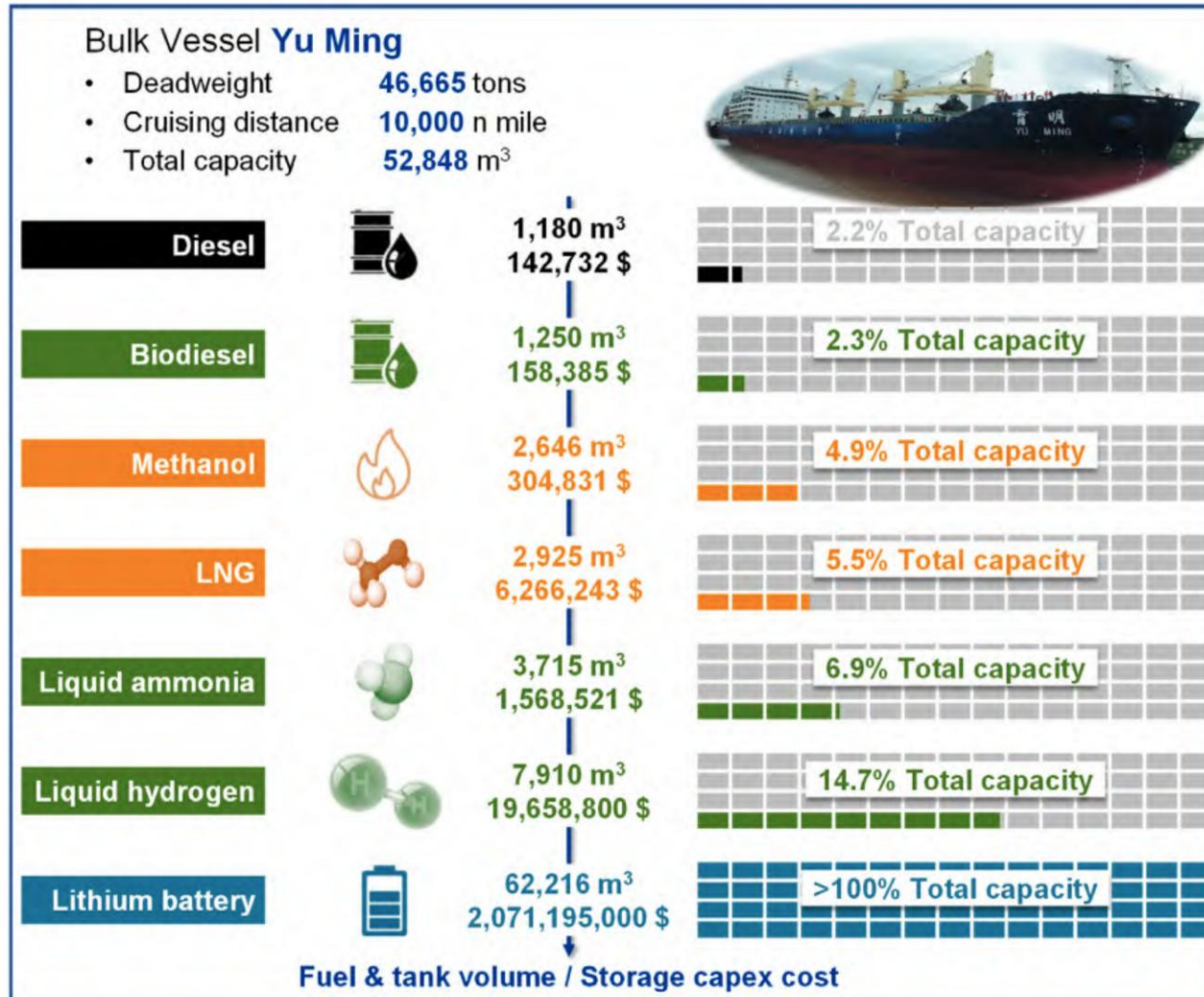
- High power/weight & volume requirement
- High energy density requirement (continuous running from days to months)
- Poor environmental conditions (humidity, dust, etc)
- Limited/no charging availability



Source: online

Challenges of moving towards net zero

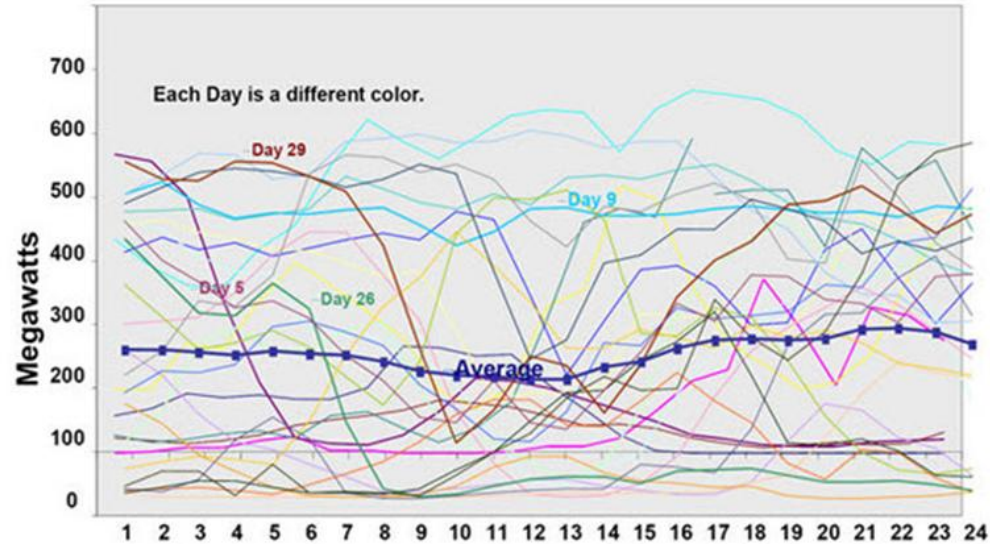
Hydrogen and hydrogen derived fuels are important to decarbonise marine sector



Reference: Pilot diesel-ignited ammonia dual fuel low-speed marine engines: A comparative analysis of ammonia premixed and high-pressure spray combustion modes with CFD simulation

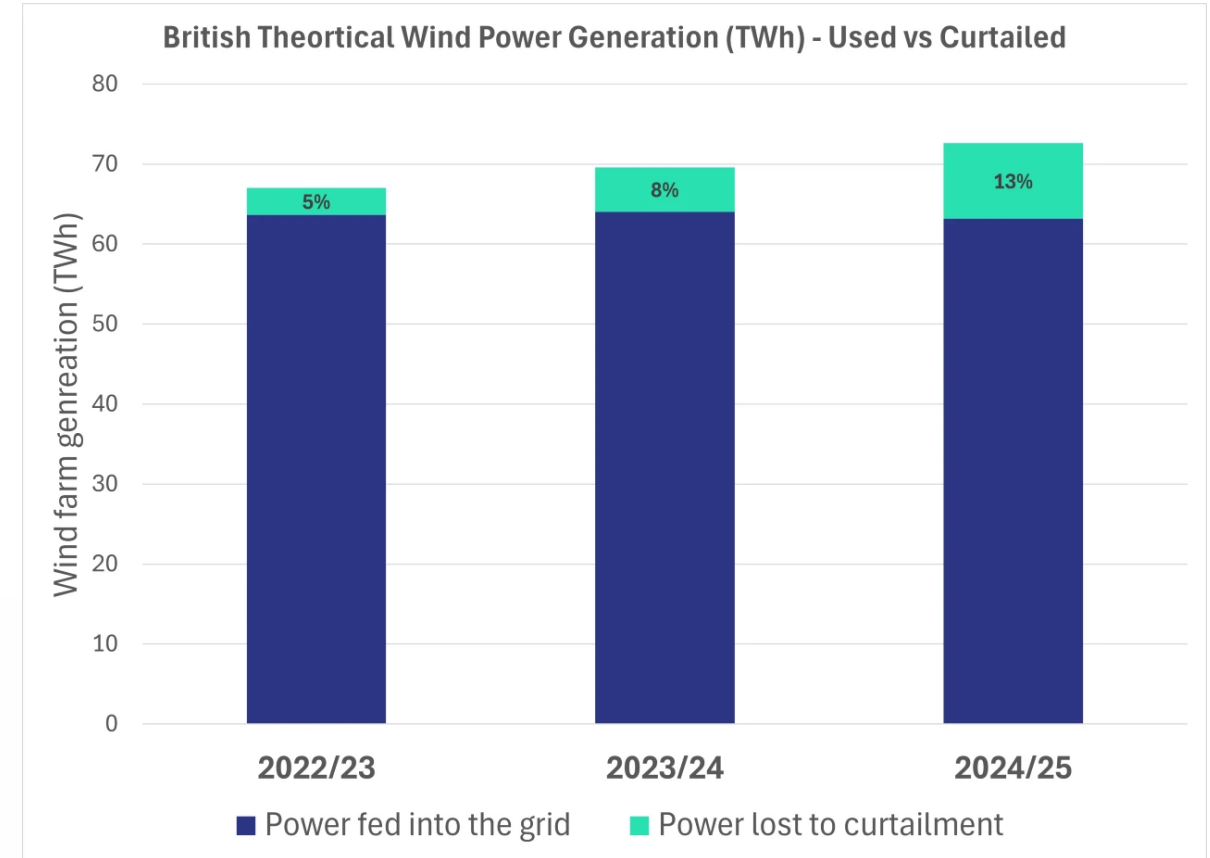
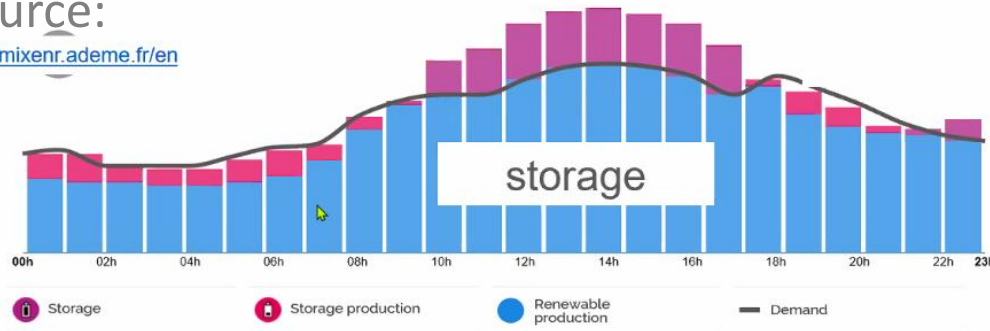
Why hydrogen and hydrogen-derived fuels?

Energy storage is key in a renewable energy future



Source:

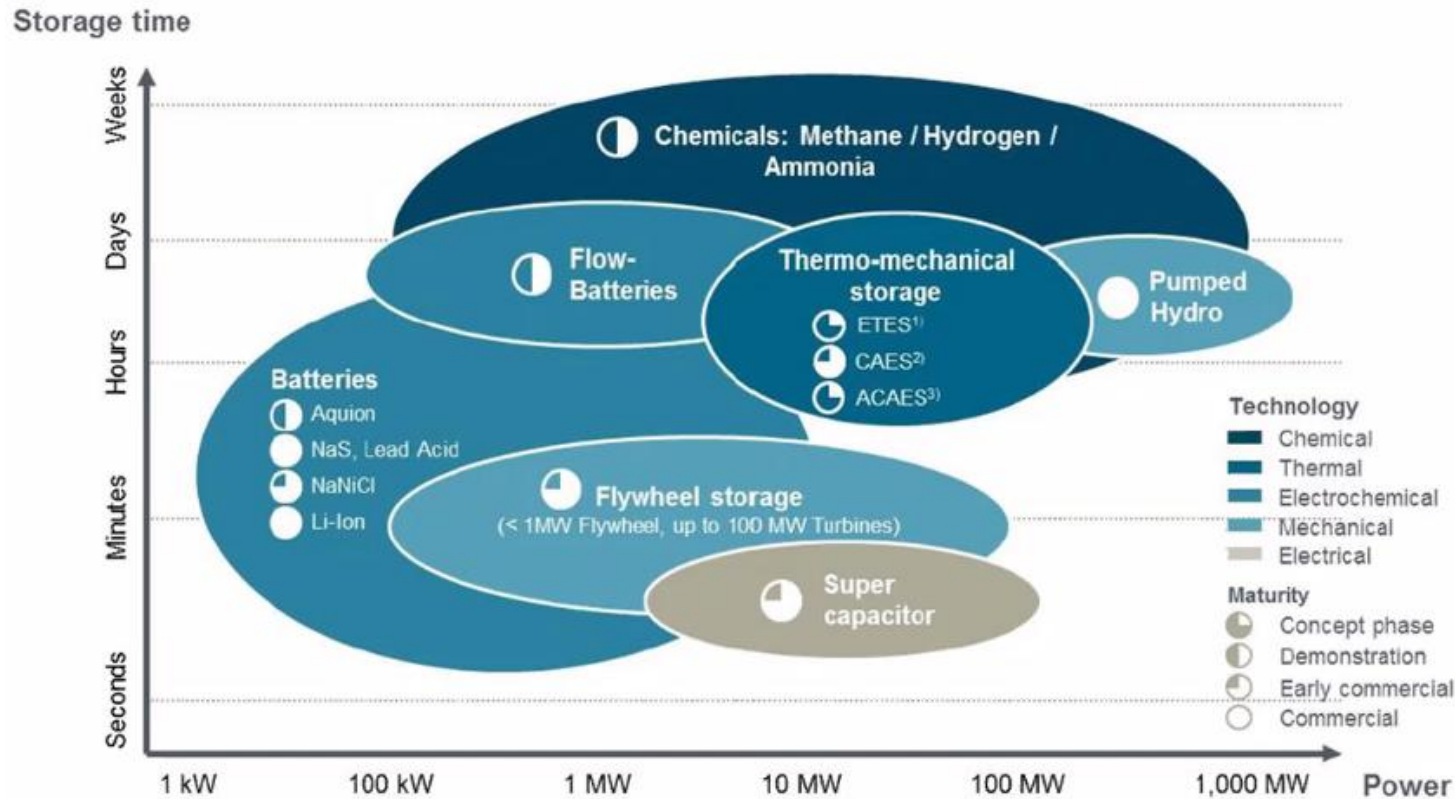
<http://mixer.ademe.fr/en>



Source: Business energy deals

Why hydrogen and hydrogen-derived fuels?

Hydrogen is an excellent chemical is hydrogen good for **long-term large-scale** energy storage



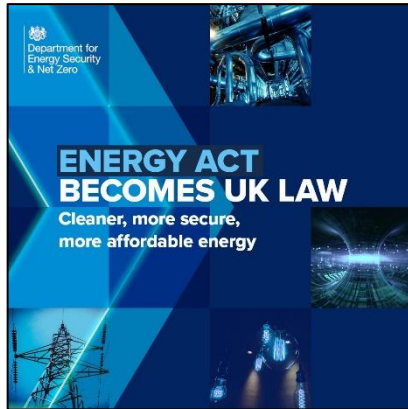
Source:
[Wilkinson, 2017, 1st NH₃ European Conference](#)

¹) Electro-Thermal Energy Storage

²) Compressed Air Energy Storage

³) Adiabatic Compressed Air Energy Storage

Why hydrogen and hydrogen-derived fuels?



Press release

Jobs unlocked as first wave of hydrogen projects sign contracts

10 projects from the first phase of the government's flagship hydrogen programme can begin construction.

From: [Department for Energy Security and Net Zero](#) and [Sarah Jones MP](#)

Published 23 July 2025

Parliamentary Bills

[UK Parliament](#) > [Business](#) > [Legislation](#) > [Parliamentary Bills](#) > [Energy Act 2023](#) [Bill feed](#)

Energy Act 2023

Government Bill

Originated in the House of Lords, Session 2022-23

Last updated: 3 November 2023 at 15:11

Lords Commons Final stages

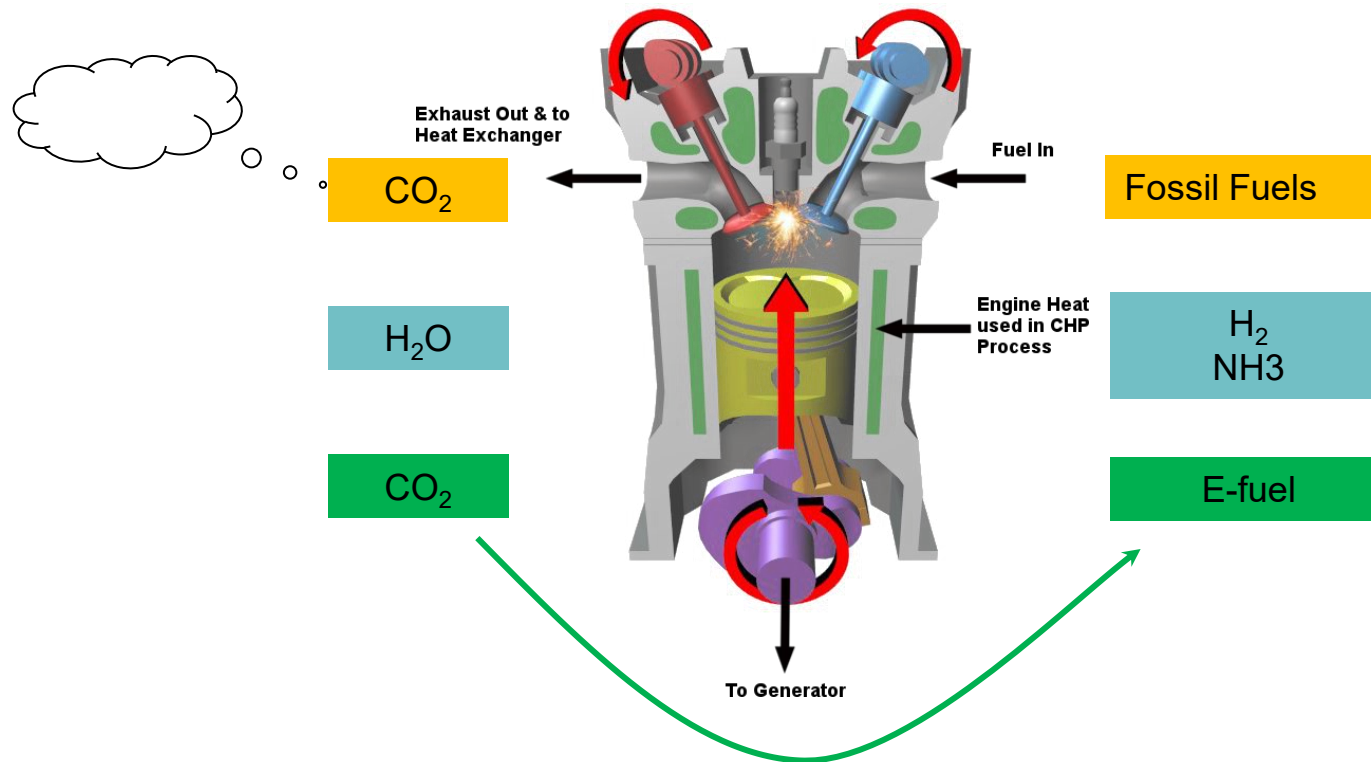
✓ ——— ✓ ——— ✓

[See full passage](#)

- Enable the scale up of CO2 and hydrogen transport and storage networks, through the establishment of regulation and licensing frameworks.
- Enable the delivery of a large village hydrogen heating trial by 2025.



- ❑ H2ICE produce zero carbon emissions

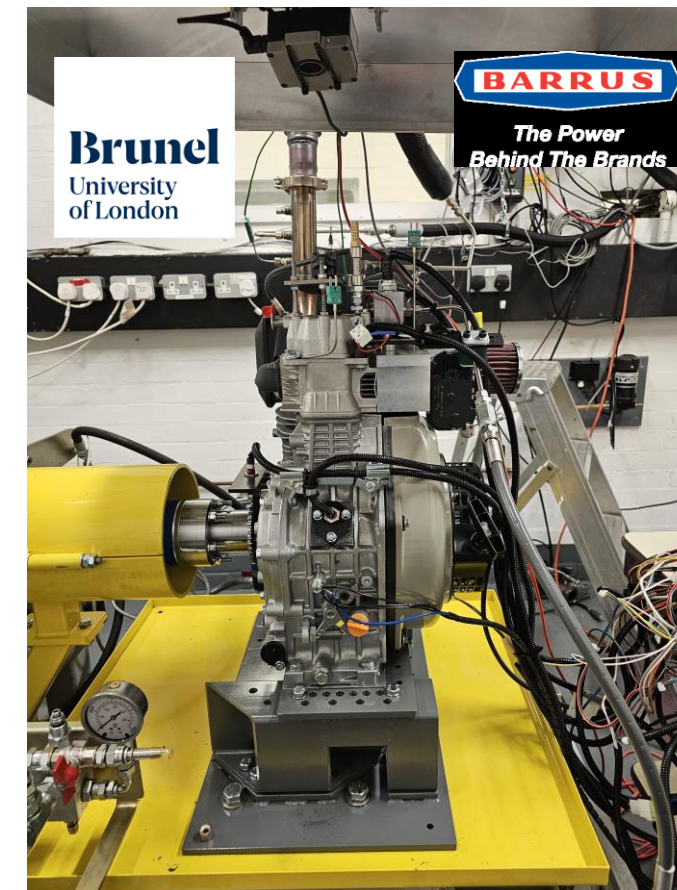
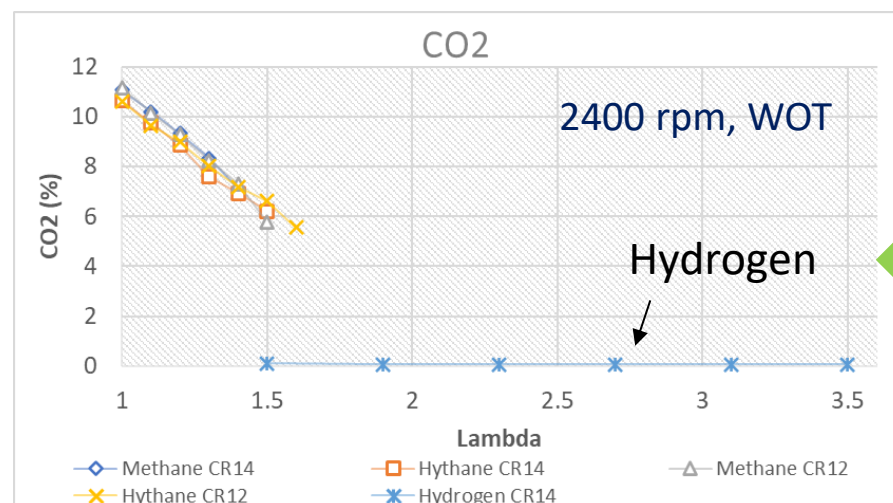
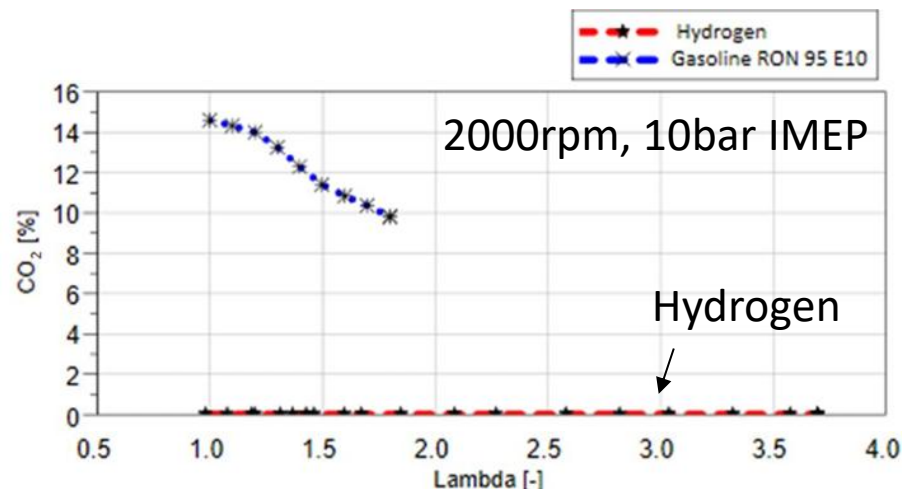


Advanced Low- and Zero-Carbon Propulsion Technologies

- ❑ H2ICE produce zero carbon (CO₂) emissions



A single cylinder 0.4litre
PFI/DI H₂ Engine



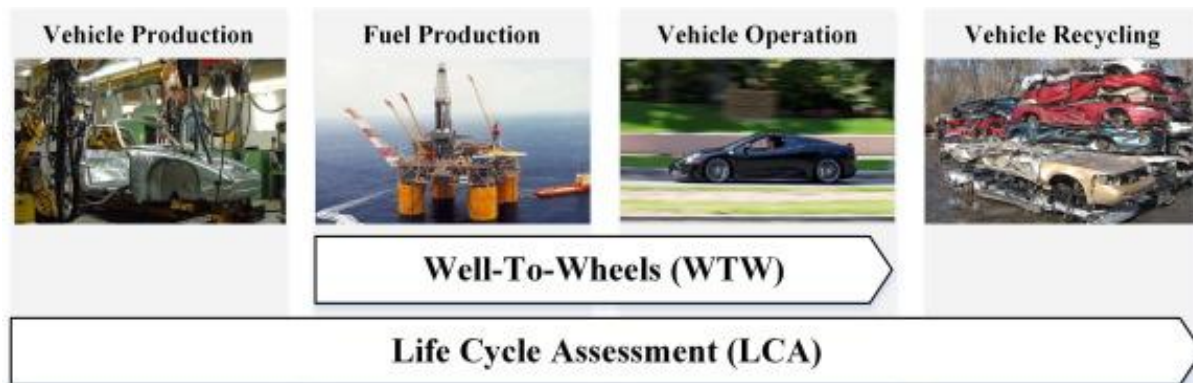
A diesel generator
converted H₂ Engine

CMDC R2

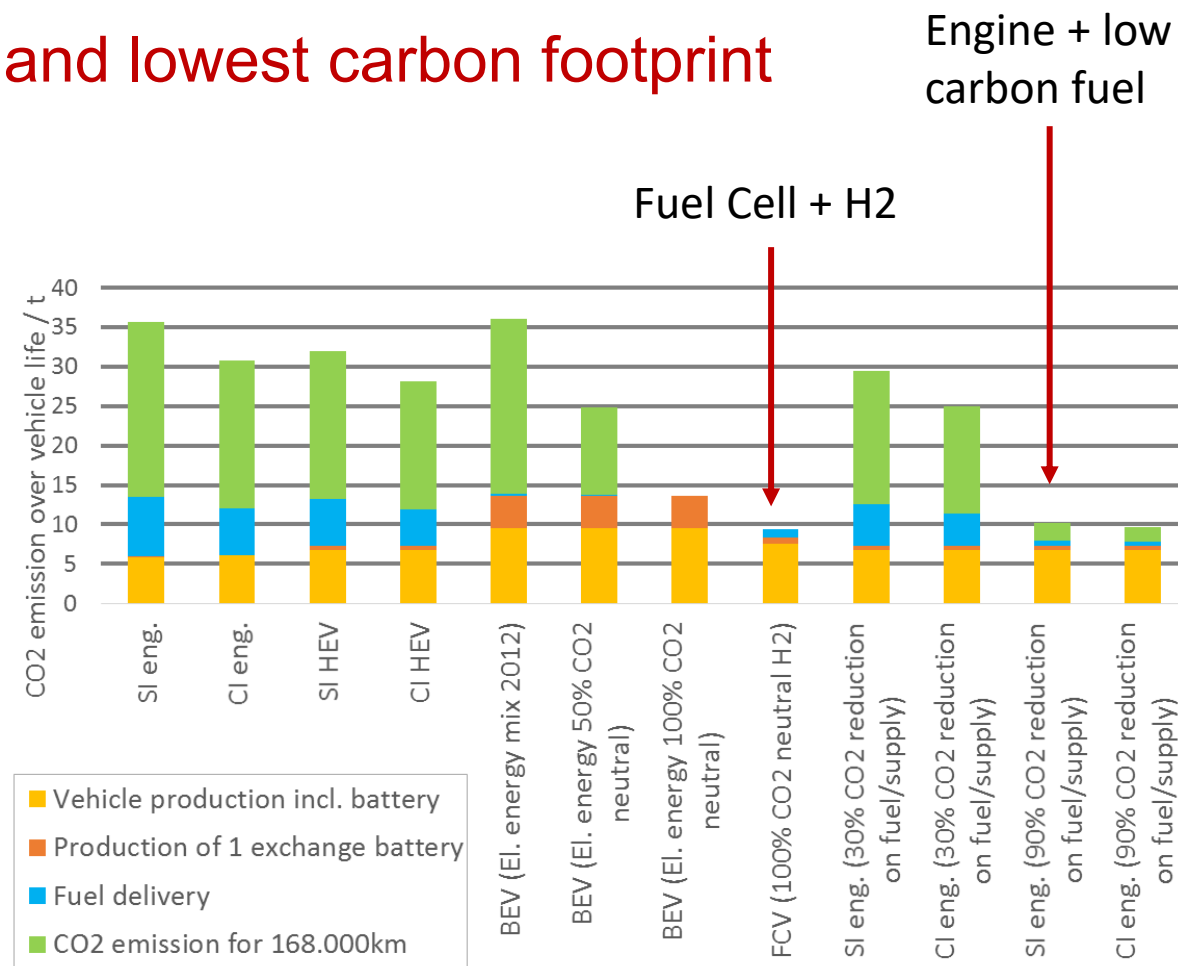
Advanced Low- and Zero-Carbon Propulsion Technologies

❑ H2ICE and FC show comparable and lowest carbon footprint

Life cycle analysis (LCA) of carbon emissions



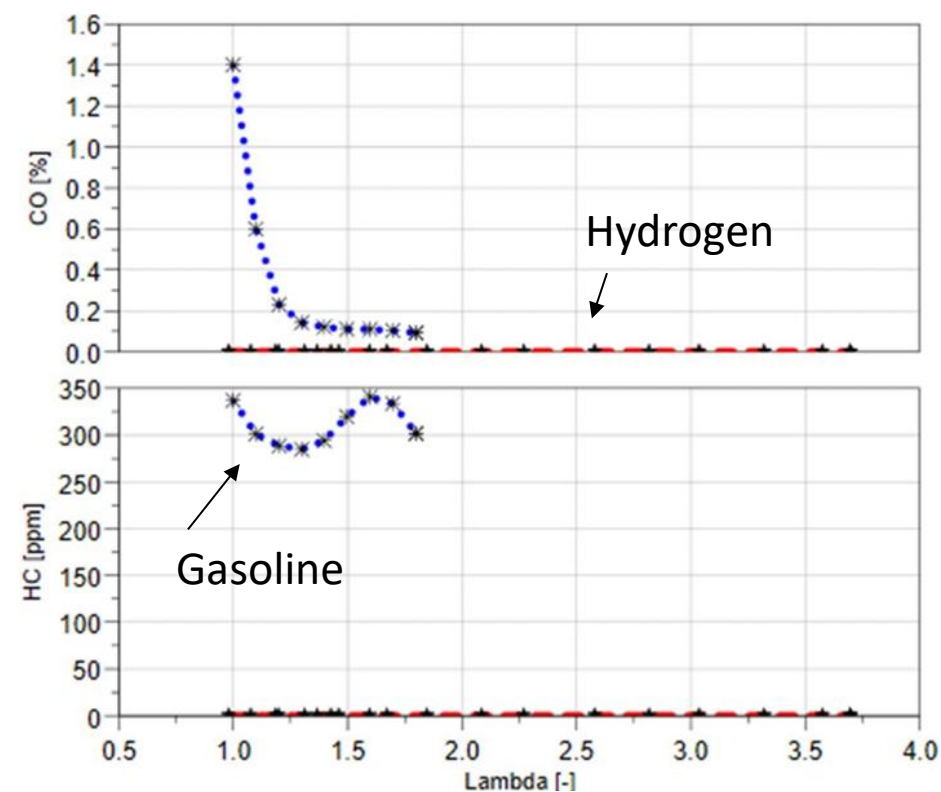
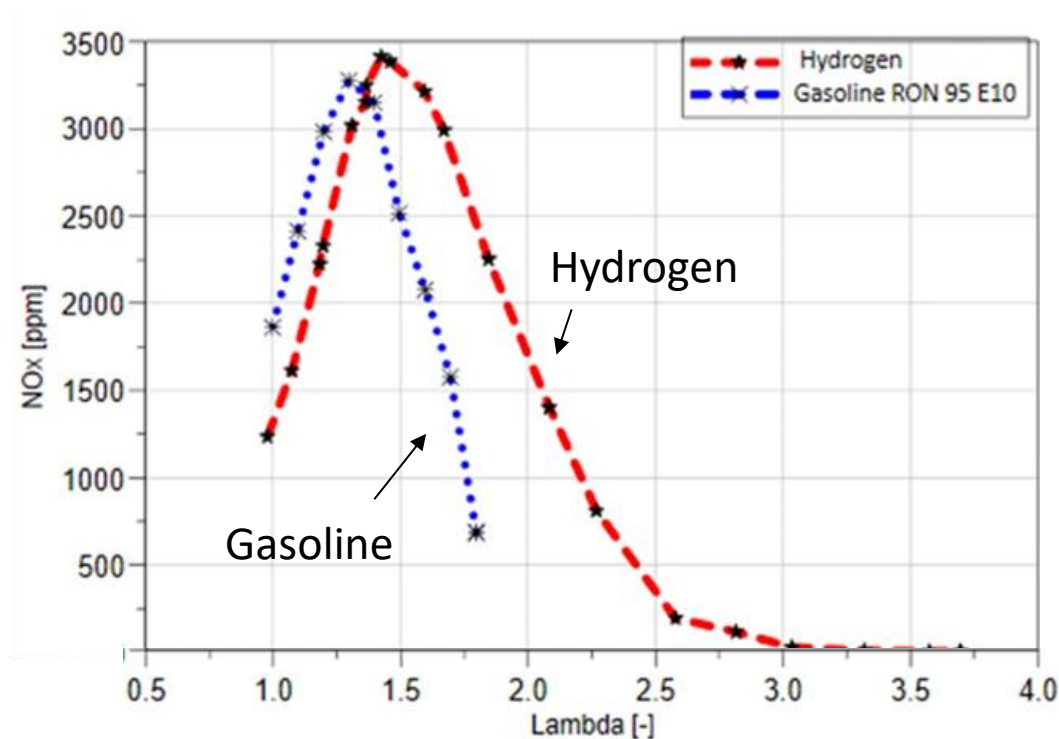
Source: online



*) Total lifetime: 168 000 km

Source: FEV 2018

❑ H2ICE produce near-zero emissions

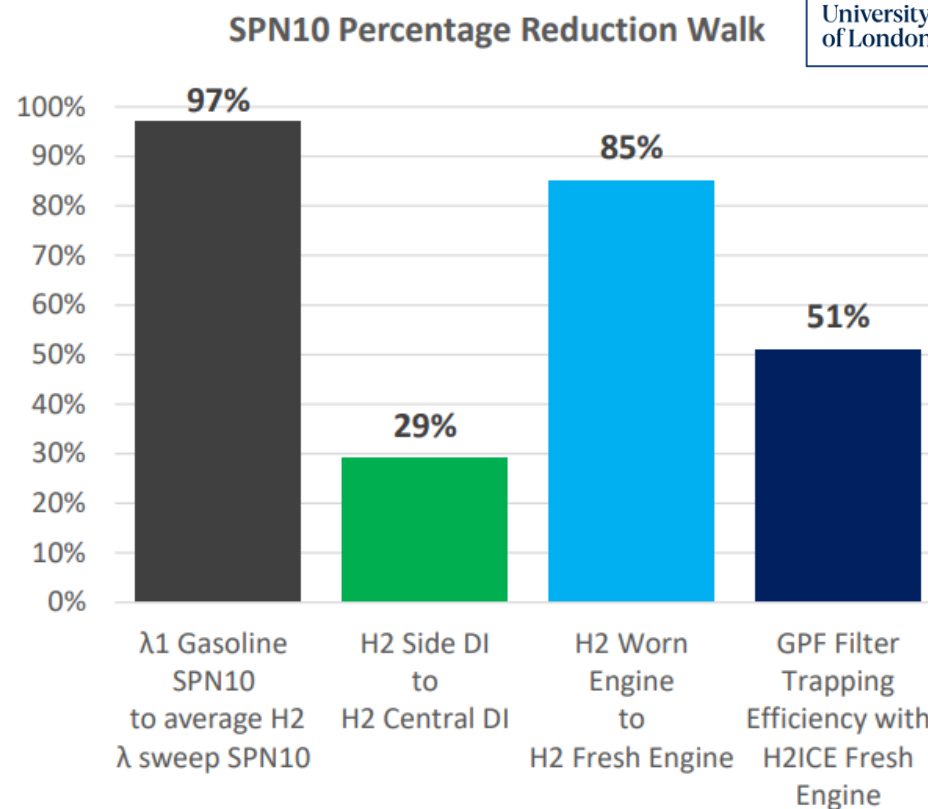
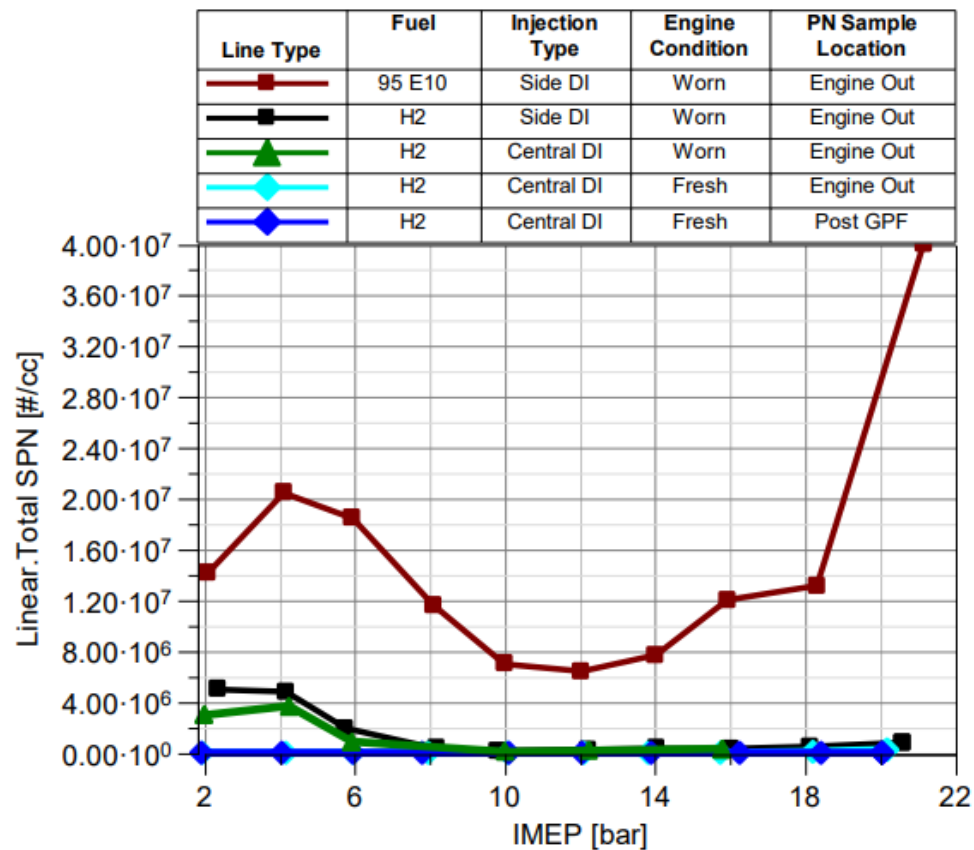


Notes: Results obtained on single cylinder 0.4litre H2 Engine at Brunel

2000rpm, 10bar IMEP

SAE Int. J. Fuels Lubr. 17(3):225-242, 2024, <https://doi.org/10.4271/04-17-03-0015>.

□ H2ICE produce near-zero emissions

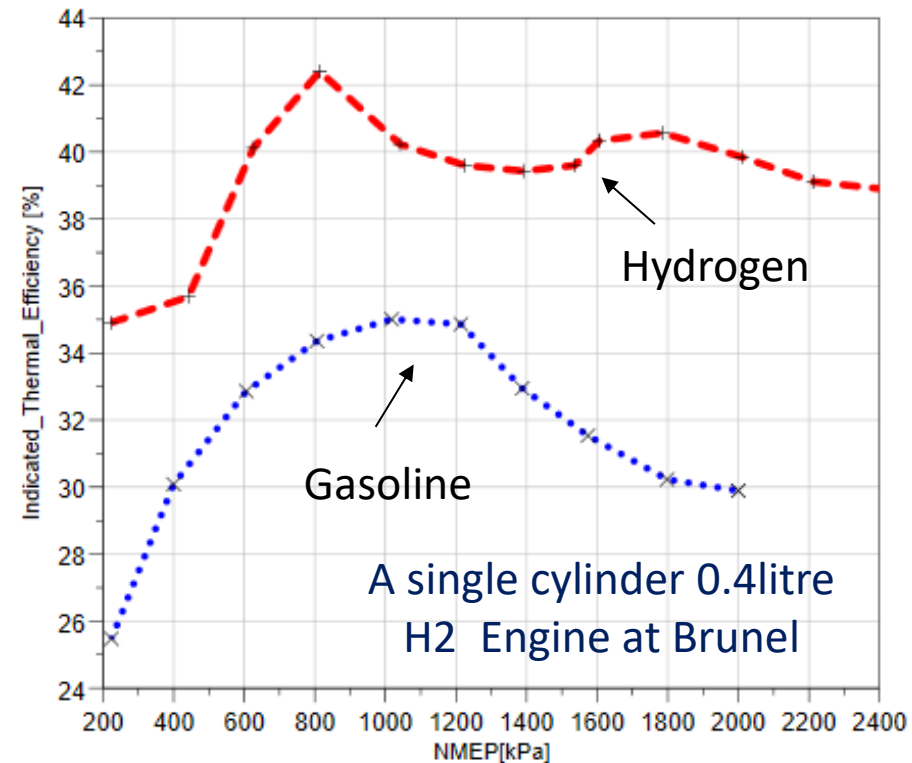


Notes: Results obtained on single cylinder 0.4litre H2 Engine at Brunel

❑ H2ICE can be more efficient



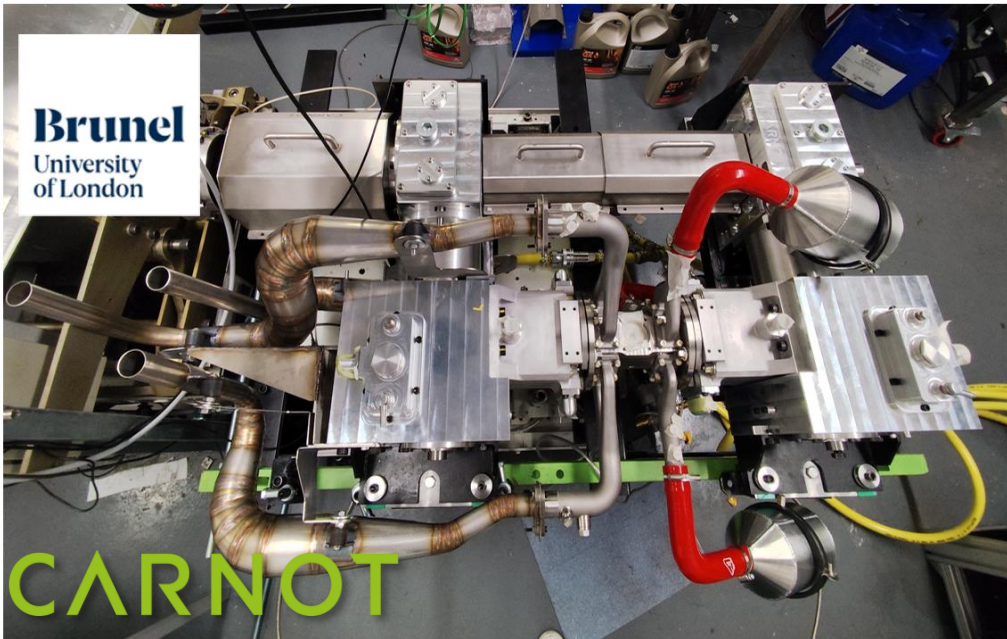
A single cylinder 0.4litre
PFI/DI H₂ Engine



SAE Int. J. Fuels Lubr. 17(3):225-242, 2024,
<https://doi.org/10.4271/04-17-03-0015>.

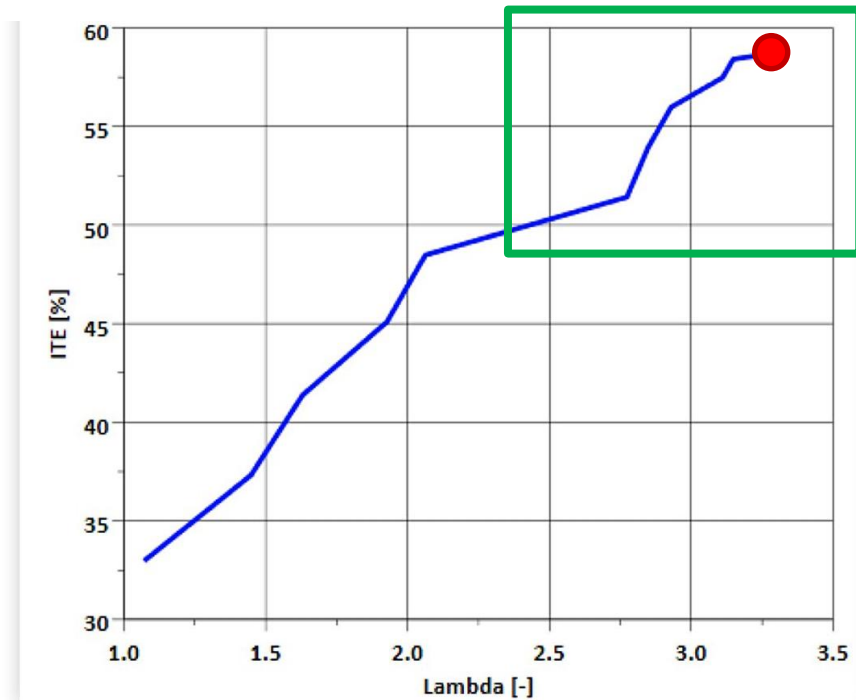
❑ H2ICE can be more efficient

CMDC R3/R4



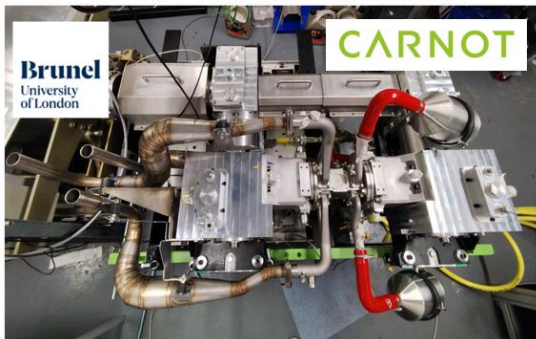
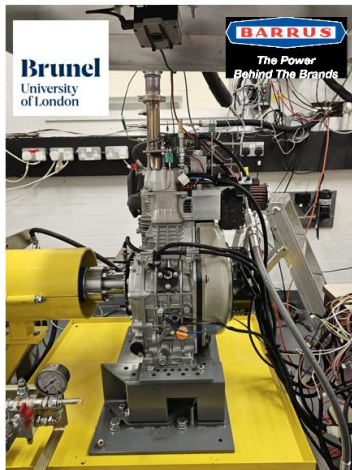
A 2-stroke opposed piston DI H₂ Engine

ITE increases from 33% ($\lambda = 1.1$) to ~**58.7%** ($\lambda \approx 3.25$)

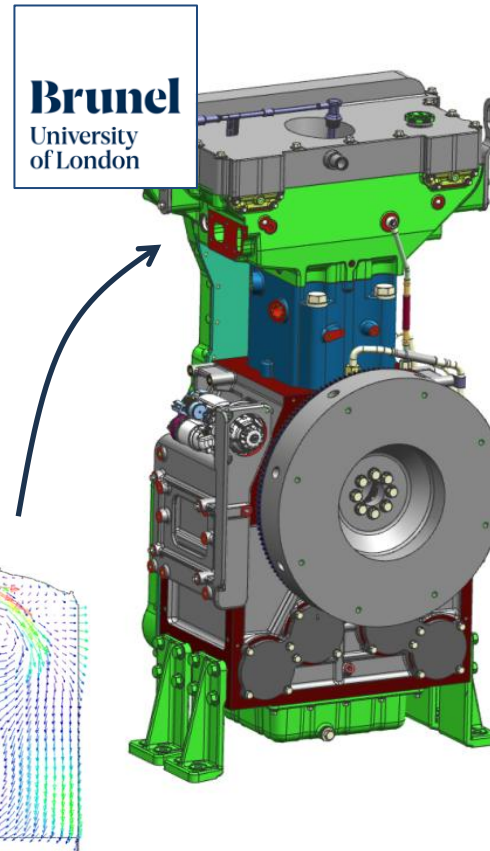


❑ Cost-effective decarbonisation from converted to dedicated H2ICEs

Converted H2ICEs at Brunel

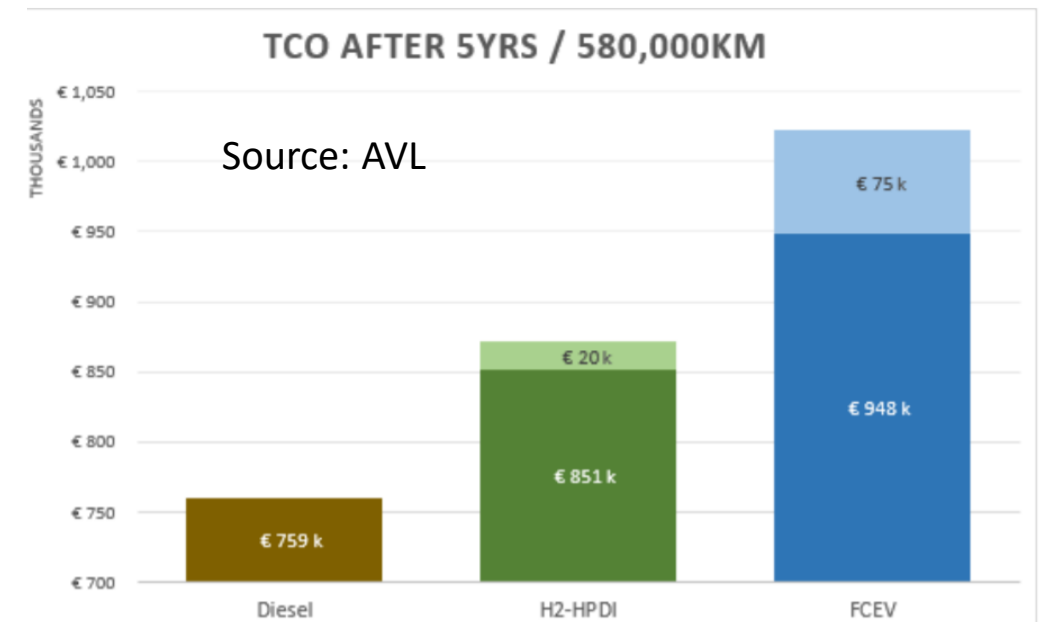


Dedicated H2ICE at Brunel

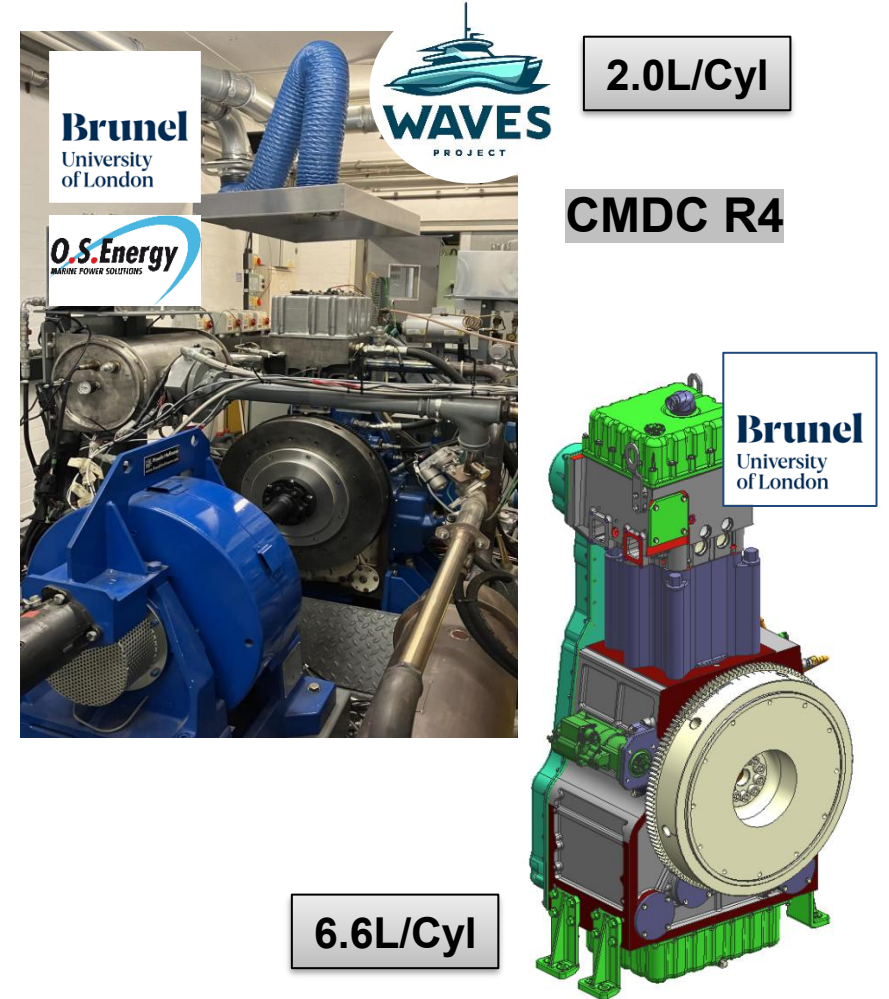
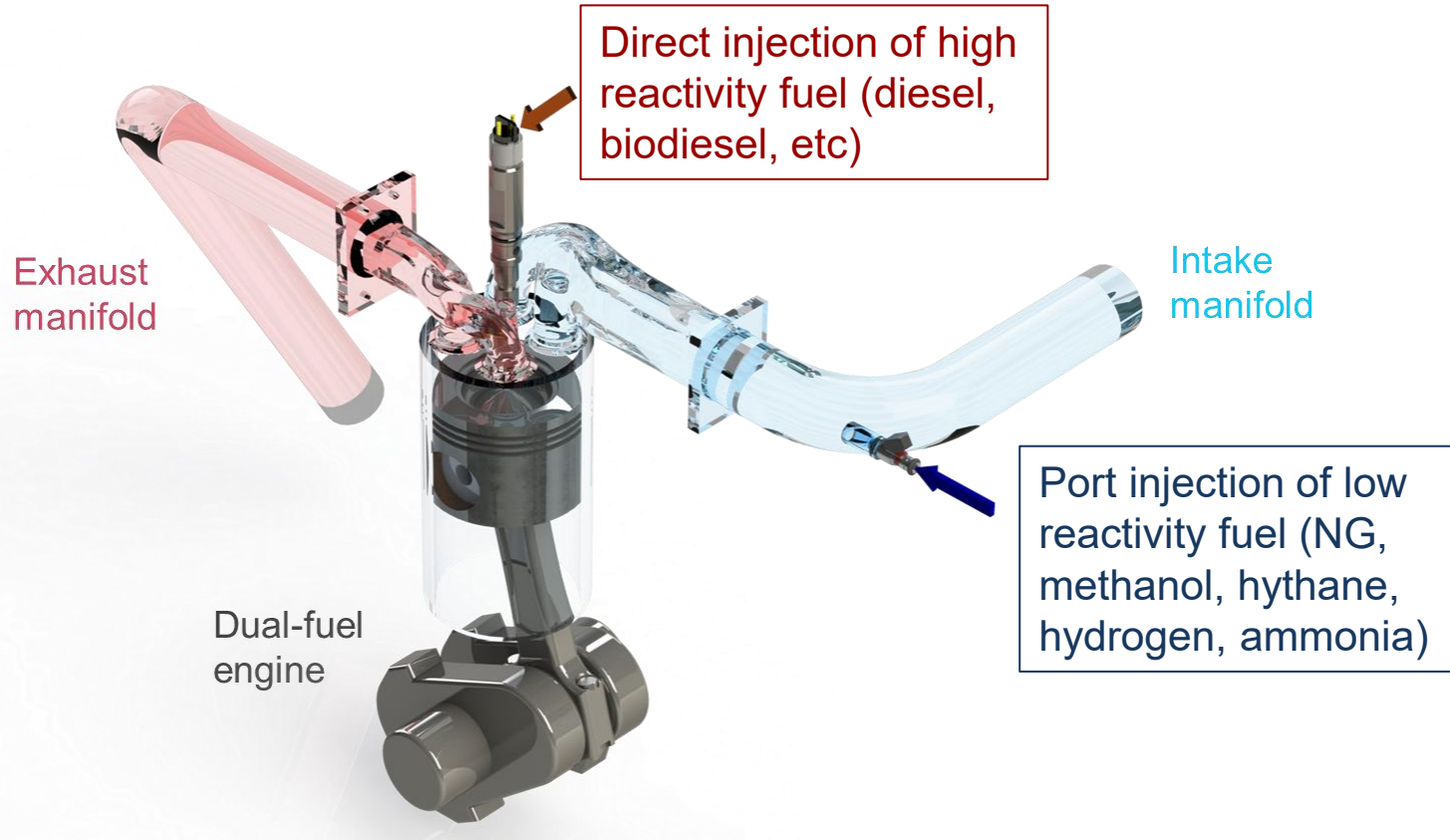


A cost-effective solution

→ Faster implementation (CO₂ reduction)

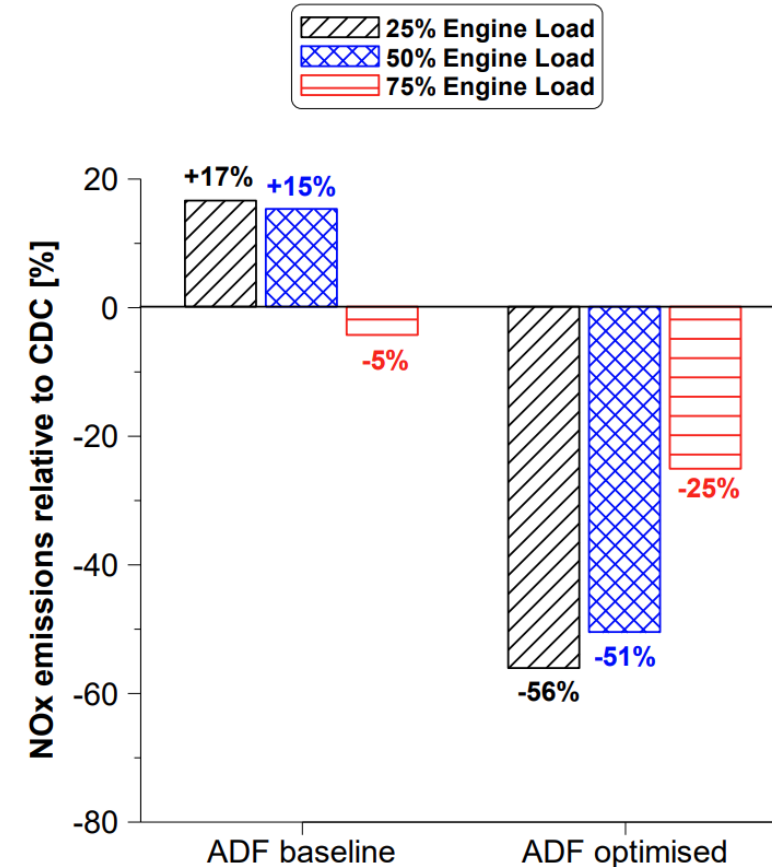
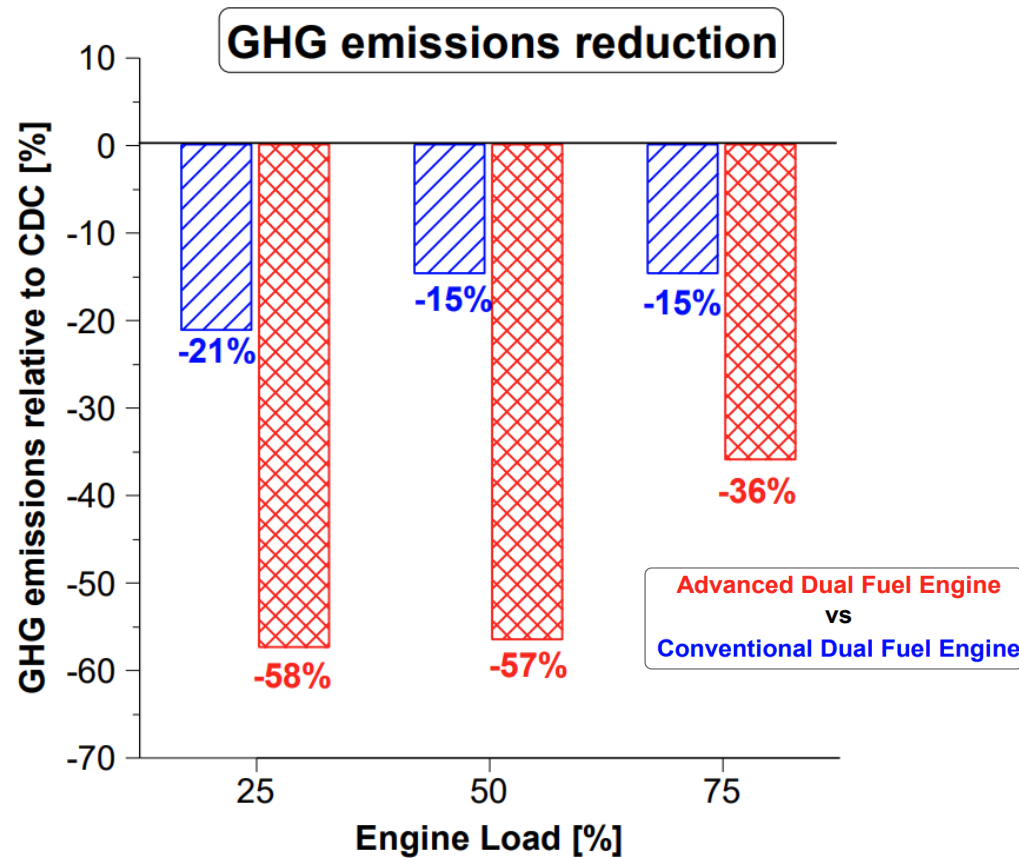


❑ An even cheaper option: dual-fuel H2ICE



Diesel-hydrogen/ammonia/methanol
Dual-fuel Engines

❑ An even cheaper option: dual-fuel H2ICE





Advanced Low- and Zero-Carbon Propulsion Technologies

FASTMOVE: Feasibility of Ammonia 4-Stroke Marine engines in Offshore Vessels

CMDC R6

RICARDO

Development of combustion system & onboard NH₃ safety concept



BRUNEL UNIVERSITY OF LONDON

Ammonia spray studies in chamber



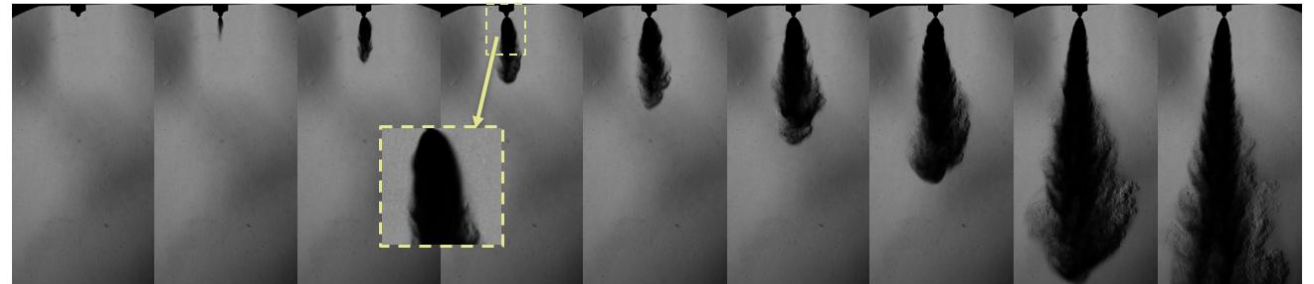
PORT OF CROMARTY FIRTH

Development of port-based bunkering and safety systems

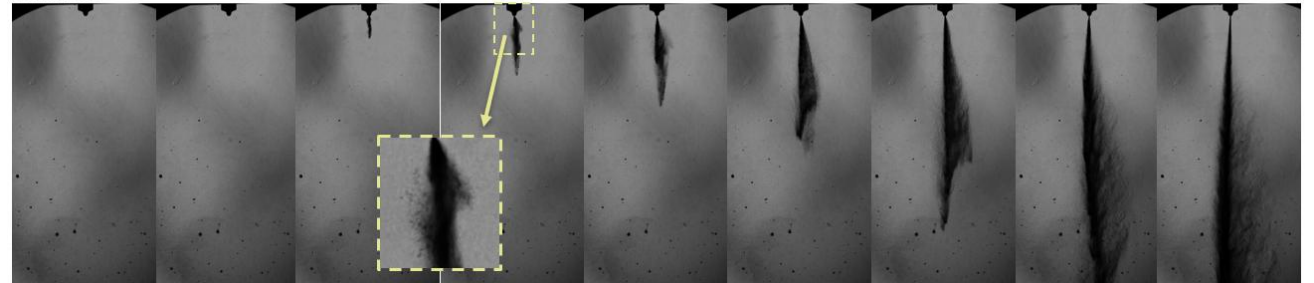
Deliver a High-Pressure Dual Fuel (HPDF) marine engine concept achieving **90% ammonia energy fraction** with **no loss in brake thermal efficiency**, full **IMO Tier III compliance**, and **N₂O < 0.1 g/kWh** to ensure minimal greenhouse impact

Liquid ammonia

$P_{inj}=200\text{bar}$, $T_{NH_3} = 26.7 \text{ deg}$

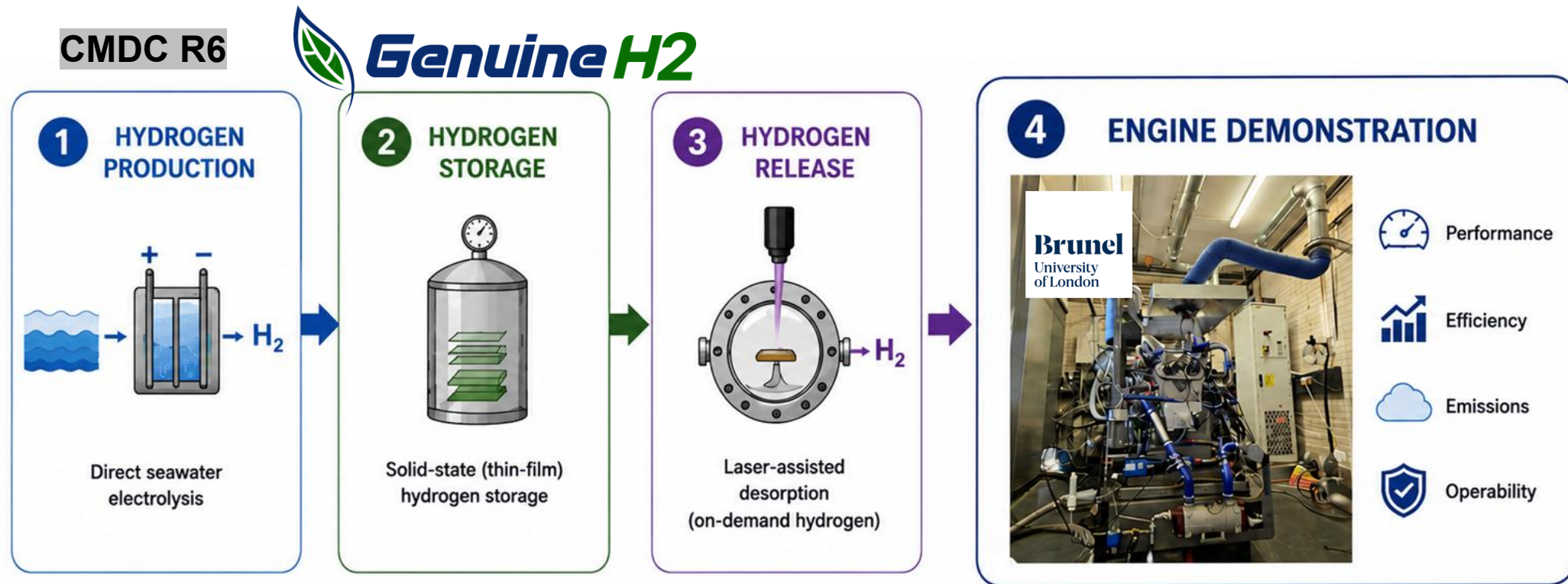


Diesel



Project FASTMOVE is funded by UK Government through the UK Shipping Office for Reducing Emissions (UK SHORE) programme in the Department for Transport.

Propulsion via Direct Seawater Electrolysis and Ambient Hydrogen Storage



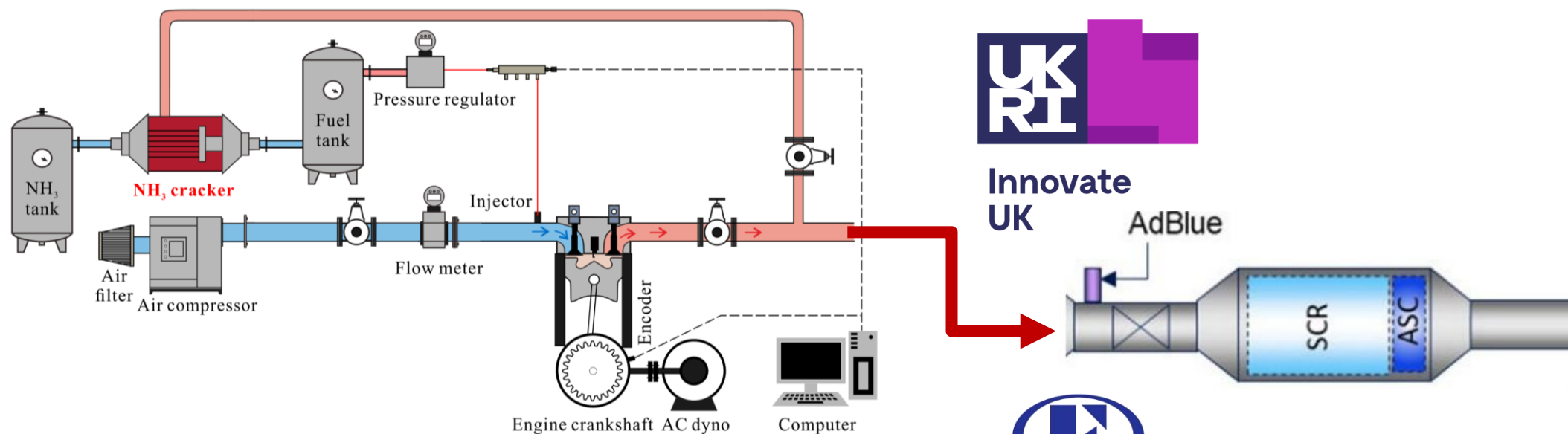
Hydrogen/ammonia combustion engine

Brunel
University of London

CATALSYS
TRANSFORMING ENERGY



UK Research
and Innovation



Innovate
UK



Summary

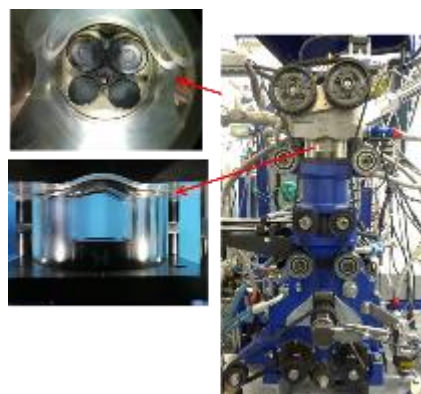
- With the support of CMDC and other government and industrial funding, Brunel has established testing, fundamental measurements and modelling capabilities of hydrogen and ammonia marine engine research.
- We see hydrogen and hydrogen derived fuel engines an enabler for quick maritime decarbonisation and hydrogen economy because they can produce zero/net-zero carbon emissions, and they are cost-effective and affordable for both retrofitted and dedicated engines.



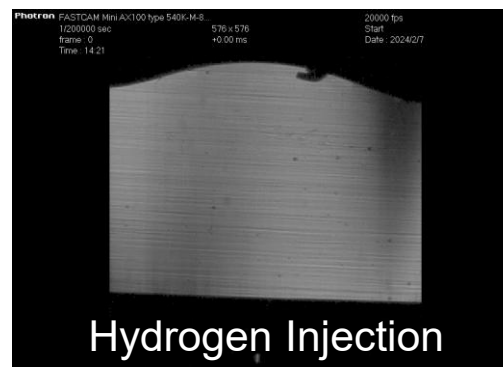
H2 engines



Dual-fuel engines



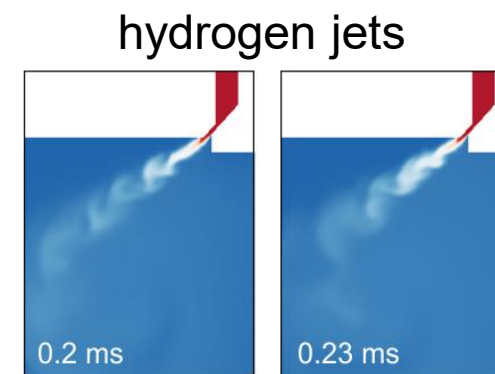
Optical engines and measurements



Hydrogen Injection



Ammonia ignition



hydrogen jets

CFD modelling



Centre for Advanced
Powertrain and Fuels



Thank you very much.

Email: Xinyan.Wang@brunel.ac.uk

Acknowledgement:

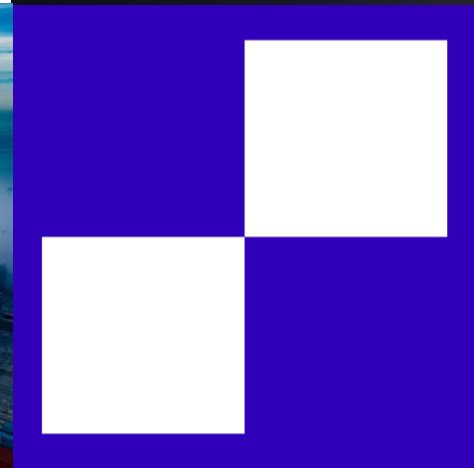
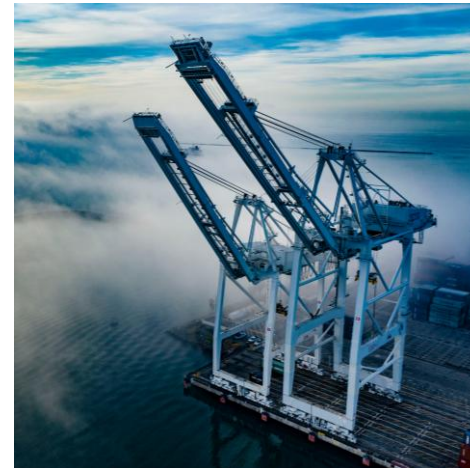
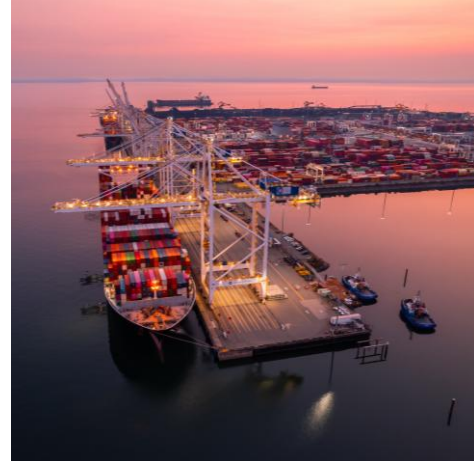
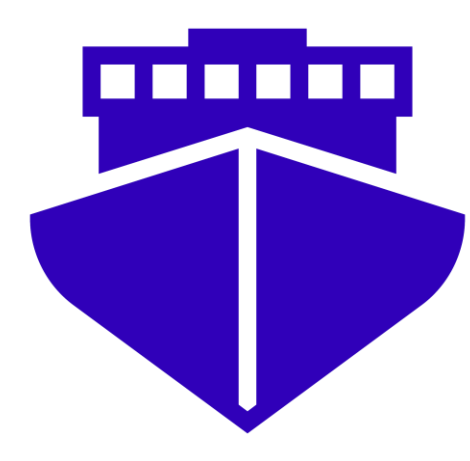
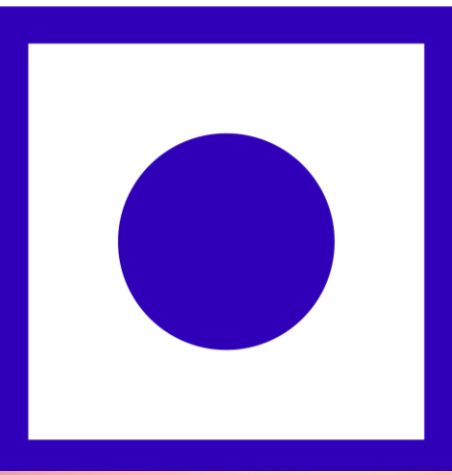
Prof H. Zhao, Dr M Mohamed, Dr C. Jiang, Dr E Lu, Z. Zaman, A. Harrington, K. Longo

The UK Government, UKRI, Innovate UK, EPSRC & industrial partners

Session 2

The Clean Energy Transition

- Dr Jonathan Wellings
- Prof Jean-Baptiste Soudpez



Breaking old habits: Marine fuel switching for cargo vessels

Dr Jonathan Wellings

Prof Rachael Rothman



UK National
Clean Maritime
Research Hub

Contents

1. Introduction
2. Case study and LCA overview
3. LCA results
4. Conclusion

Introduction

- ❑ With the ever increasing demand for emissions reduction from the maritime sector, alternative ICE fuels for marine vessels are an area of great interest.
- ❑ A range of potential candidates stand out:
 - Methanol
 - Ammonia
 - Hydrogen

Ports of interest

<u>Ports of origin</u>	<u>Destinations</u>	<u>Vessel types</u>
Liverpool	New Orleans, US	Dry bulk
Dover	Calais, France	Ro-Pax
Felixstowe	Rotterdam, the Netherlands	Container
Port of Tyne	Port of Tyne	Service vessel
Teesport	Szczecin, Poland	Liquid bulk
Portsmouth	Fishmouth, Isle of Wight	Ro-Pax



Port of Liverpool



Port of Tyne

Fuels of interest

Marine diesel – Ultra Low Sulfur Diesel

- ❑ One of the major fuels used in marine engines, the C9-C20 carbon chain length fossil fuel is used as the base comparison for this study.

Alternative fuels

- ❑ Methanol

A promising fuel, already in use with some cargo ships, it can be produced by synthesis of carbon dioxide and hydrogen, or through fermentation of biowaste.

- ❑ Ammonia

Produced by the well established Haber-Bosch process, ammonia has been used for ICE engines, although concerns persist on its safety relating to human exposure.

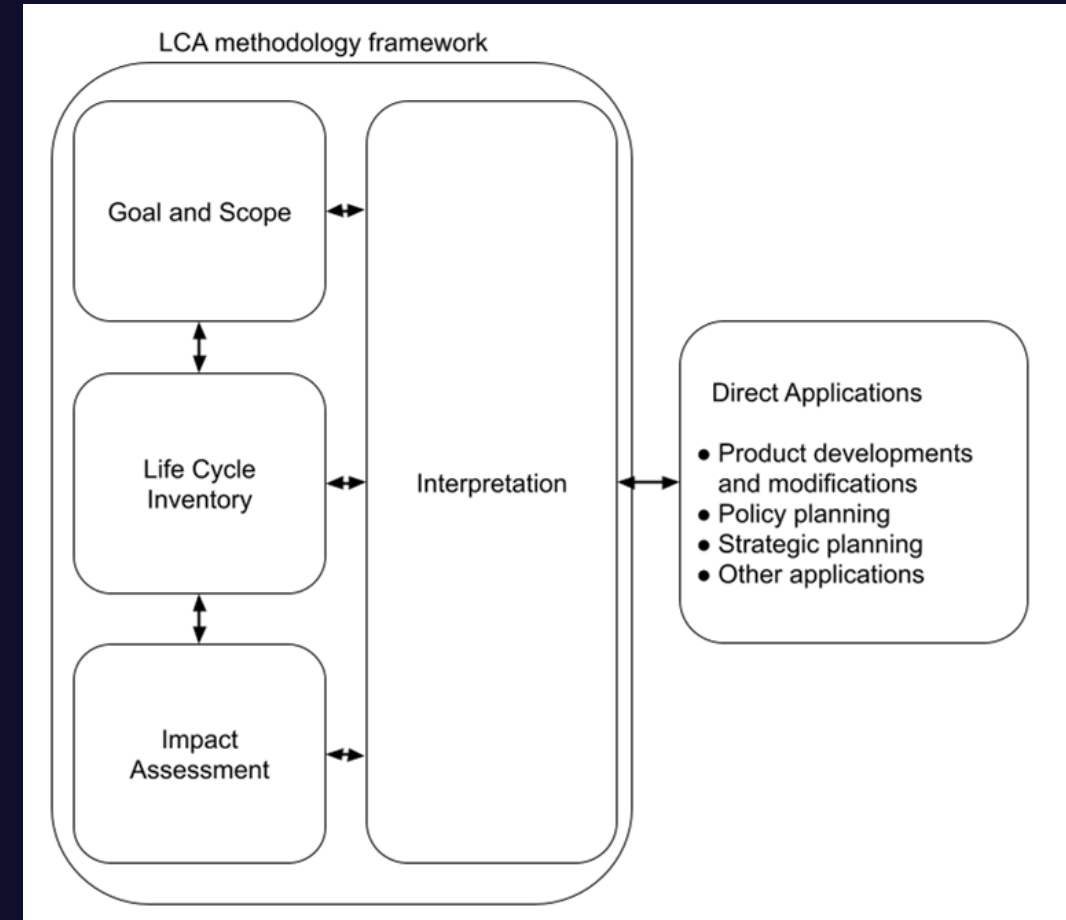
- ❑ Hydrogen

Offering the highest energy density of the examined fuels, hydrogen is often touted as the fuel of the future, although storage seems to be a consistent obstacle, especially for cryogenic storage.

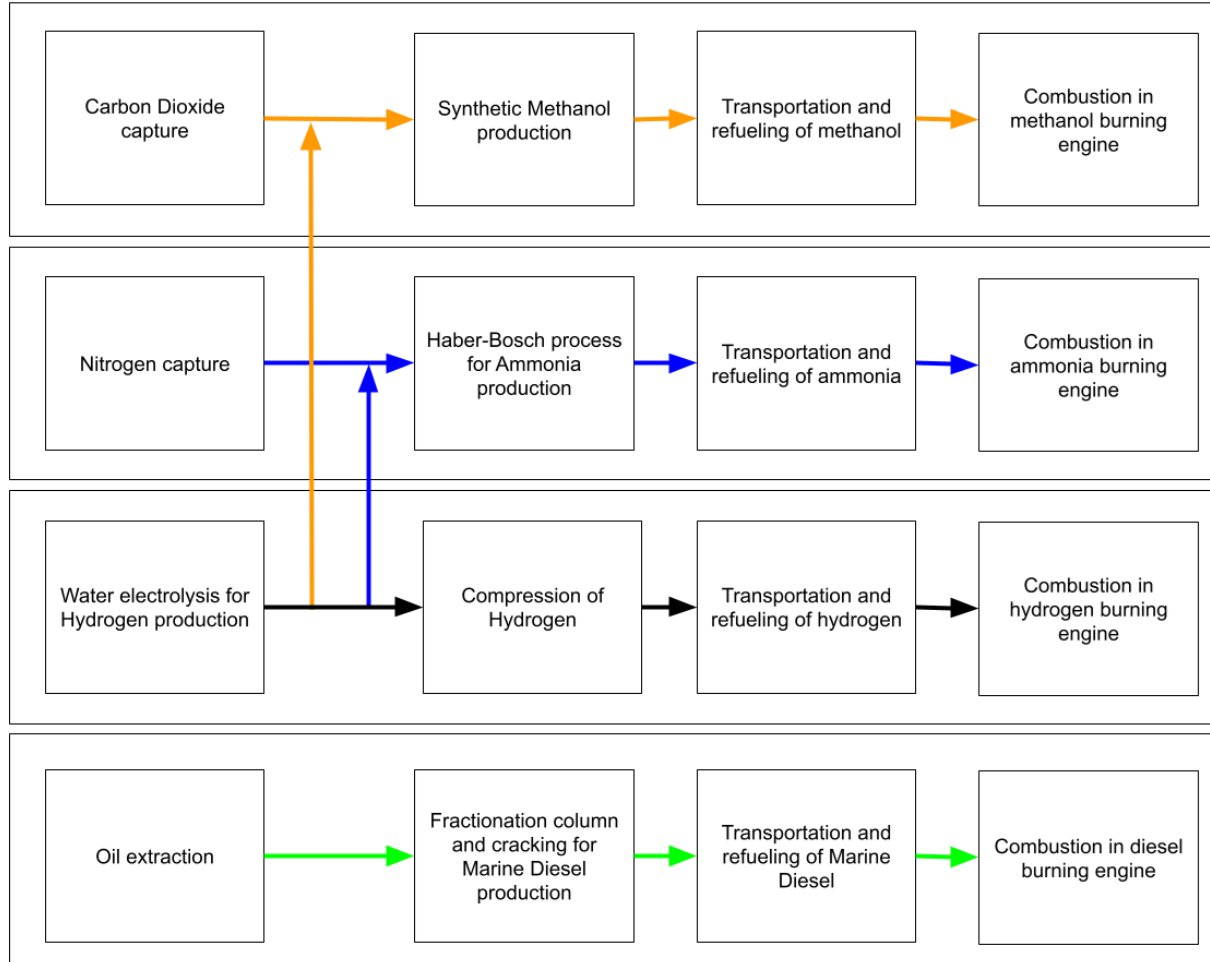


Life Cycle Assessment

- ❑ Life cycle assessment is a methodology used for examining the impacts of different processes based on their inputs and outputs.
- ❑ It is broken down into 5 major sections, detailed by IMO RESOLUTION MEPC.391(81) in Annex 10.
- ❑ Case studies will examine well-to-wake impacts for each fuel.



System boundaries and assumptions



Key Assumptions

- ❑ Synthetic manufacturing methods used for alternative fuels.
- ❑ Marine diesel is used for slow speed maneuvering, such as in port.
- ❑ UK national grid impacts are used for electricity contributions.
- ❑ Fuel demands are calculated using fuel energy density, engine power, time for journey, speed, and expected propulsion efficiency.

Fuel assumptions

Marine diesel

- ❑ The well established fractional column and cracking processes are used to convert crude oil into the fraction of diesel used.
- ❑ Marine diesel has an energy density of 42.8 MJ/kg

Methanol

- ❑ A synthetic process, utilising captured CO₂ from a gas power station and electrolytic hydrogen, is used to manufacture the methanol examined in these case studies.
- ❑ Within the processes, it is assumed that the intaken CO₂ is allocated to the process it is sourced from.
- ❑ Methanol has an energy density of 19.9 MJ/kg



Fuel assumptions



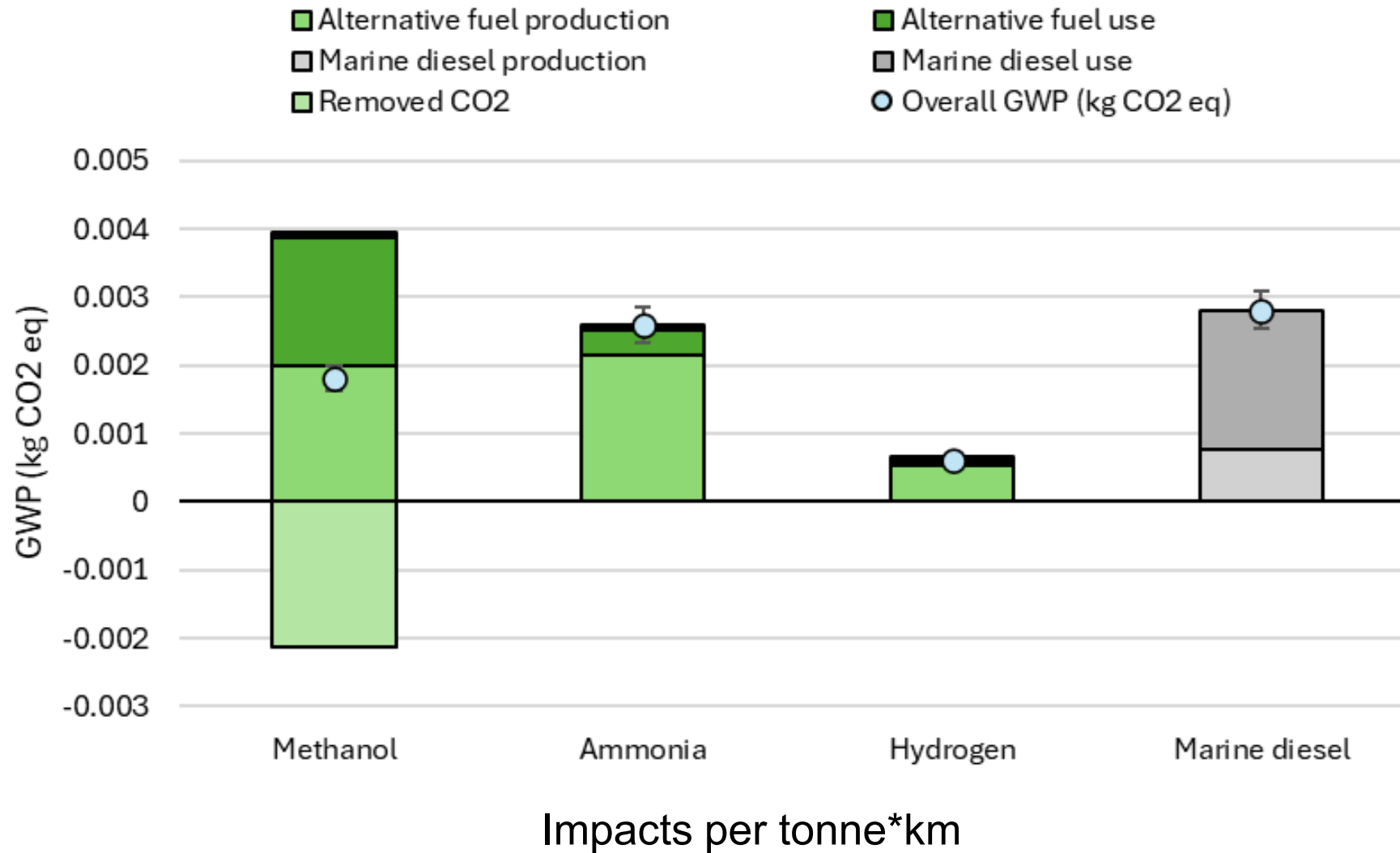
Ammonia

- ❑ A synthetic process, utilising captured nitrogen and electrolytic hydrogen, is used to manufacture the ammonia examined in these case studies.
- ❑ It is assumed that there is a small consumption of catalysis in the Haber-Bosch process.
- ❑ Ammonia has an energy density of 18.9 MJ/kg

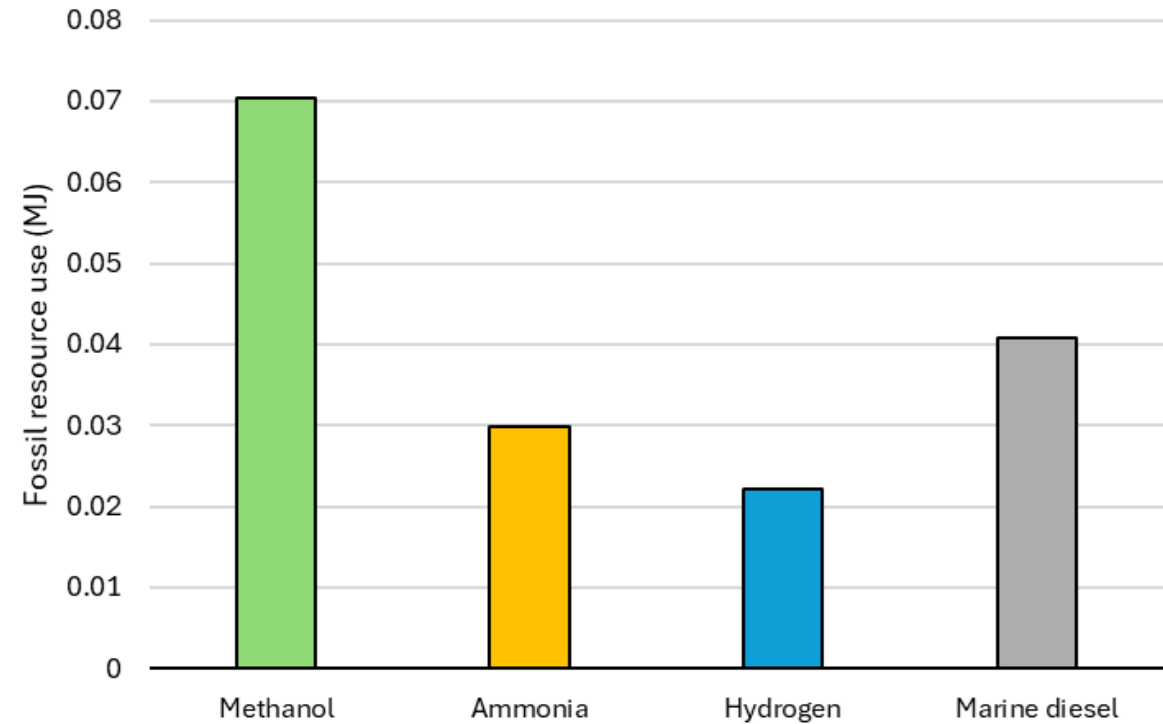
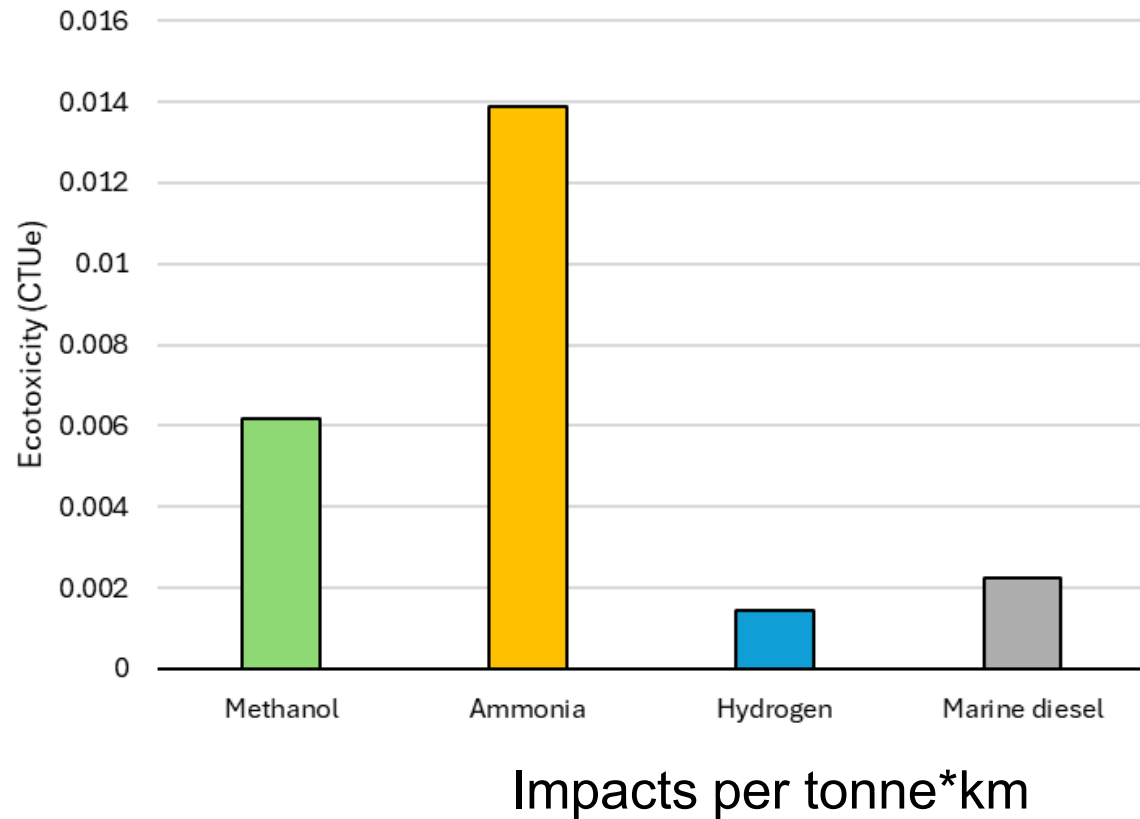
Hydrogen

- ❑ A synthetic process, utilising electrolysis of water, is used to manufacture the hydrogen examined in these case studies.
- ❑ The hydrogen is stored at 300 bars at room temperature, which has its own compression energy demand.
- ❑ Hydrogen has an energy density of 120 MJ/kg.

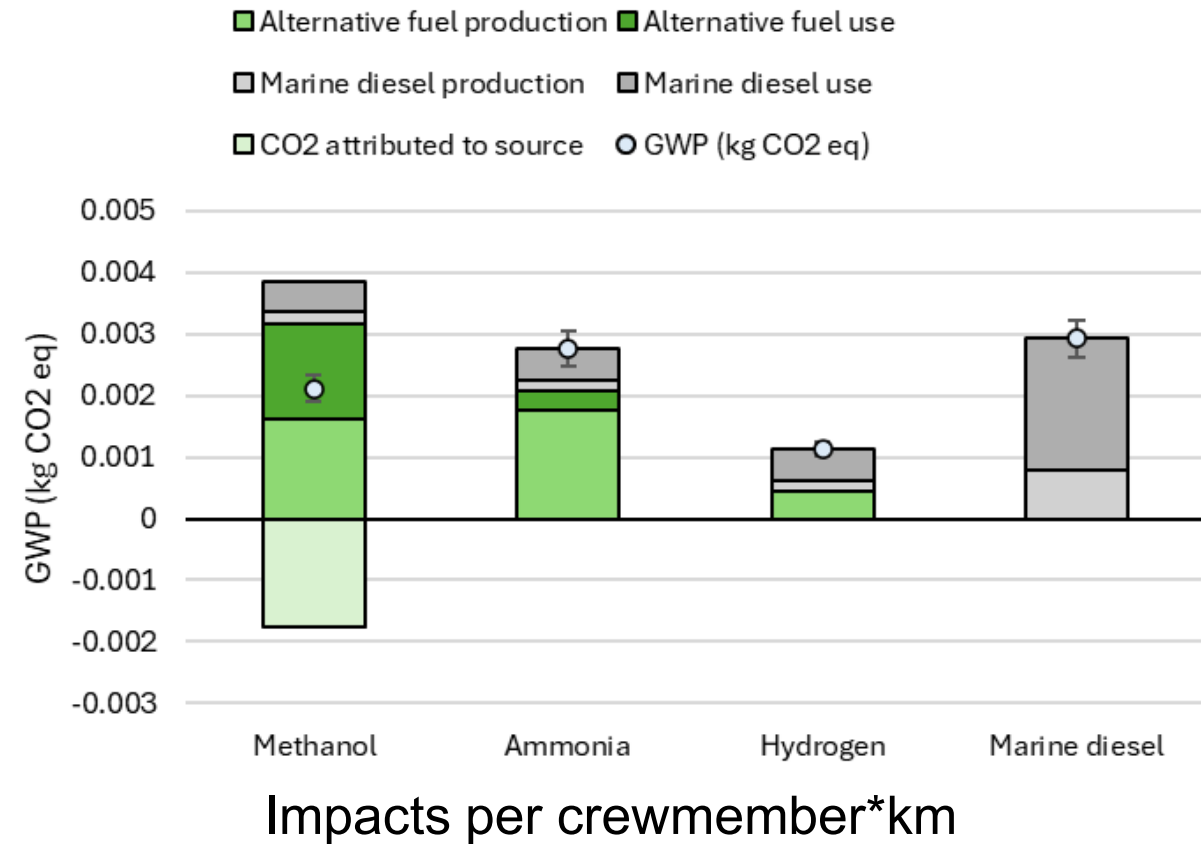
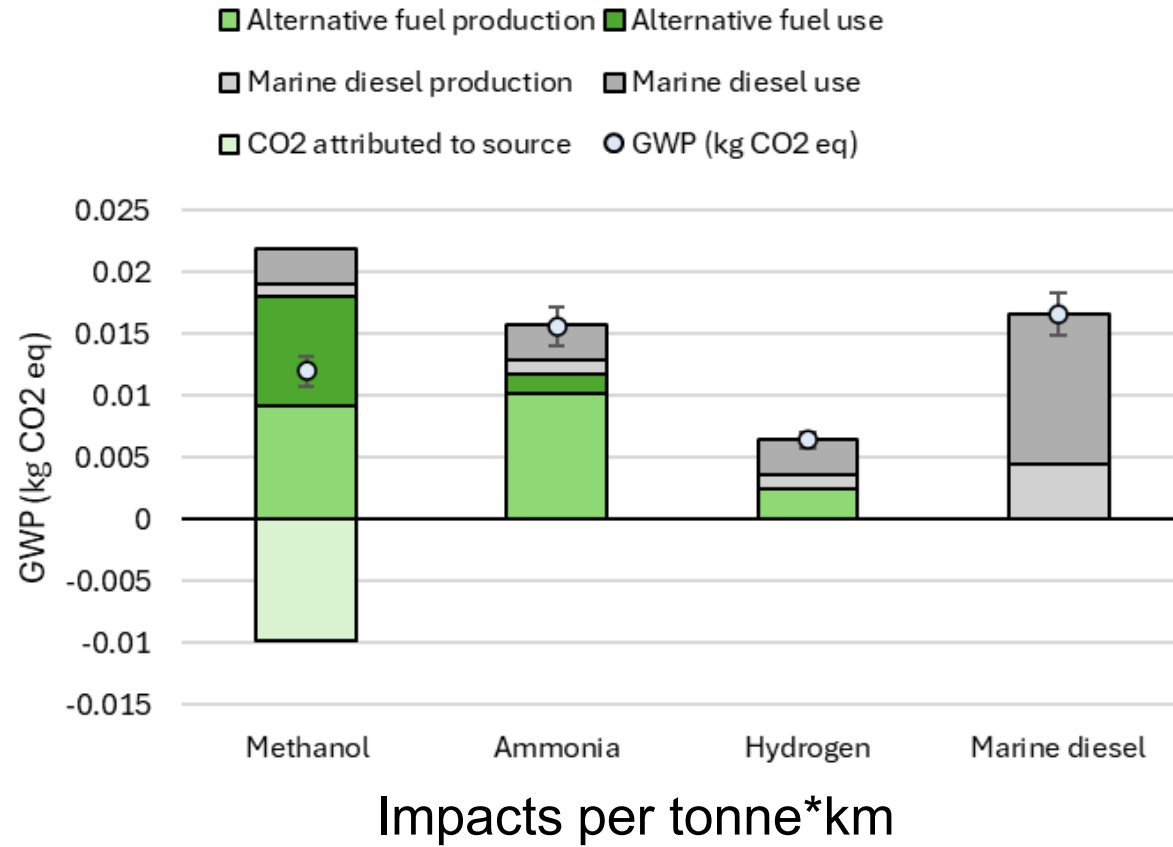
Results – Felixstowe to Rotterdam Container Ship



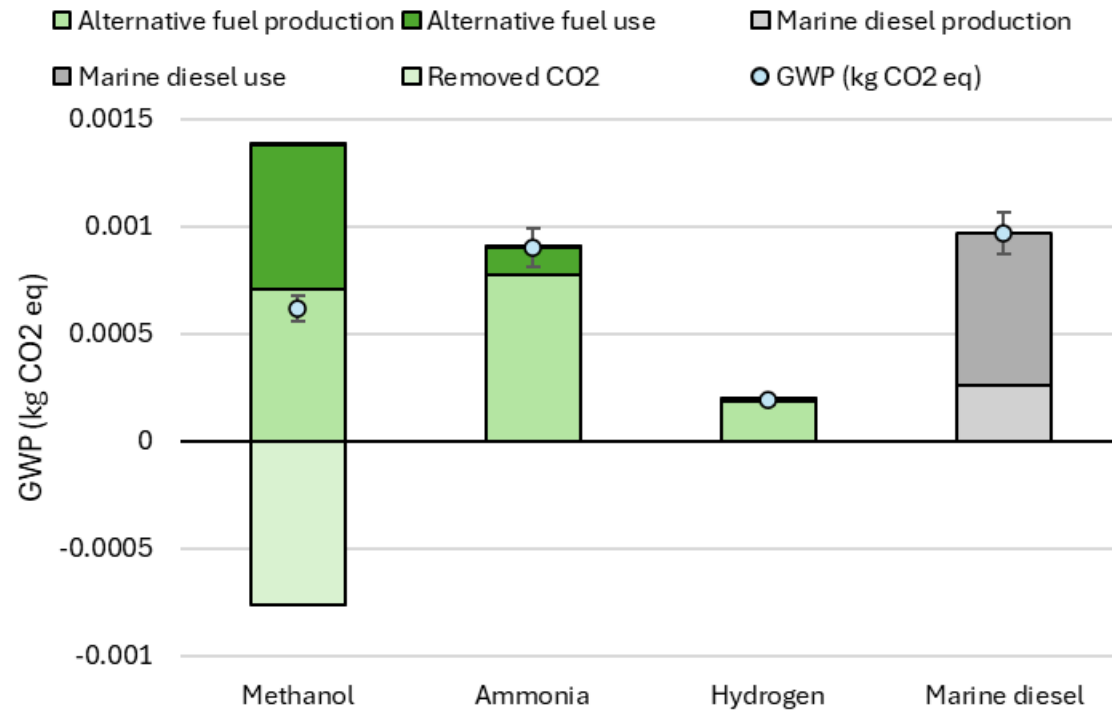
Results – Felixstowe to Rotterdam Container Ship



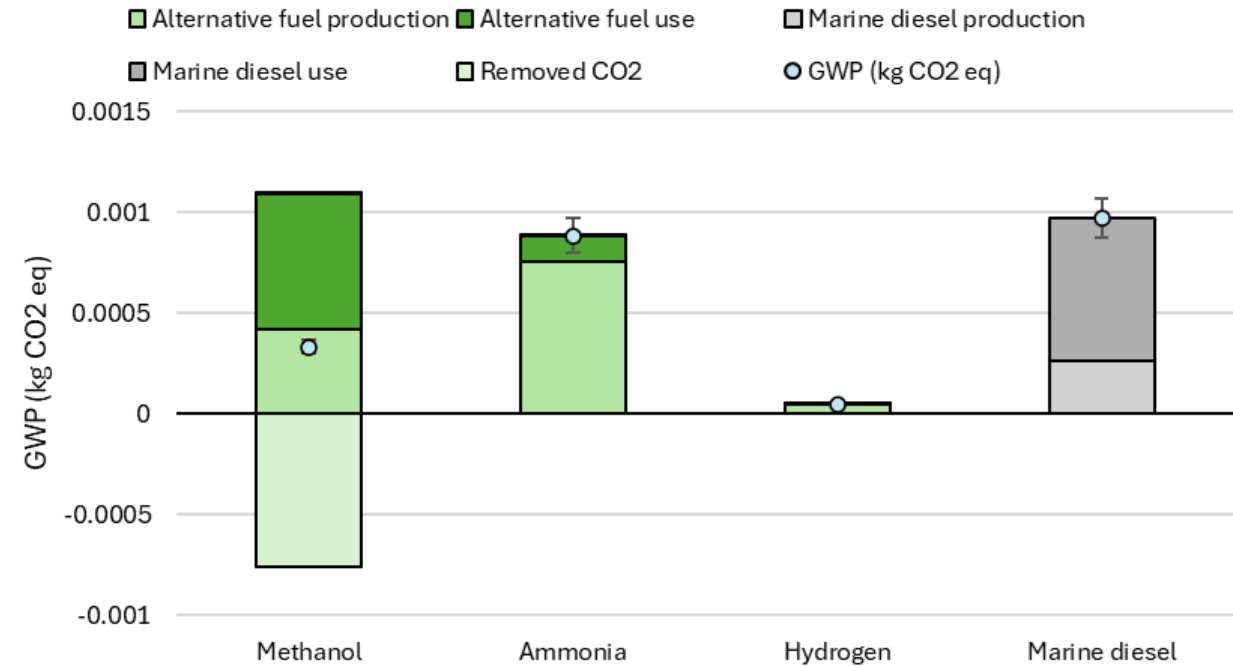
Results – Tyne Offshore Service Ship



Results – Liverpool dry bulk ship

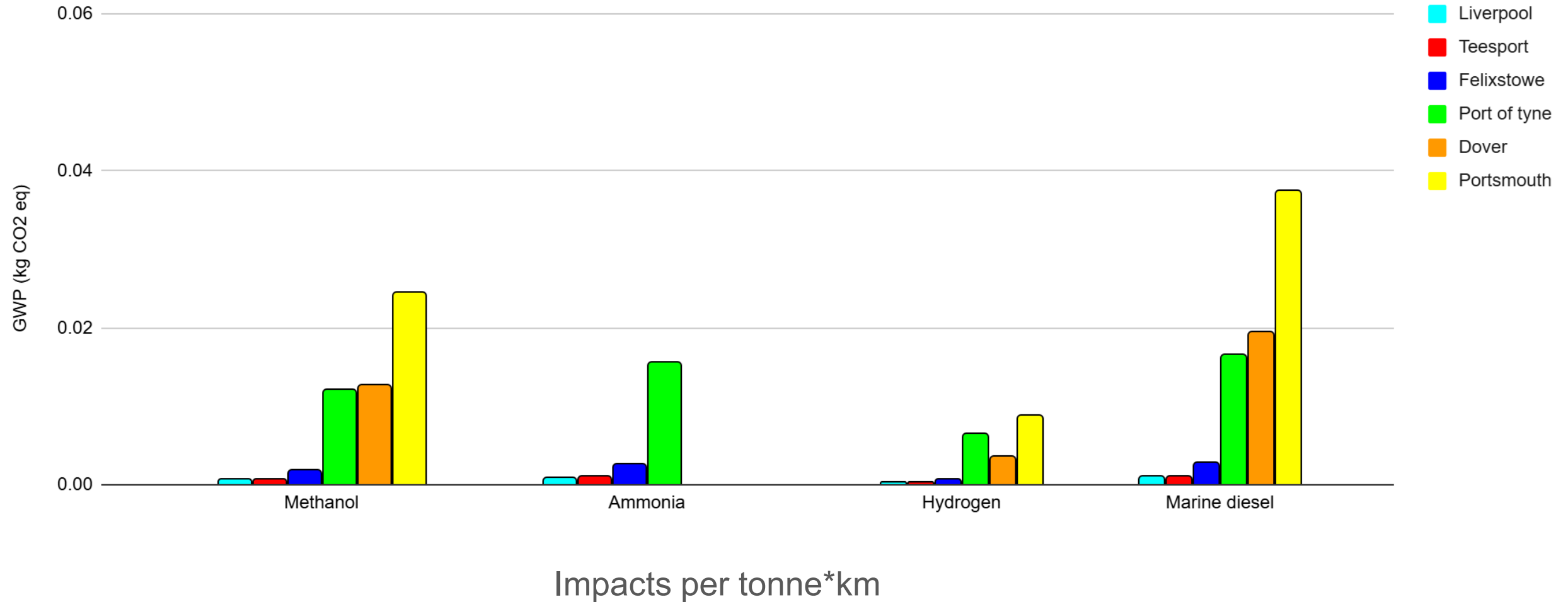


Impacts per tonne*km from UK energy grid



Impacts per tonne*km from wind turbine usage

Results – Case study comparisons



Results – Case study comparisons – Total GWP

<u>GWP (kg CO2 eq)</u>	<u>Felixstowe</u>	<u>Dover</u>	<u>Liverpool</u>	<u>Tyne</u>	<u>Teesport</u>	<u>Portsmouth</u>
Methanol	81,160	3,310	420,590	2,990	77,700	330
Ammonia	115,910	-	611,520	3,880	112,380	-
Hydrogen	27,240	950	129,100	1,590	24,030	120
Marine Diesel	125,270	5,110	660,440	4,130	121,280	510

Results – Felixstowe fuel consumption – mass and volume

Fuel used for Felixstowe case study	Mass (kg)	Volume (m ³)
Methanol	67,960	86
Ammonia	71,560	118
Hydrogen (300 bar compressed)	11,270	549
Marine Diesel	31,600	35

Conclusions – Key points

- ❑ Methanol has high production GWP but the allocation of CO₂ from capture lowers the overall GWP.
- ❑ Within the fuels examined, Hydrogen ultimately offered the lowest GWP impacts over the case studies examined.
- ❑ Ammonia offers lower overall GWP compared with Marine diesel, but has the highest impacts for its production of all the fuels.
- ❑ The slow maneuvering at sea notably increased the Tyne case study impacts.



Pa Wire

Conclusion – Future work

- ❑ Biofuel comparison to synthetic fuels.
- ❑ Comparison between compressed and cryogenic hydrogen.
- ❑ Examination of prospective LCA for key net-zero dates:
 - 2030
 - 2040
 - 2050
- ❑ Case studies for further ship types, such as cruise ships.
- ❑ Comparison of alternative fuels to electrification for appropriate case studies, such as Portsmouth to The Isle of Wight, and tug boats in port.

Thank you for listening



University of Sheffield



The University of
Nottingham



Aston University

BIRMINGHAM UK



Prof. Jean-Baptiste R. G. Souppez

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Navigating Maritime Decarbonisation: A Systematic Review of Technologies, Measures, and CO₂ Reduction Potential

Clean Maritime Assembly 2026



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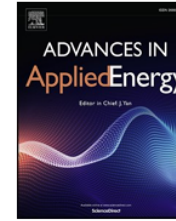
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Contents lists available at ScienceDirect

Advances in Applied Energy

journal homepage: www.elsevier.com/locate/adapenA systematic review of technologies, measures, and CO₂ emission reduction potential for maritime transport decarbonisationSina Fadaie^{a,*}, Patricia Thornley^a, Jean-Baptiste Soupez^b^a Aston University, Energy and Bioproducts Research Institute, Birmingham, UK^b Birmingham City University, School of Architecture, Built Environment, Computing and Engineering, Department of Engineering, Birmingham, UK

ARTICLE INFO



ABSTRACT

The maritime shipping sector is a significant contributor to global carbon dioxide (CO₂) emissions, accounting for approximately 2.7%–3% of global emissions. In response, the International Maritime Organization (IMO) has set ambitious targets: a 30% reduction in emissions by 2030, 80% by 2040, and net-zero by 2050, relative to 2008 levels. Meeting these goals requires a comprehensive understanding of the full range of viable decarbonisation measures. Therefore, this study conducts a systematic review of maritime decarbonisation measures, applying the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. Unlike previous studies, this paper not only provides an updated overview of CO₂ reduction measures but also maps them to specific vessel types based on data reported in the literature. Furthermore, the findings are compared with literature to highlight shifts in mitigation potential. A case study is also included to schematically demonstrate how these measures can be applied in practice. Following a rigorous analysis: (i) thirty-two individual CO₂ mitigation measures were identified and classified into six categories, (ii) alternative fuels shown the highest long-term potential (5–100 % CO₂ emission reduction), whereas hull design improvements show the lowest (1–20 %), (iii) the wide disparity in reported abatement values is attributed to inconsistent system boundaries, variability in fuel origin, partial-blend scenarios, and differing assumptions across studies, (iv) combinations of measures provide the most practical and realistic pathway to phased emissions reduction. These findings are expected to assist decision-makers in selecting effective, context-appropriate strategies to support global maritime decarbonisation and ensure long-term sectoral sustainability.

<https://doi.org/10.1016/j.adapen.2025.100255>
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Dr Sina Fadaie



Stantec



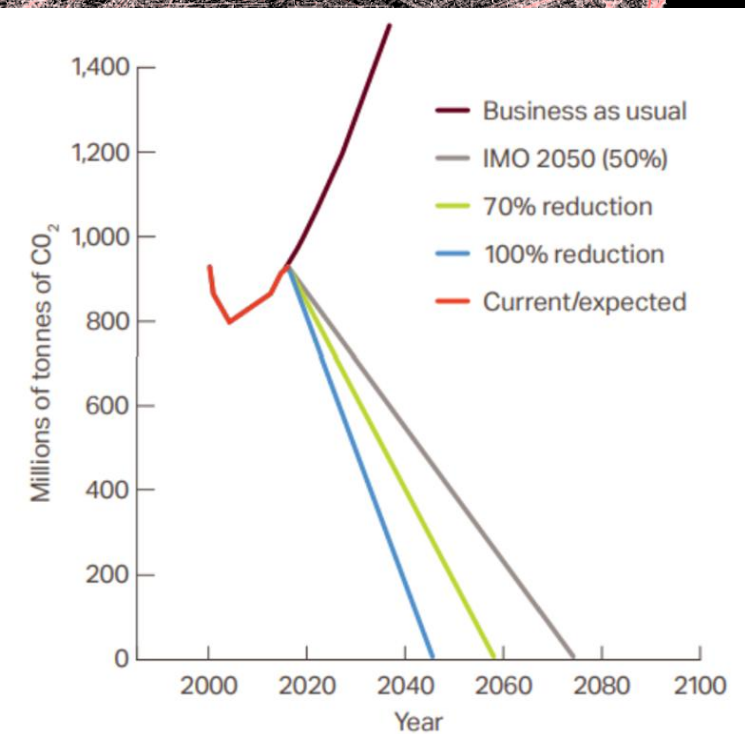
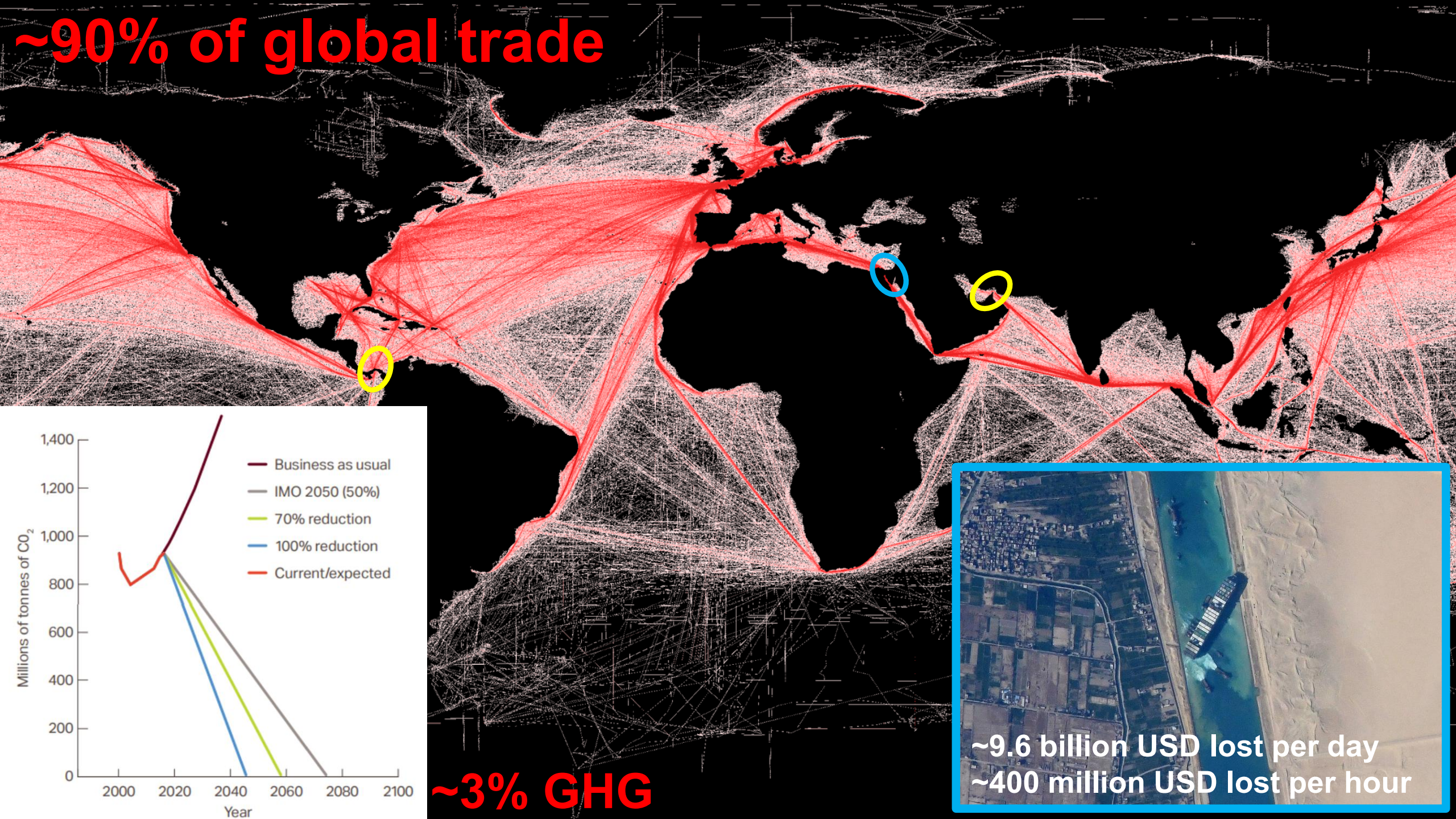
Prof Patricia Thornley

Department
for Transport

Prof JB Soupez

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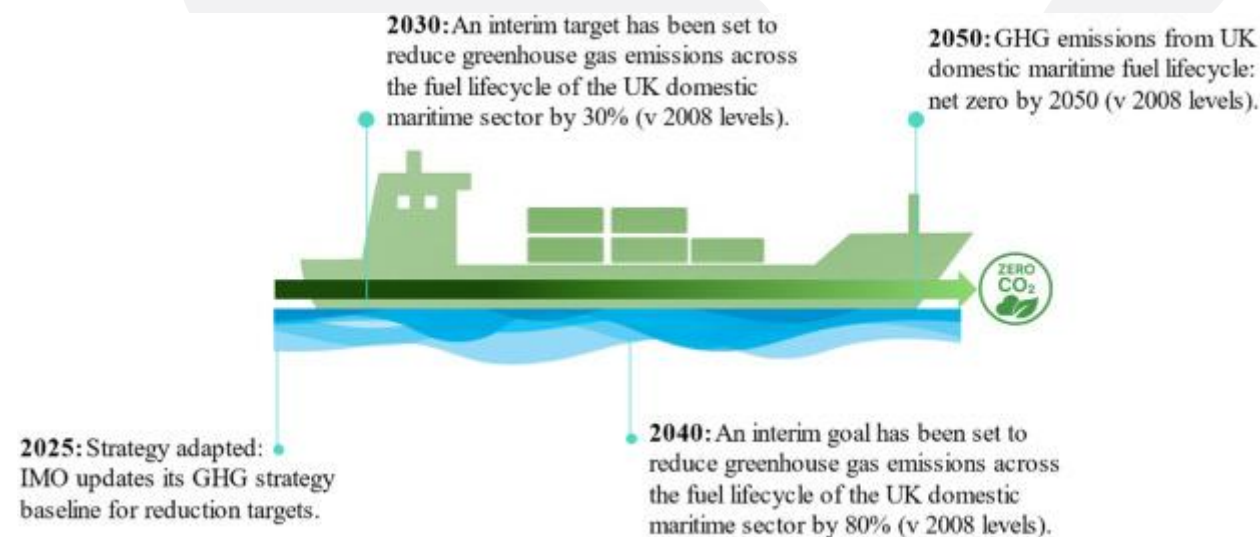
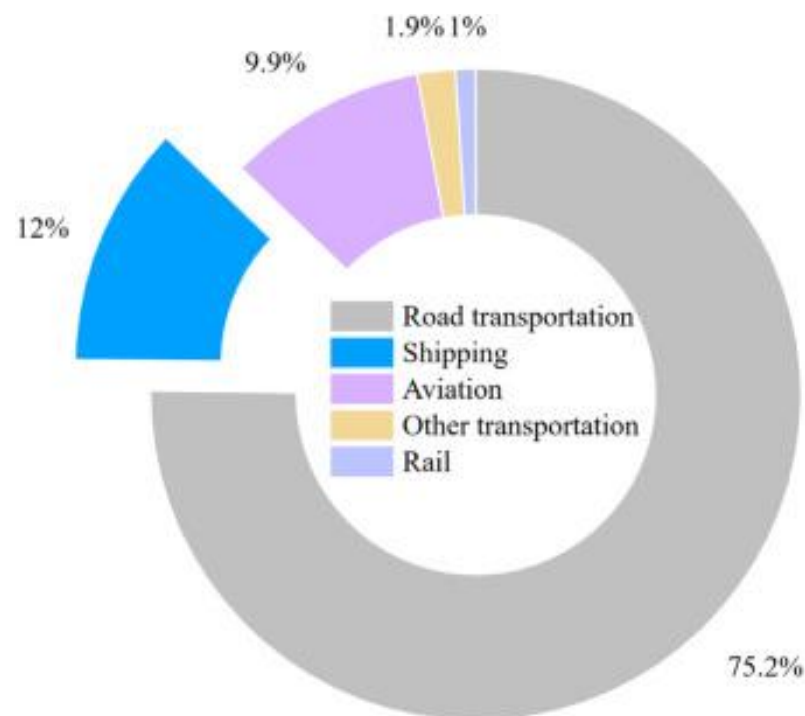
~90% of global trade



~3% GHG



~9.6 billion USD lost per day
~400 million USD lost per hour



Systematic Literature Review

- Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)
- Search terms: *((green OR clean OR sustainable OR eco-friendly OR low-carbon) AND (ship OR shipping)) OR ((maritime OR Marine OR shipping) AND decarbonisation)*
- We present the technologies and associated CO₂ (proxy for GHG) emission reduction as reported in the literature

Systematic Literature Review

Identification

Screening

Inclusion

13 119 papers

2850 papers

592 papers

326 papers

241 papers

Exclusions:

- Pre 2018
- Not journal papers
- Not open access
- Not in English

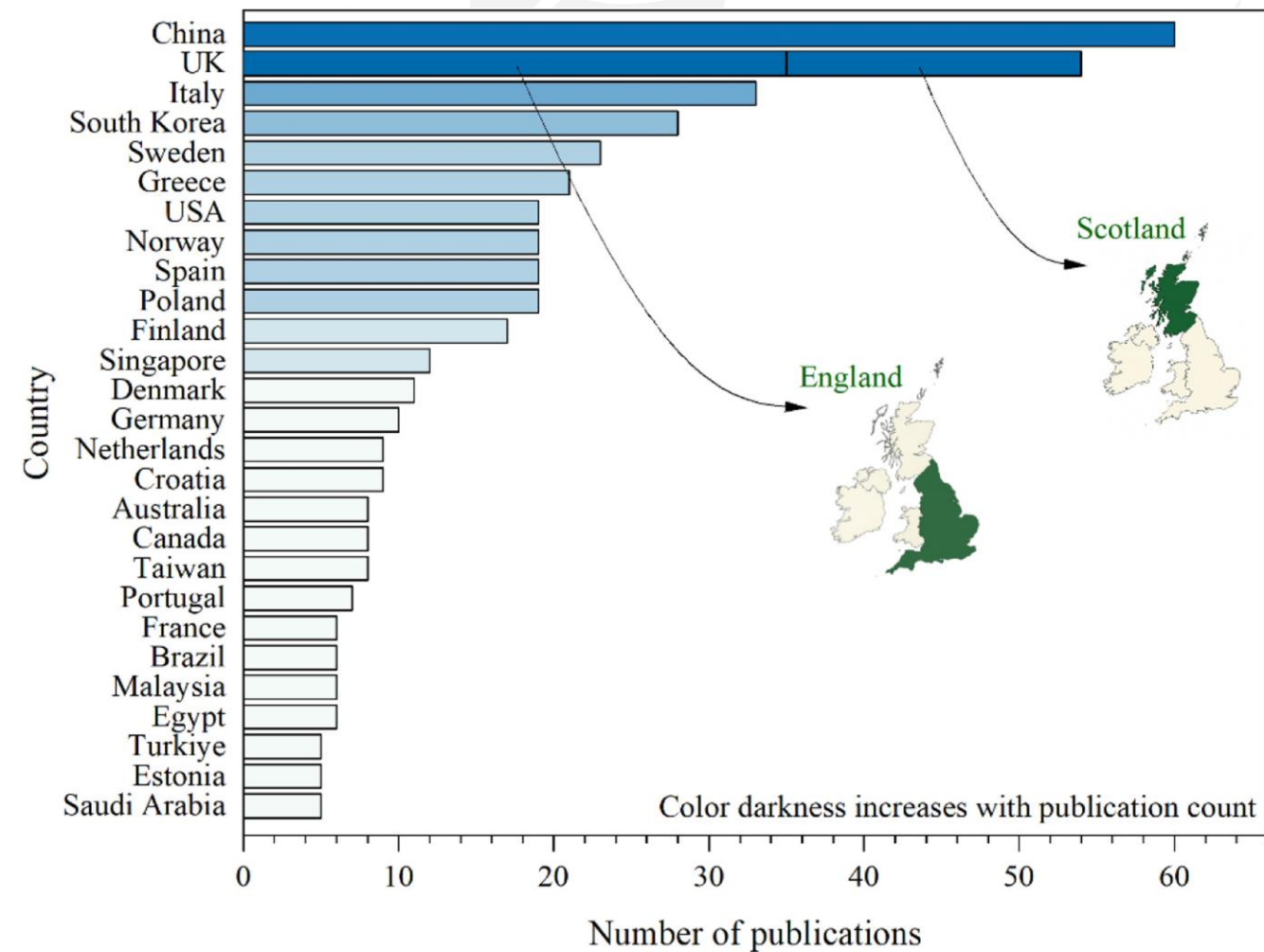
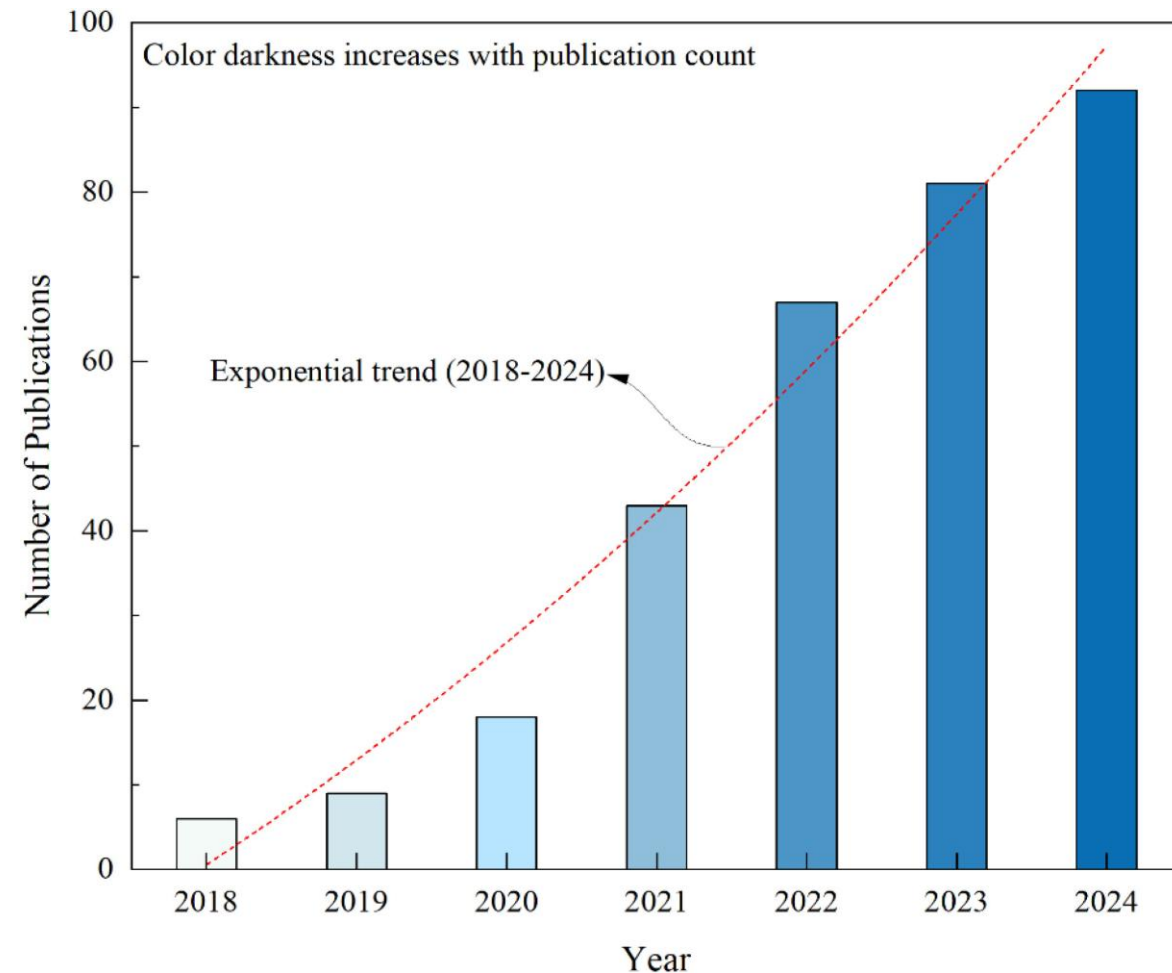
Title
screening

Abstract
screening

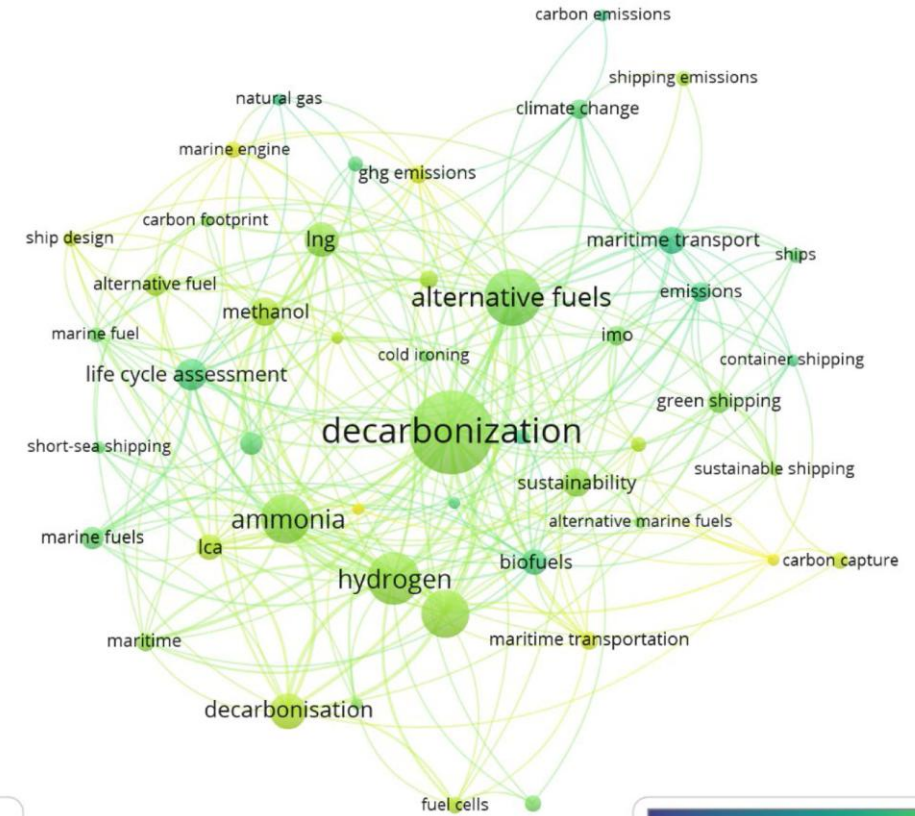
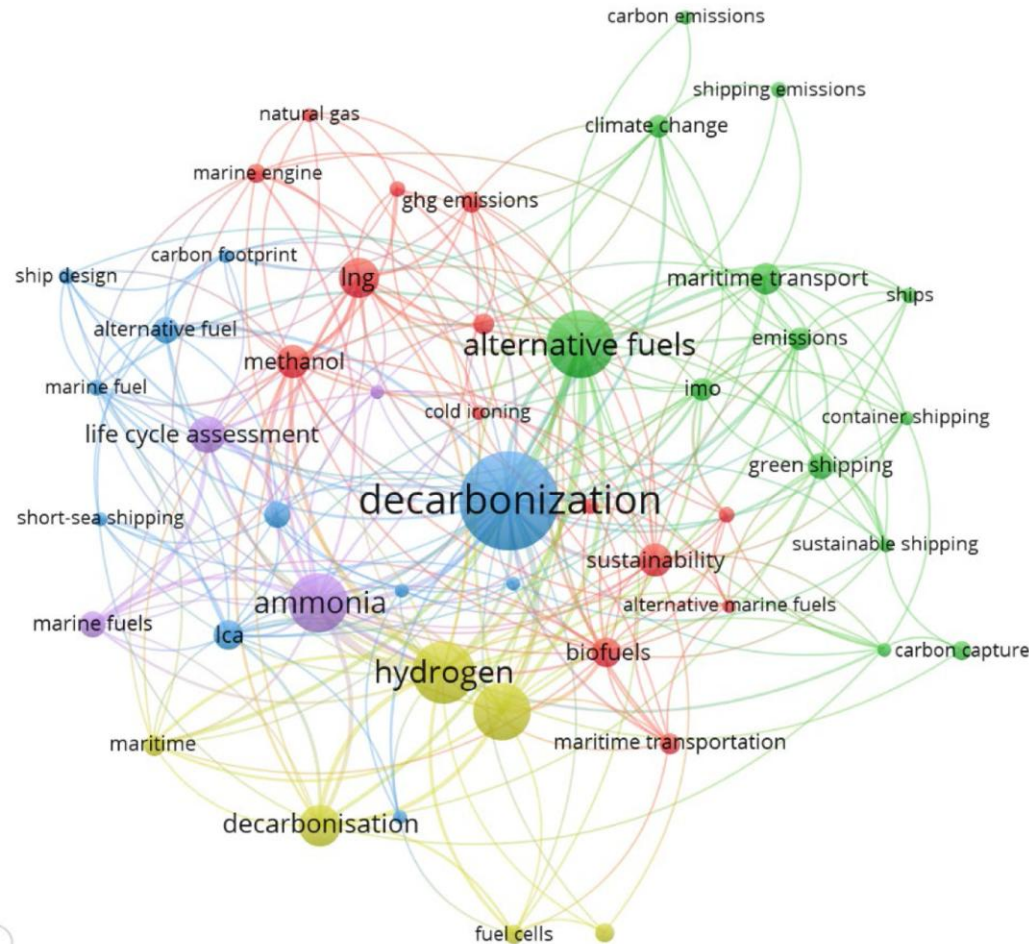
Exclusions:

- No CO2 data
- Irrelevant sector
- Insufficient data
- Etc

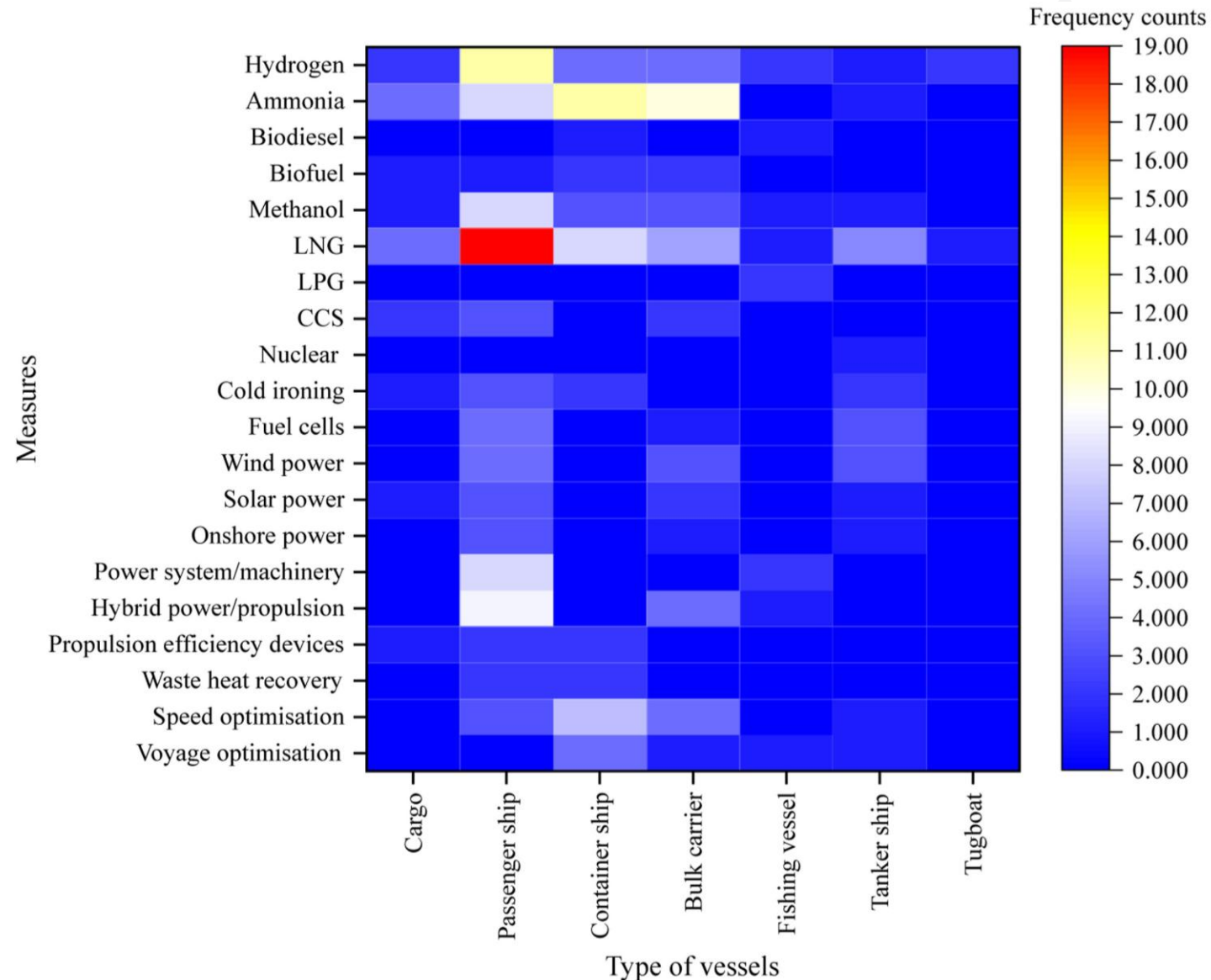
Publications



Publications



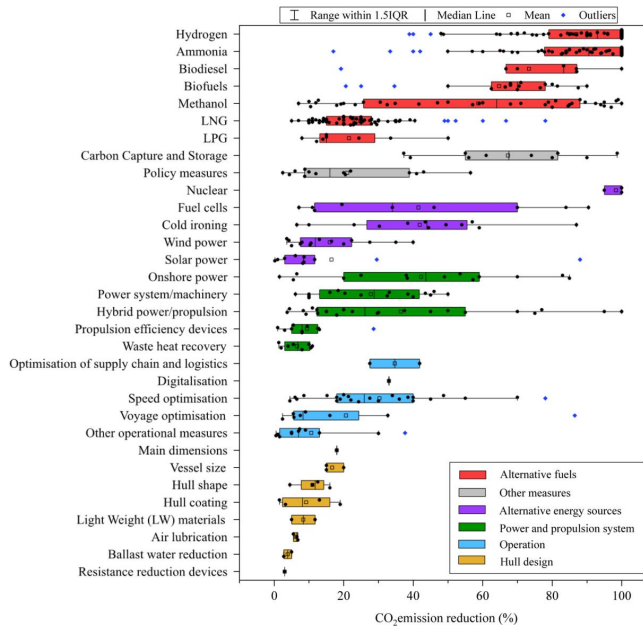
Publications per Vessel Type



Categories



How to read this...



● Individual studies

| Median

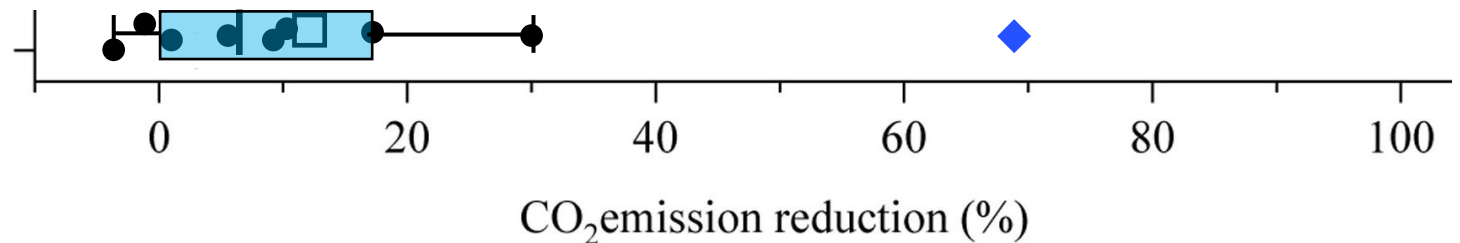
□ Mean

▭ Interquartile range

├─┤ Whiskers (max 1.5 IQR)

◆ Outliers

Technology



Alternative fuels

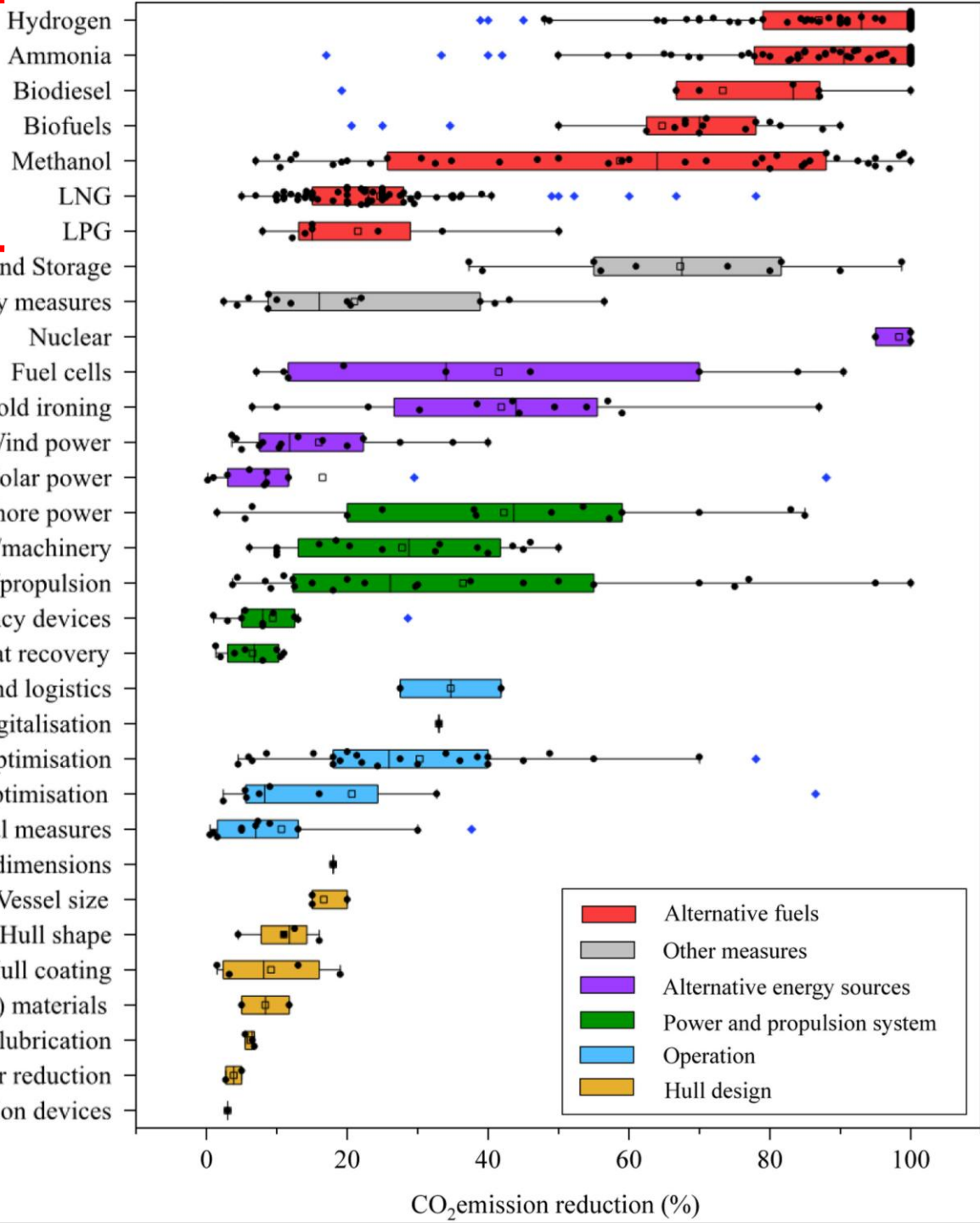
Others

Alternative energy sources

Power

Operation

Design



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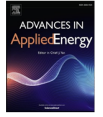
Results

Advances in Applied Energy 20 (2025) 100255

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/adapen



A systematic review of technologies, measures, and CO₂ emission reduction potential for maritime transport decarbonisation

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^b Birmingham City University, School of Architecture, Built Environment, Computing and Engineering, Department of Engineering, Birmingham, UK

ARTICLE INFO

Keywords:
Decarbonisation
Clean maritime
Shipping
CO₂ emission reduction
Sustainability

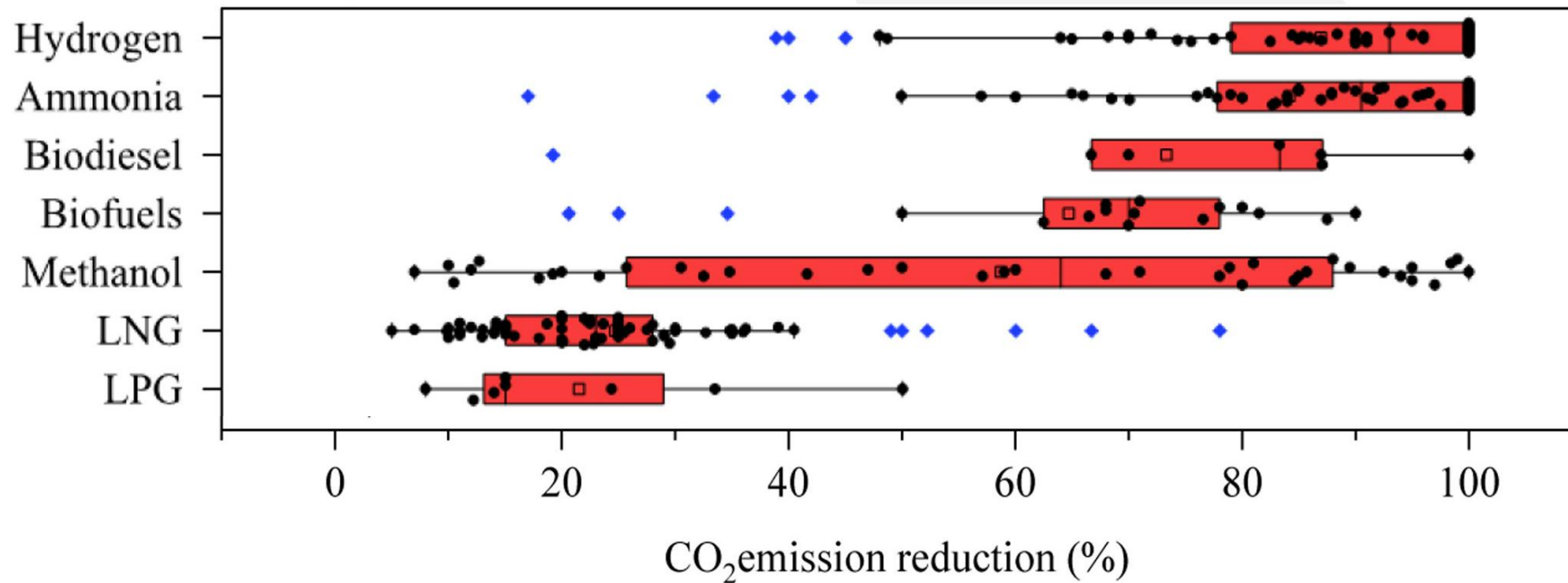
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The maritime shipping sector is a significant contributor to global carbon dioxide (CO₂) emissions, accounting for approximately 2.7%–3% of global emissions. In response, the International Maritime Organization (IMO) has set ambitious targets: a 30% reduction in emissions by 2030, 80% by 2040, and net-zero by 2050, relative to 2008 levels. Meeting these goals requires a comprehensive understanding of the full range of viable decarbonisation measures. Therefore, this study conducts a systematic review of maritime decarbonisation measures, applying the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. Unlike previous studies, this paper not only provides an updated overview of CO₂ reduction measures but also maps them to specific vessel types based on data reported in the literature. Furthermore, the findings are compared with literature to highlight shifts in mitigation potential. A case study is also included to schematically demonstrate how these measures can be applied in practice. Following a rigorous analysis: (i) thirty-two individual CO₂ mitigation measures were identified and classified into six categories, (ii) alternative fuels shown the highest long-term potential (5–100 % CO₂ emission reduction), whereas hull design improvements show the lowest (1–20 %), (iii) the wide disparity in reported abatement values is attributed to inconsistent system boundaries, variability in fuel origin, partial-blend scenarios, and differing assumptions across studies, (iv) combinations of measures provide the most practical and realistic pathway to phased emissions reduction. These findings are expected to assist decision-makers in selecting effective, context-appropriate strategies to support global maritime decarbonisation and ensure long-term sectoral sustainability.

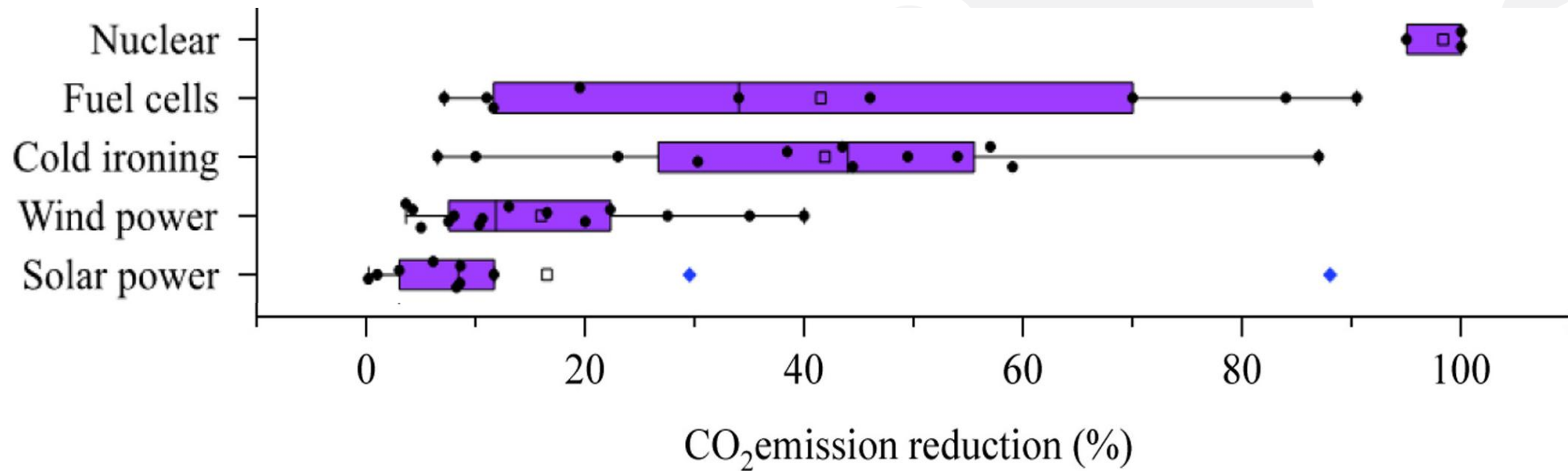


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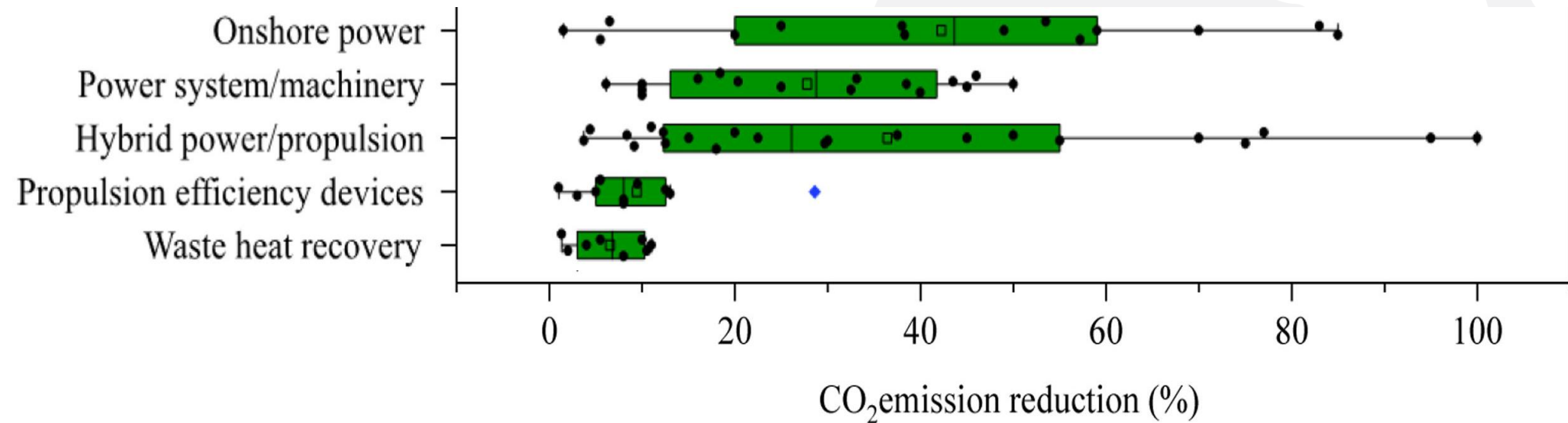
Alternative Fuels



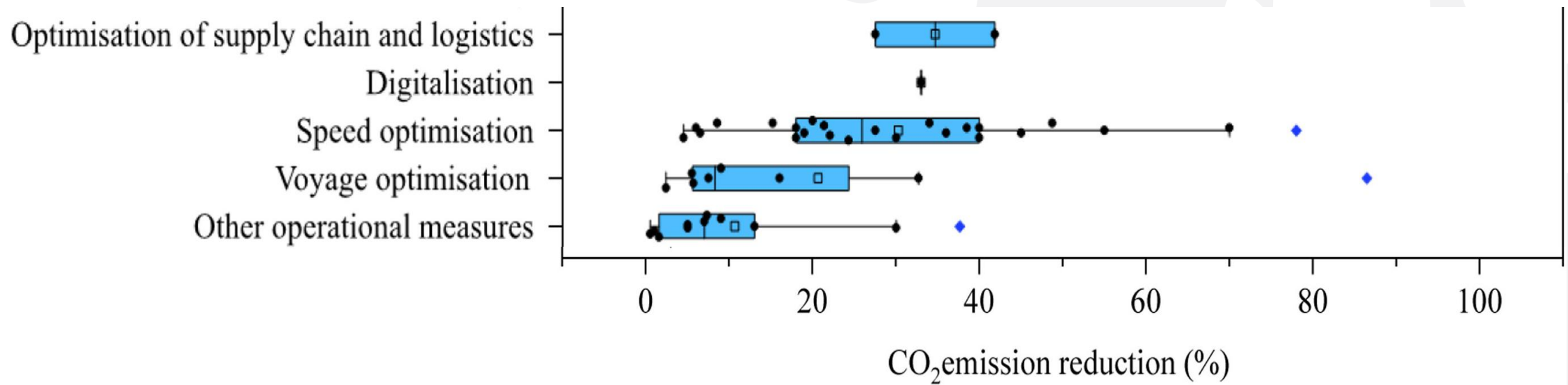
Alternative Energy Sources



Power and Propulsion System



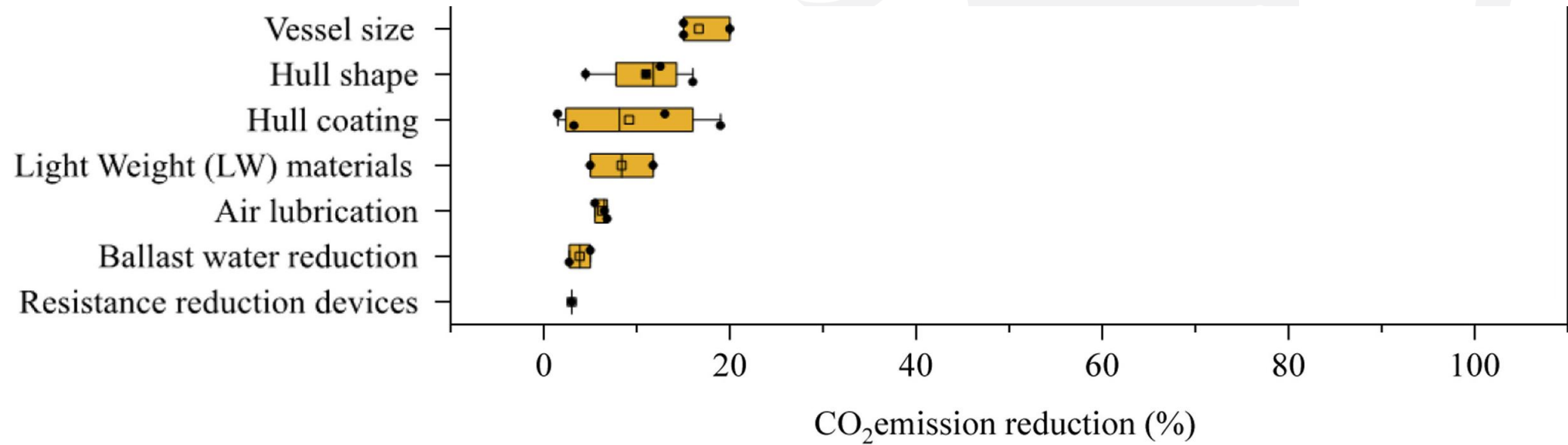
Operation



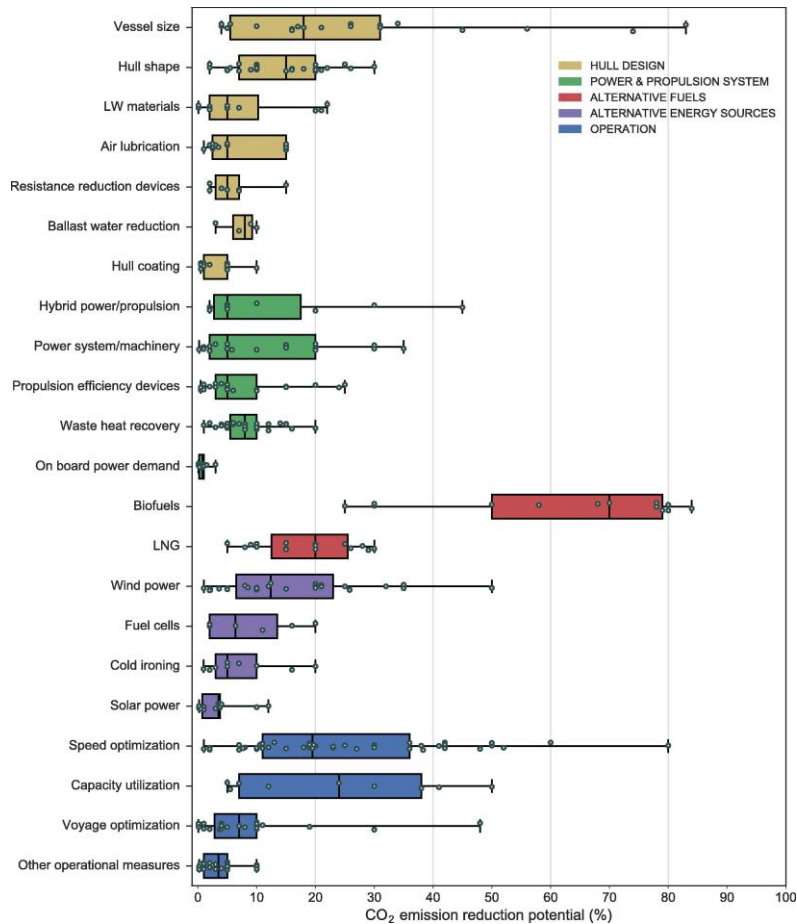
Design



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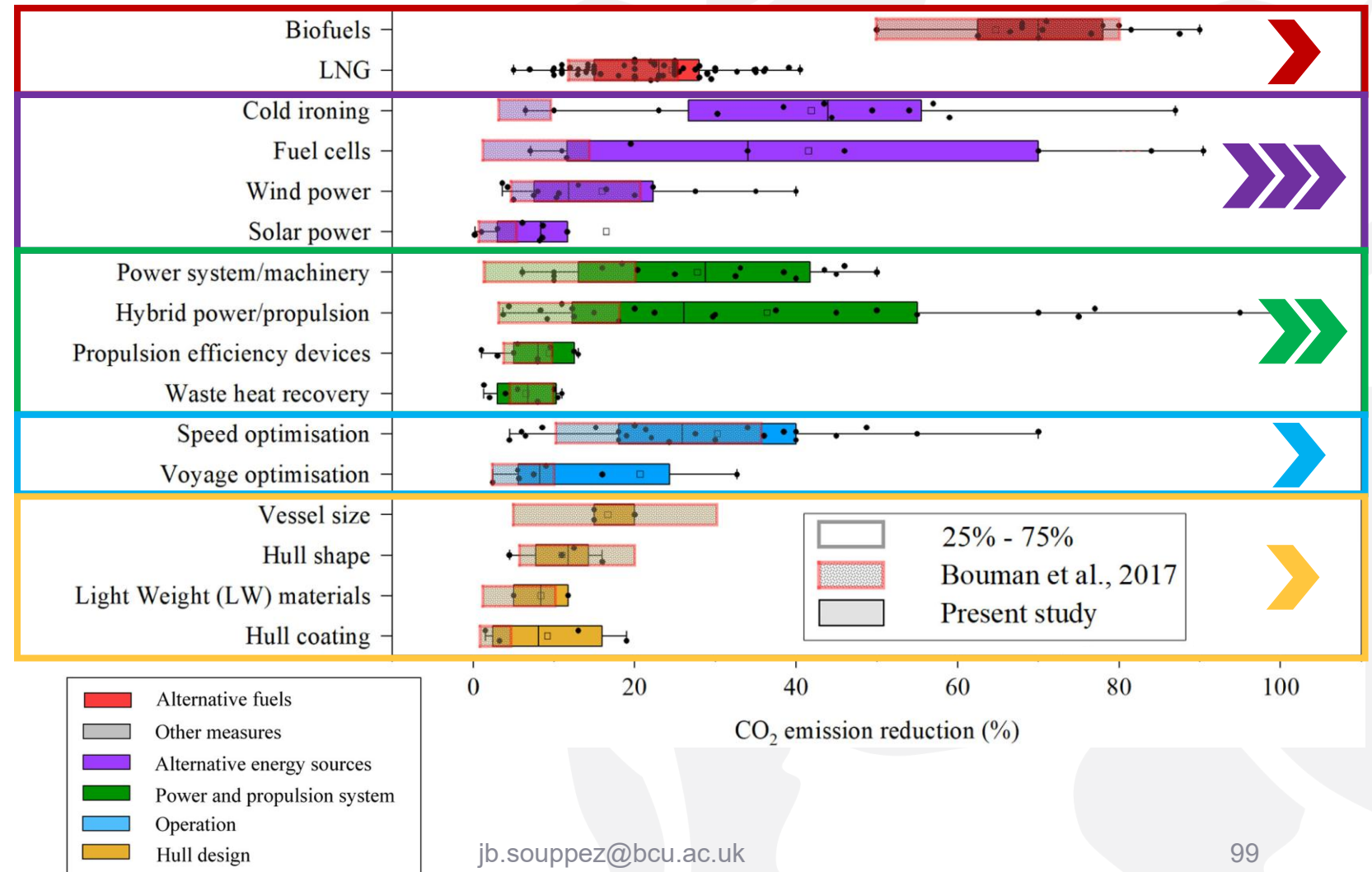


2017 – 2025 Evolution



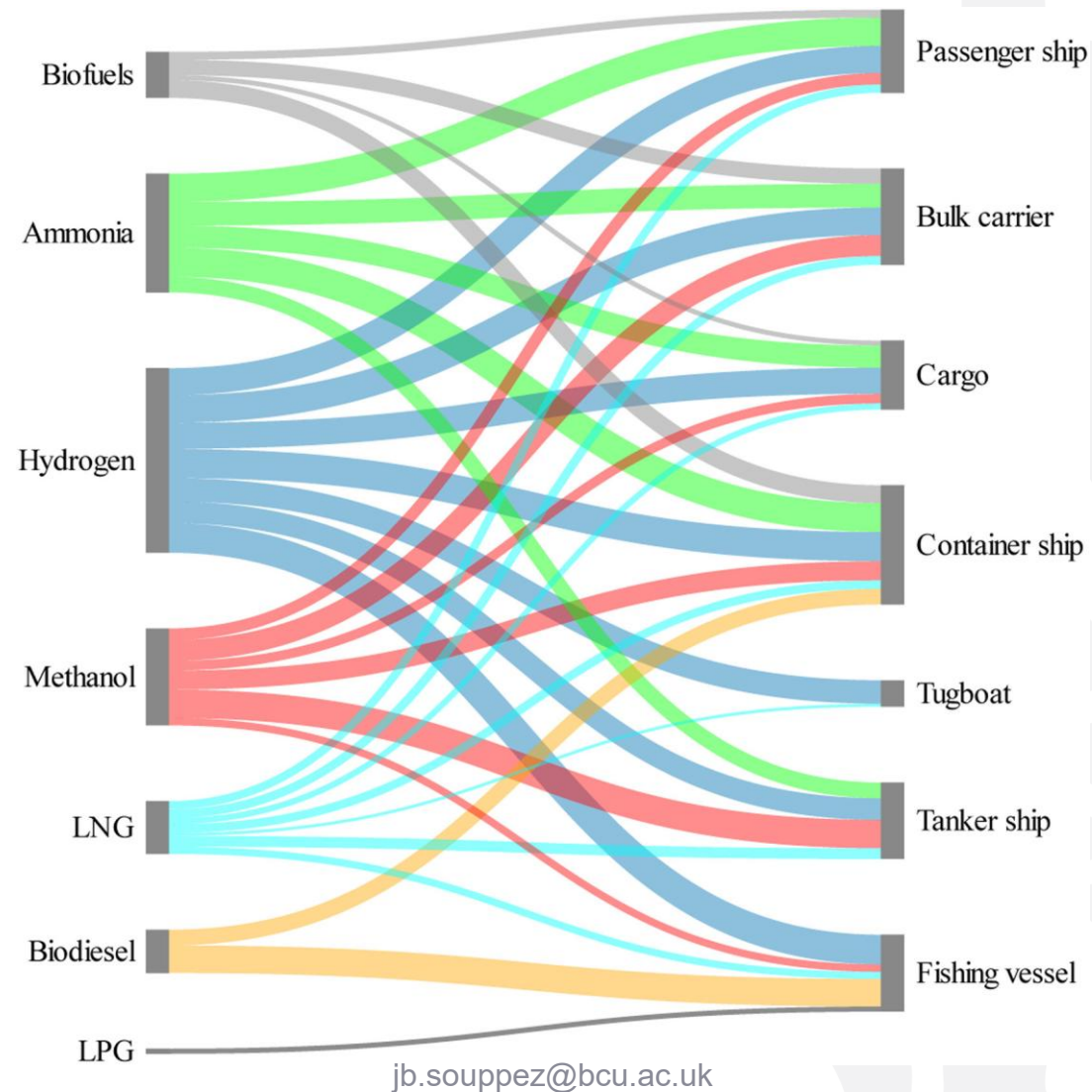
Bouman et al, 2017

<https://doi.org/10.1016/j.trd.2017.03.022>



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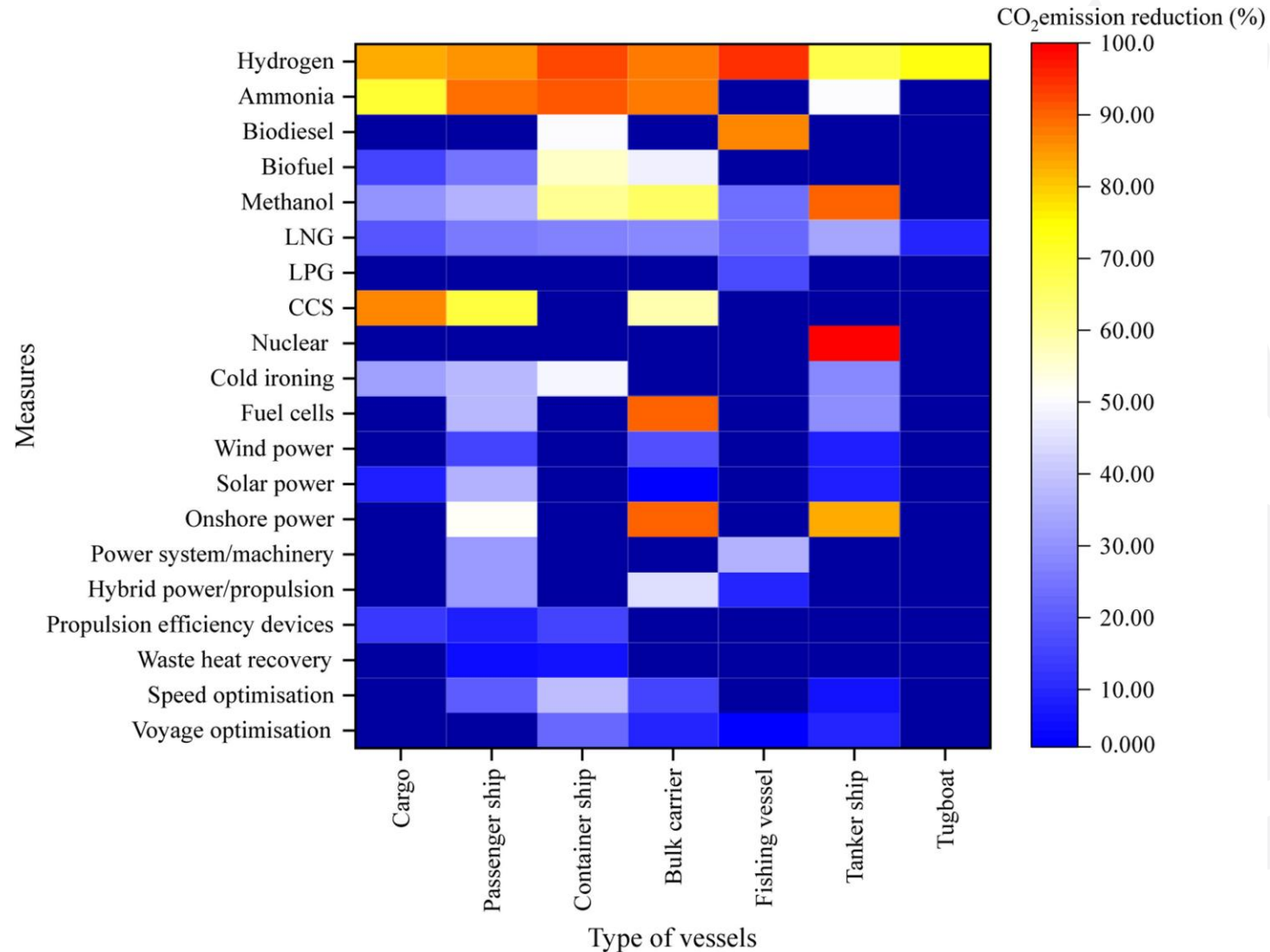
Fuels and Vessel types



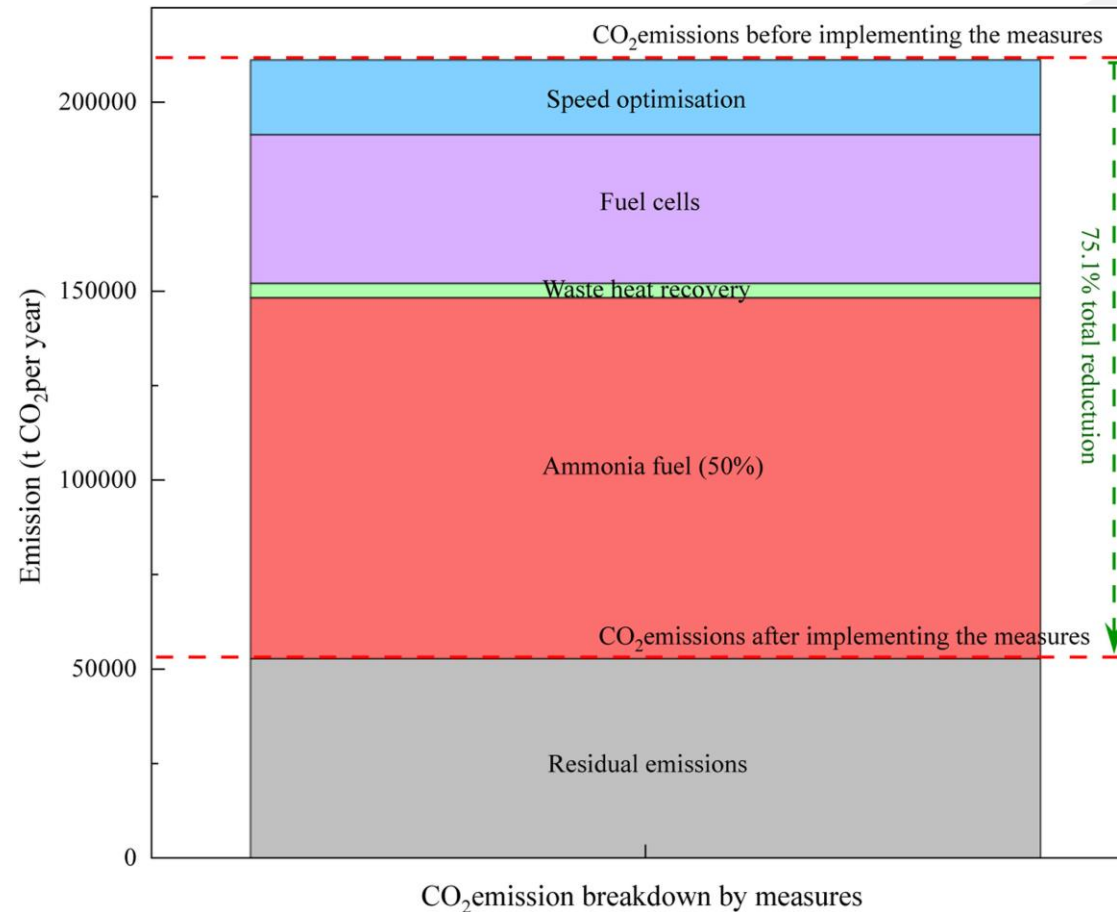
CO₂ reduction



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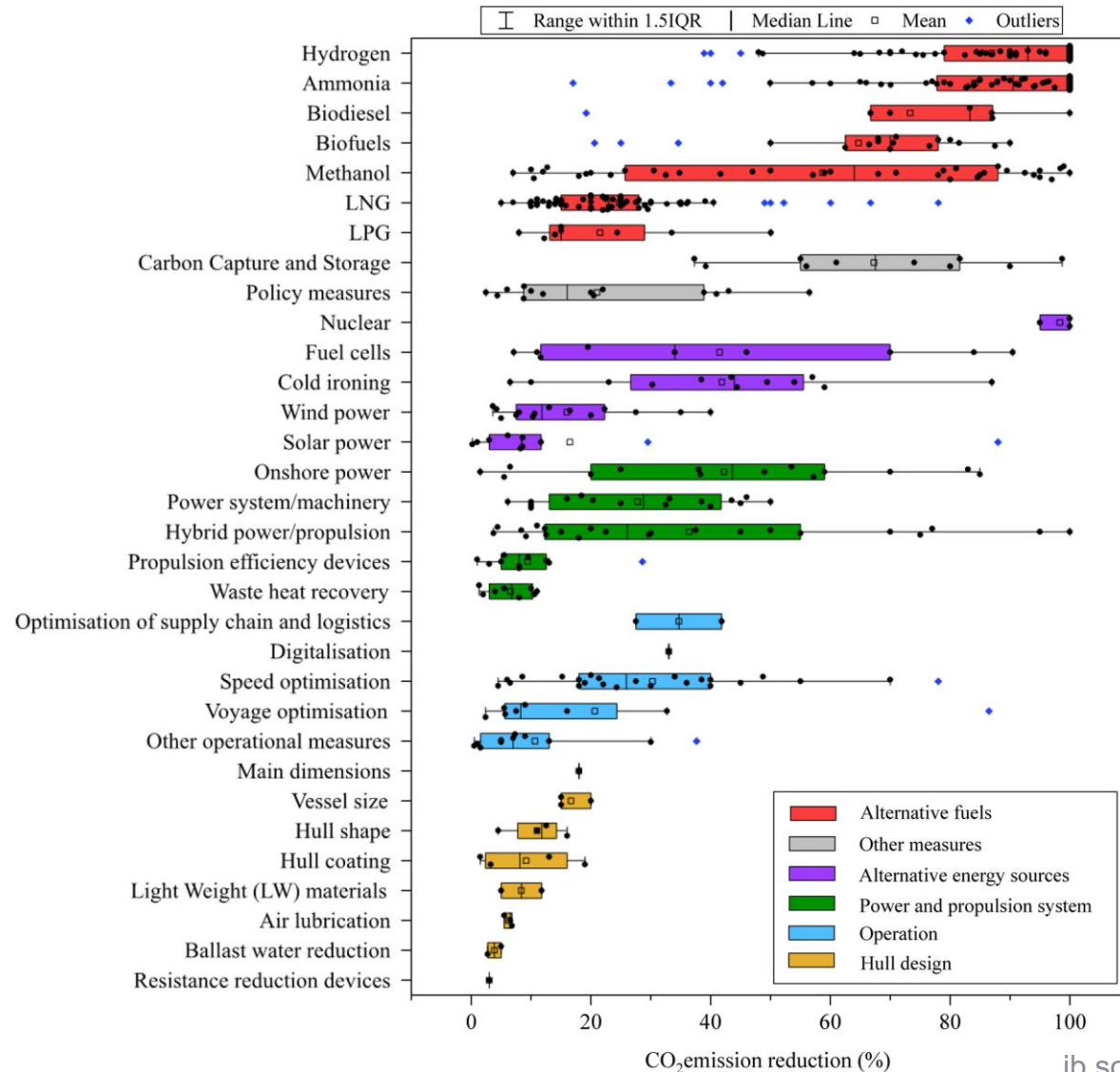
Case Study



No magic bullet:

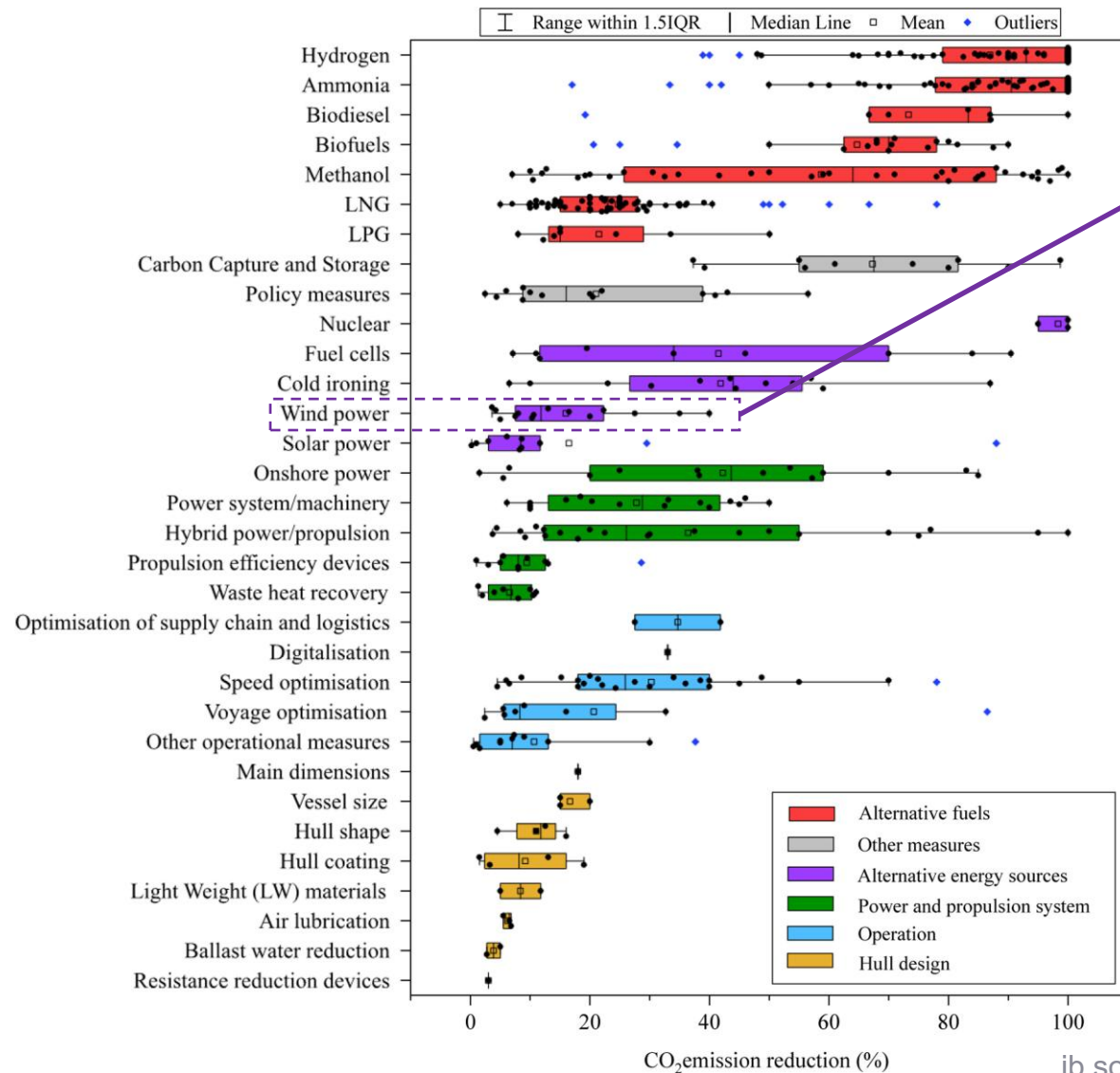
A combination of technologies is the key to maritime decarbonisation

Conclusions



- 32 CO₂ reduction measures and associated CO₂ reduction
- Based on a systematic review of published literature: 2018-2025
- Very few 100% CO₂ reduction potential...
- Combination of technologies to achieve decarbonisation

Up next...



Wind power

 **Prof. Jean-Baptiste R. G. Soupez**
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Wind-Assisted Ship Propulsion

Clean Maritime Assembly 2026



A wide-angle shot of a modern lecture hall. The room features a complex, geometric ceiling with white and grey panels. The seating consists of blue upholstered benches with attached wooden desks. Each desk has a small black monitor or tablet. The room is well-lit, with large windows on the sides and a central stage area at the front. The text "Thank you" is overlaid in the center of the image.

Thank you



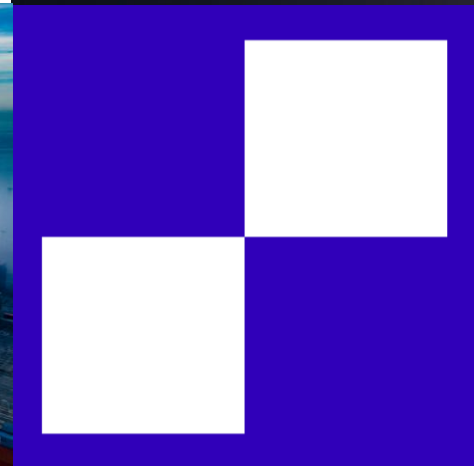
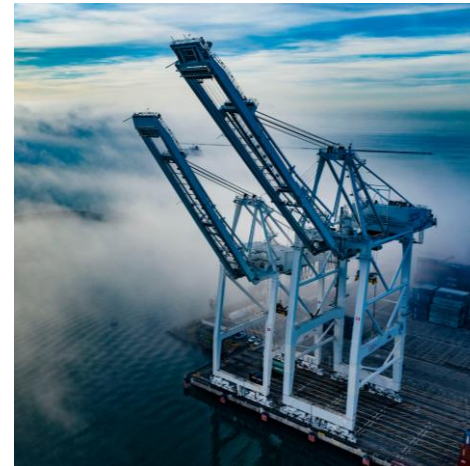
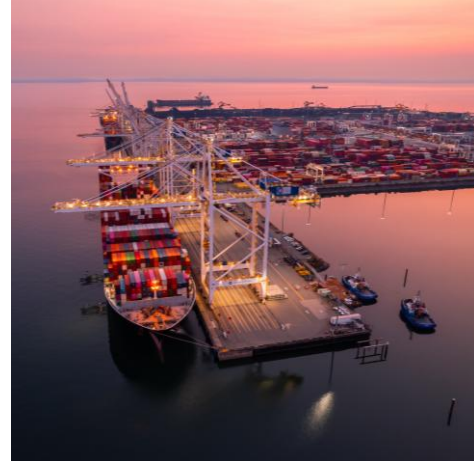
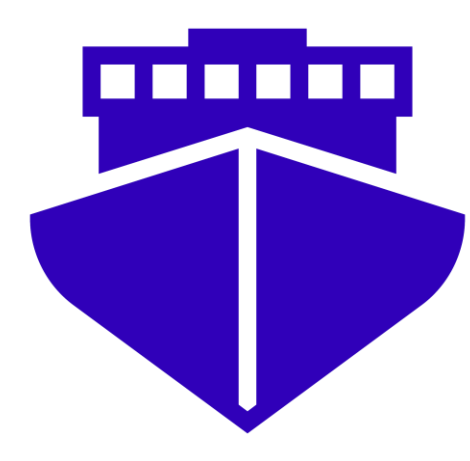
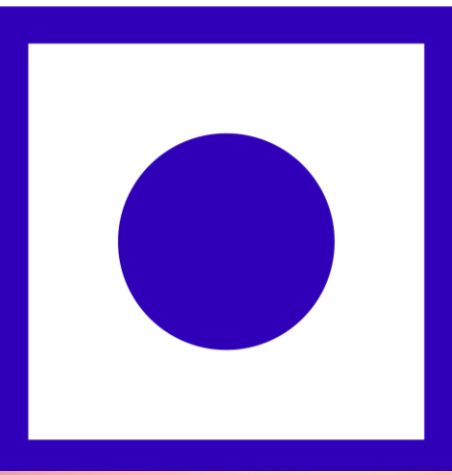
Prof. Jean-Baptiste R. G. Soupez

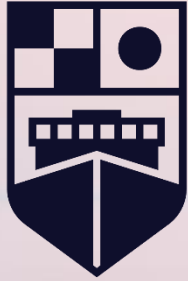
Professor of Mechanical Engineering and STEAM Education
Editor-in-Chief | ISO Convenor | National Teaching Fellow
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Session 3

Smarter Shipping: Ports, Scheduling & Wind Assisted Propulsion

- Prof Dongping Song
- Dr Asefe Forghani
- Prof Jean-Baptiste Soudpez





UK National
Clean Maritime
Research Hub



UNIVERSITY OF
LIVERPOOL

Viability of Rerouting Deep-Sea Container Services to Regional Ports in a Decarbonizing World

Professor Dongping Song

University of Liverpool

Dongping.Song@Liverpool.ac.uk

Clean Maritime Assembly 2026 (CMA26), Durham, 24-25 June 2026

Outline

- Background & Objective
- Cost and Emission Evaluation for Rerouting Scenarios
- Results and Findings
- Managerial Insights and Implications



Background

- Maritime decarbonization pressures are increasing
- IMO and regional regulations drive emissions reduction, e.g. IMO CII, IMO NZF; EU ETS, FuelEU Maritime.
- Use of low-carbon fuels, e.g., LNG, biofuels
- Shipping lines redesign service networks

Service Route Redesign

- Maersk and Hapag-Lloyd formed **Gemini** Cooperation in 2025
- Ocean Network Express, Yang Ming, and HMM formed **Premier Alliance** in 2025
- Gemini adopt a hub-and-spoke system
- MSC focus on multi-port direct services to smaller destinations, including secondary ports
- In North Europe, Antwerp loses four Asia-North Europe calls, Hamburg gains one call, Bremerhaven loses one, and Le Havre gains one call.
- In the UK, Felixstowe loses two calls, London Gateway gains two calls. MSC added Liverpool to one of its Asia-Europe service routes from July 2024

Port Competitiveness

- **Major ports**: scale, connectivity, volume
- **Regional ports**: smaller but closer to customers
- **Potential advantages**: lower congestion and inland transport distances
- Supply chain perspective
 - Deep-sea shipping
 - Port operations
 - Road transport
 - Rail transport
 - End-to-end supply chain assessment

Can regional ports gain competitiveness in a decarbonizing world?

Objective

- Assess economic and environmental viability of rerouting to regional-ports
 - Examine impacts of key factors on viability
 - Port of Liverpool vs Southampton
 - Asia–Europe container service
 - Supply chain viewpoint
- 
- A map of Ireland with the island of Ireland in light beige and the surrounding sea in light blue. Two red dots mark the locations of Belfast on the northeast coast and Dublin on the east coast. A black arrow points from the sea towards Dublin, and another black arrow points from the sea towards Belfast. The word 'Ireland' is written in a small, italicized font in the center of the island. The names 'Belfast' and 'Dublin' are written in black text next to their respective red dots. A small portion of the word 'Great Britain' is visible on the right edge of the map.

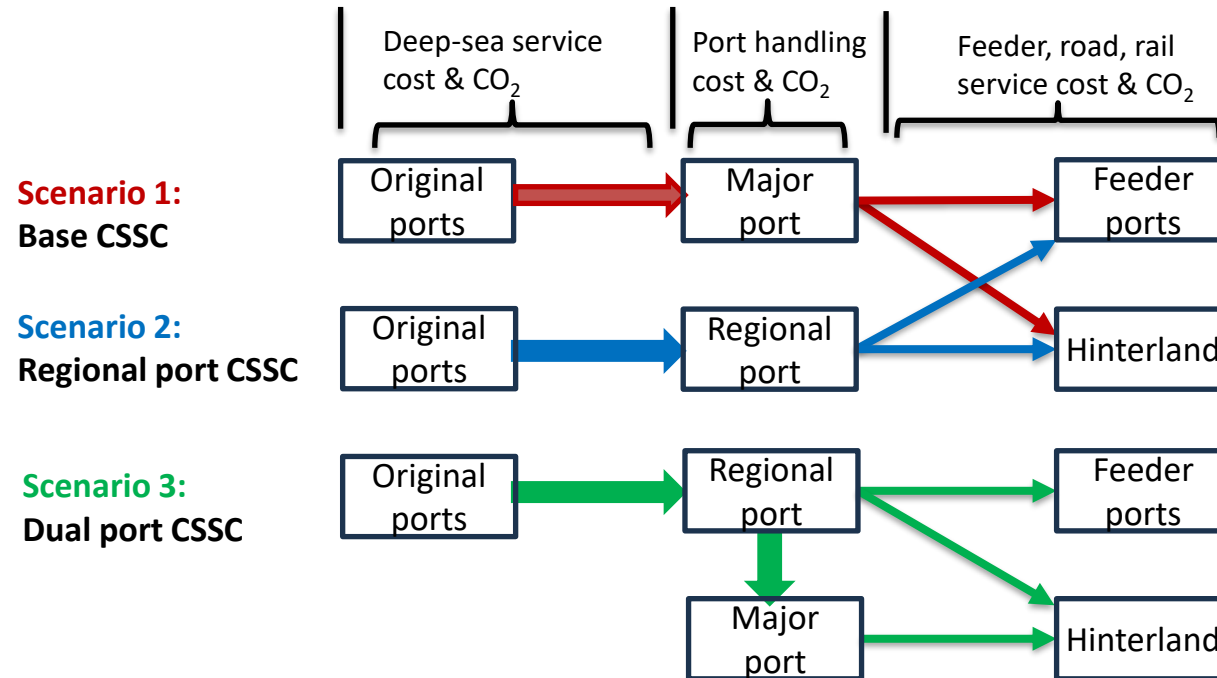


Rerouting To Regional Port



Total Cost & CO2 emission of container shipping supply chain:
from overseas ports → UK ports → feeder vessel, road, rail → inland destinations

Rerouting CSSC Scenarios



- Scenario 1: Southampton only
- Scenario 2: Liverpool replaces Southampton
- Scenario 3: Liverpool + Southampton

Scenario Evaluation Procedure

Step 1. Calculate deep-sea service costs and CO2 emissions

Step 2. Calculate port handling costs and CO2 emissions

Step 3. Calculate feeder service costs and CO2 emissions

Step 4. Calculate inland rail and road transportation costs and CO2 emissions

Step 5. Obtain total relevant costs and CO2 emissions for three scenarios, and calculate the performance differences between rerouting scenarios and the base scenario

1. Deep-sea service costs and CO₂ emissions

The relevant **deep-sea service cost** for scenario j , denoted by RC_{dj} , is given by:

- $RC_{dj} = C_{fuel} \cdot G_d(s_{dj}) \cdot d_{dj} / (24s_{dj})$, for $j=1,2,3$.
- $s_{d2} = d_{d2} \cdot s_{d1} / d_{d1}$.
- $s_{d3} = d_{d3} / (d_{d1}/s_{d1} - 8)$.
- $G_d(s_{dj}) := F_d \cdot (s_{dj} / s_{d0})^3$, for $j=1,2,3$.

The relevant **CO₂ emissions** of a vessel in deep-sea service, RE_{dj} for scenario j , are given by:

- $RE_{dj} = K_m \cdot G_d(s_{dj}) \cdot d_{dj} / (24s_{dj})$, for $j=1,2,3$.

2. Port handling costs and CO₂ emissions

The relevant **port handling costs**, RC_{pj} for $j=1,2,3$,

- $RC_{p1} = Y(V_d) + Y(V_f) + (W_1 + Z_1) \cdot (2h + 4g)$,
- $RC_{p2} = Y(V_d) + Y(V_f) + (W_2 + Z_2) \cdot (2h + 4g)$
- $RC_{p3} = 2Y(V_d) + Y(V_f) + (W_1 + Z_1) \cdot 2h_{3,1} + (W_2 + Z_2) \cdot (2h - 2h_{3,1} + 4g)$.
- Where $h_{3,1} = \sum_i h_i \cdot (\theta_{3,1i} + \delta_{3,1i})$ represents the hinterland shipment volume handled at Southampton in Scenario 3

Vessel berthing
THC
Congestion

The relevant **port operations emissions** RE_{pj} for $j=1,2,3$,

- $RE_{p1} = K_{w1} \cdot 2h$,
- $RE_{p2} = K_{w2} \cdot 2h$,
- $RC_{p3} = K_{w1} \cdot 2h_{3,1} + K_{w2} \cdot 2(h - h_{3,1})$.

3. Feeder service costs and CO₂ emissions

The relevant **feeder service cost** for scenario j , RC_{jj} , is given by

- $RC_{jj} = C_{fuel} \cdot G_f(s_{jj}) \cdot d_{jj} / (24s_{jj})$, for $j=1,2,3$
- $s_{jj} = d_{jj} \cdot s_{f1} / d_{f1}$, for $j=1,2,3$
- $G_f(s_{jj}) := F_f \cdot (s_{jj} / s_{f0})^3$, for $j=1,2,3$

The relevant **CO₂ emissions** of a vessel in feeder service, RE_{jj} for scenario j , is given by

- $RE_{jj} = K_m \cdot G_f(s_{jj}) \cdot d_{jj} / (24s_{jj})$, for $j=1,2,3$.

4. Inland rail and road transportation costs and CO₂ emissions

The relevant **hinterland transportation costs** by road hauliers and rail services for 3 scenarios, RC_{hj} for $j=1,2,3$, are

- $RC_{h1} = C_h \cdot \sum_i (\theta_{1i} \cdot 2h_i \cdot d_{1i}) + \sum_i 2h_i \cdot (1 - \theta_{1i}) \cdot (C_r \cdot d_{1i} + 2C_{rt} + 30C_h);$
- $RC_{h2} = C_h \cdot \sum_i (\theta_{2i} \cdot 2h_i \cdot d_{2i}) + \sum_i 2h_i \cdot (1 - \theta_{2i}) \cdot (C_r \cdot d_{2i} + 2C_{rt} + 30C_h);$
- $RC_{h3} = C_h \cdot \sum_i (\theta_{3,1i} \cdot 2h_i \cdot d_{1i} + \theta_{3,2i} \cdot 2h_i \cdot d_{2i}) + \sum_i 2h_i \cdot \delta_{3,1i} \cdot (C_r \cdot d_{1i} + 2C_{rt} + 30C_h) + \sum_i 2h_i \cdot \delta_{3,2i} \cdot (C_r \cdot d_{2i} + 2C_{rt} + 30C_h).$

The relevant **CO₂ emissions** in tonnes from hinterland transportation by road hauliers and rail services for 3 scenarios, RE_{hj} for $j=1,2,3$, are

- $RE_{h1} = 15K_h \cdot \sum_i (\theta_{1i} \cdot 2h_i \cdot d_{1i}) \cdot 10^{-6} + \sum_i (1 - \theta_{1i}) \cdot 2h_i \cdot (15K_r \cdot d_{1i} + 2K_{rt} + 15K_h \cdot 30) \cdot 10^{-6};$
- $RE_{h2} = 15K_h \cdot \sum_i (\theta_{2i} \cdot 2h_i \cdot d_{2i}) \cdot 10^{-6} + \sum_i (1 - \theta_{2i}) \cdot 2h_i \cdot (15K_r \cdot d_{2i} + 2K_{rt} + 15K_h \cdot 30) \cdot 10^{-6};$
- $RE_{h3} = 15K_h \cdot \sum_i (\theta_{3,1i} \cdot 2h_i \cdot d_{1i} + \theta_{3,2i} \cdot 2h_i \cdot d_{2i}) \cdot 10^{-6} + \sum_i [\delta_{3,1i} \cdot 2h_i \cdot (10K_r \cdot d_{1i} + 2K_{rt} + 15K_h \cdot 30) + \delta_{3,2i} \cdot 2h_i \cdot (15K_r \cdot d_{2i} + 2K_{rt} + 15K_h \cdot 30)] \cdot 10^{-6}.$

5. Total relevant costs and CO₂ emissions in three scenarios

The **total relevant costs and CO₂ emissions** in three CSSC scenarios, denoted by TRC_j and TRE_j for $j=1,2,3$, are given by

- $TRC_j = RC_{dj} + RC_{pj} + RC_{fj} + RC_{hj}$, for $j=1,2,3$.
- $TRE_j = RE_{dj} + RE_{pj} + RE_{fj} + RE_{hj}$, for $j=1,2,3$.

The **relative total relevant costs and CO₂ emissions** between Scenarios 2 and 3 compared to Scenario 1

- $TRC_j - TRC_1$, for $j=2,3$.
- $TRE_j - TRE_1$, for $j=2,3$.

Proposition 1: Cost Sensitivity

- Suppose that the major port has a closer proximity to **maritime routes** ($d_{d3} > d_{d2} > d_{d1}$), while the regional port has a closer proximity to **transshipment markets** ($d_{f3} = d_{f2} < d_{f1}$). Additionally, the regional port has lower **THCs** ($W_1 > W_2$) and lower **port congestion** costs ($Z_1 > Z_2$).
 - $TRC_2 - TRC_1$ and $TRC_3 - TRC_1$ are increasing in s_{d1} but decreasing in s_{f1} .
 - $TRC_2 - TRC_1$ and $TRC_3 - TRC_1$ are decreasing in d_{d1} .
 - $TRC_2 - TRC_1$ and $TRC_3 - TRC_1$ are decreasing in $W_1 - W_2$ and $Z_1 - Z_2$.
 - $TRC_2 - TRC_1$ and $TRC_3 - TRC_1$ are decreasing in g .

Proposition 2: Emission Sensitivity

- Suppose that the major port has a closer proximity to **maritime routes** ($d_{d3} > d_{d2} > d_{d1}$), while the regional port has a closer proximity to **transshipment markets** ($d_{f3} = d_{f2} < d_{f1}$). Additionally, the regional port has lower **THCs** ($W_1 > W_2$) and lower **port congestion** costs ($Z_1 > Z_2$).
 - $TRE_2 - TRE_1$ and $TRE_3 - TRE_1$ are increasing in s_{d1} but decreasing in s_{f1} .
 - $TRE_2 - TRE_1$ and $TRE_3 - TRE_1$ are decreasing in d_{d1} .
 - $TRC_2 - TRC_1$ and $TRC_3 - TRC_1$ are decreasing in $(K_{w2} - K_{w1})$.

Numerical Experiments

- The deep-sea vessel $V_d = 10,000$ TEUs; $s_{d0} = 23$ knots;
- the feeder vessel $V_f = 600$ TEUs; $s_{f0} = 18$ knots;
- In the base scenario, the feeder vessel's sailing speed is 5 knots less than the deep-sea vessel, i.e. $s_{f1} = s_{d1} - 5$.
- Both deep-sea vessels and feeder vessels use **biofuel**. The fuel consumption per day at designed speed $F_d = 205\text{t}$; $F_f = 33\text{t}$.
- The biofuel cost $C_{fuel} = \$1000/\text{ton}$. The fuel emission factor $K_m = 1.2 \text{ g CO}_2/\text{g}$.

Asia-Europe Service Route

- **Scenario 1 (base):** Far East ports - Singapore - Rotterdam - Hamburg - **Southampton** - Singapore -- Far East ports.
- **Scenario 2:** Far East ports - Singapore - Rotterdam - Hamburg - **Liverpool** - Singapore -- Far East ports.
- **Scenario 3:** Far East ports - Singapore – **Liverpool** - Rotterdam - Hamburg - **Southampton** - Singapore -- Far East ports.
- The round-trip journey distances for the deep-sea services in Scenario 2 and Scenario 3 are 503 and 605 nautical miles longer than the base scenario, i.e. $d_{d2} = d_{d1} + 503$, $d_{d3} = d_{d1} + 605$.
- The round-trip journey distance in the feeder service is: $d_{f1} = 1227$ in the base scenario; and $d_{f2} = d_{f3} = 549$ in Scenarios 2 & 3.

Port-related parameters

- THC at Liverpool is £15 less than Southampton, $W_2 - W_1 = -\$15$;
- Liverpool is less congested,
- $Z_2 - Z_1 = -\$10$;
- $K_{w2} - K_{w1} = -1072$ g CO₂ /container, representing the amount of CO₂ emissions for additional 10~15 minutes waiting at ports for an external truck.
- The fixed vessel berthing costs per call at a port is given by $Y(V) = 1.95 * V + 5200$.

Hinterland transport-related parameters

- The cost of transport a container by truck $C_h = \$2.5/\text{km}$;
- The cost of transport a container by rail $C_r = \$0.3/\text{km}$.
- For rail containers, handling costs at both seaport and inland rail terminals, i.e. $C_{rt} = \$187.5/\text{container}$.
- Assume the average distance between inland terminals and customers is 30km, with deliveries made by trucks.
- $K_h = 106.5 \text{ g CO}_2$ per tonne-km by truck;
- $K_r = 26 \text{ g CO}_2$ per tonne-km by rail;
- $K_{rt} = 8040 \text{ g CO}_2$ per container handled at rail terminals;
- The average container weight is 15 tonnes
- **Rail-to-road modal split:** 0.3:0.7 for SOU and 0.1:0.9 for LIV.

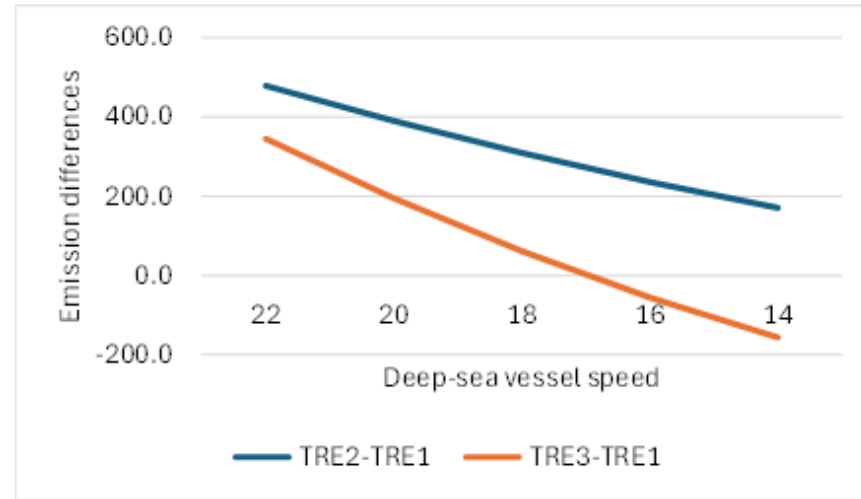
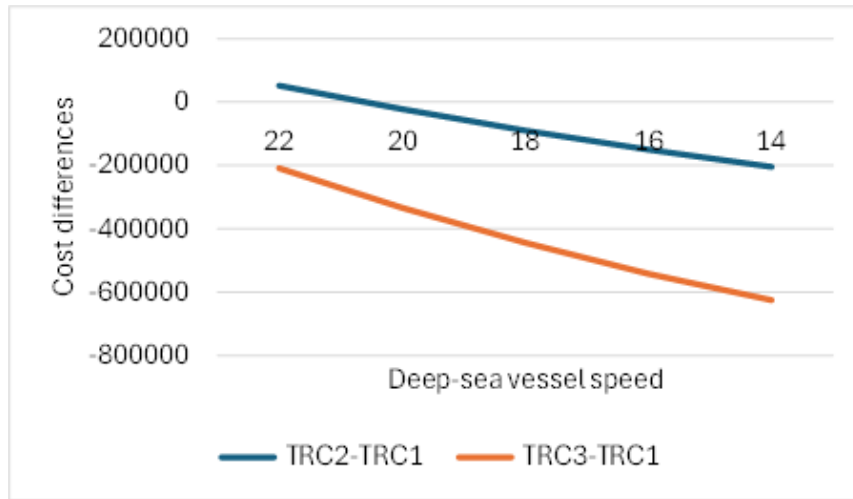
Hinterland shipment distribution in the UK

Region	Reference cities	% of TEU	Liverpool (km)	Southampton (km)
North East	Newcastle	2.98	282	526
York & Humber	Leeds & Sheffield	9.55	141	365
East Midland	Derby	29.70	156	277
East England	Northampton	8.64	242	153
South East	London	24.12	343	129
South West	Exeter	2.51	411	151
North West	Liverpool & Manchester	16.83	30	380
Wales	Swansea	1.07	391	279
Scotland	Edinburgh	4.59	354	692

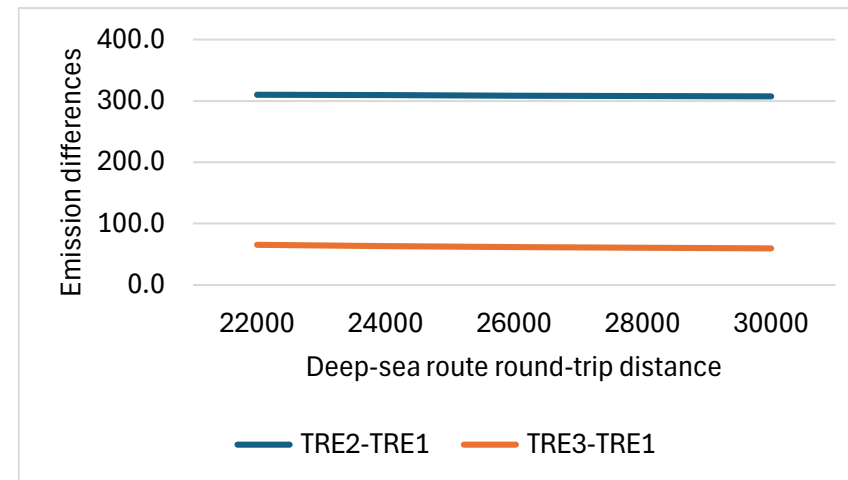
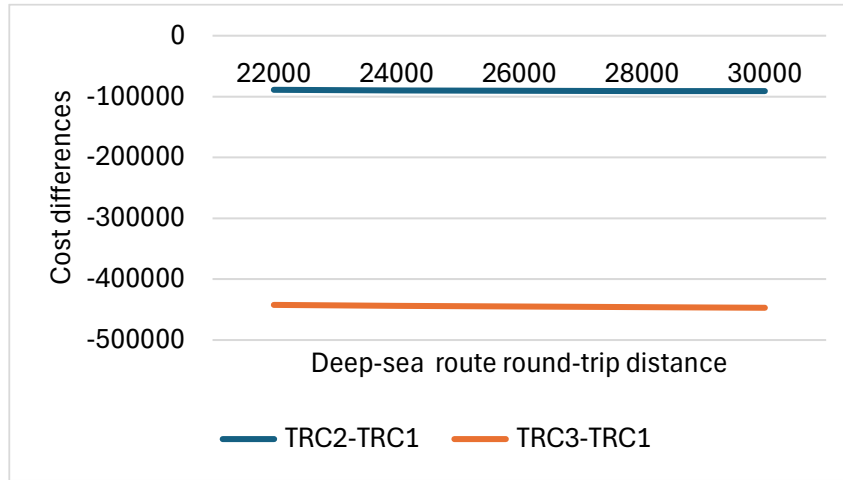
Impact of Key Factors

- Deep-sea vessel speed s_{d1} ,
- The round-trip distance in deep-sea service d_{d1} ,
- The hinterland shipment volume h ,
- The CO₂ emission factor of marine fuel K_m ,
- The marine fuel cost per tonne C_{fuel} ,
- The reduction of THC at Liverpool $W_1 - W_2$,
- The modal split at Liverpool $modalSplit_2$.

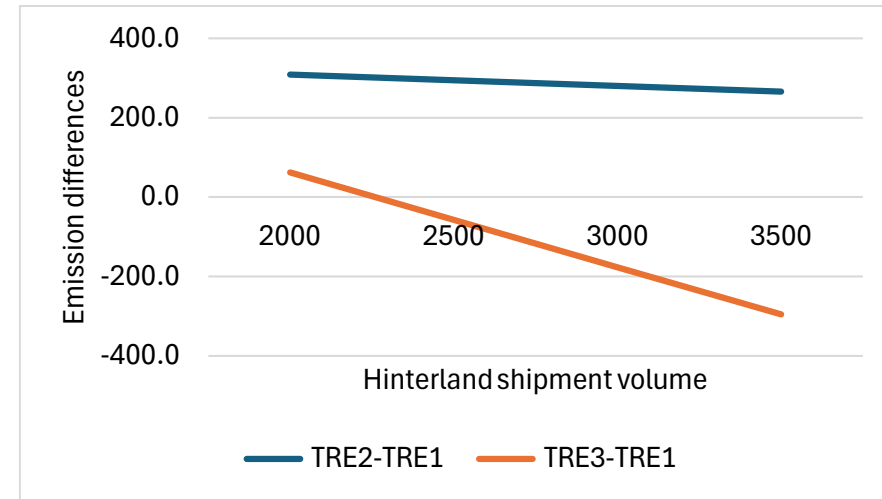
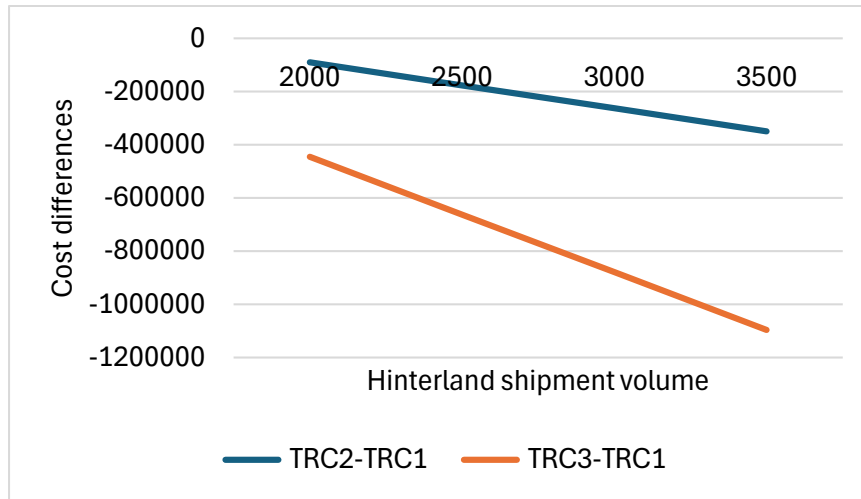
Deep-sea vessel speed



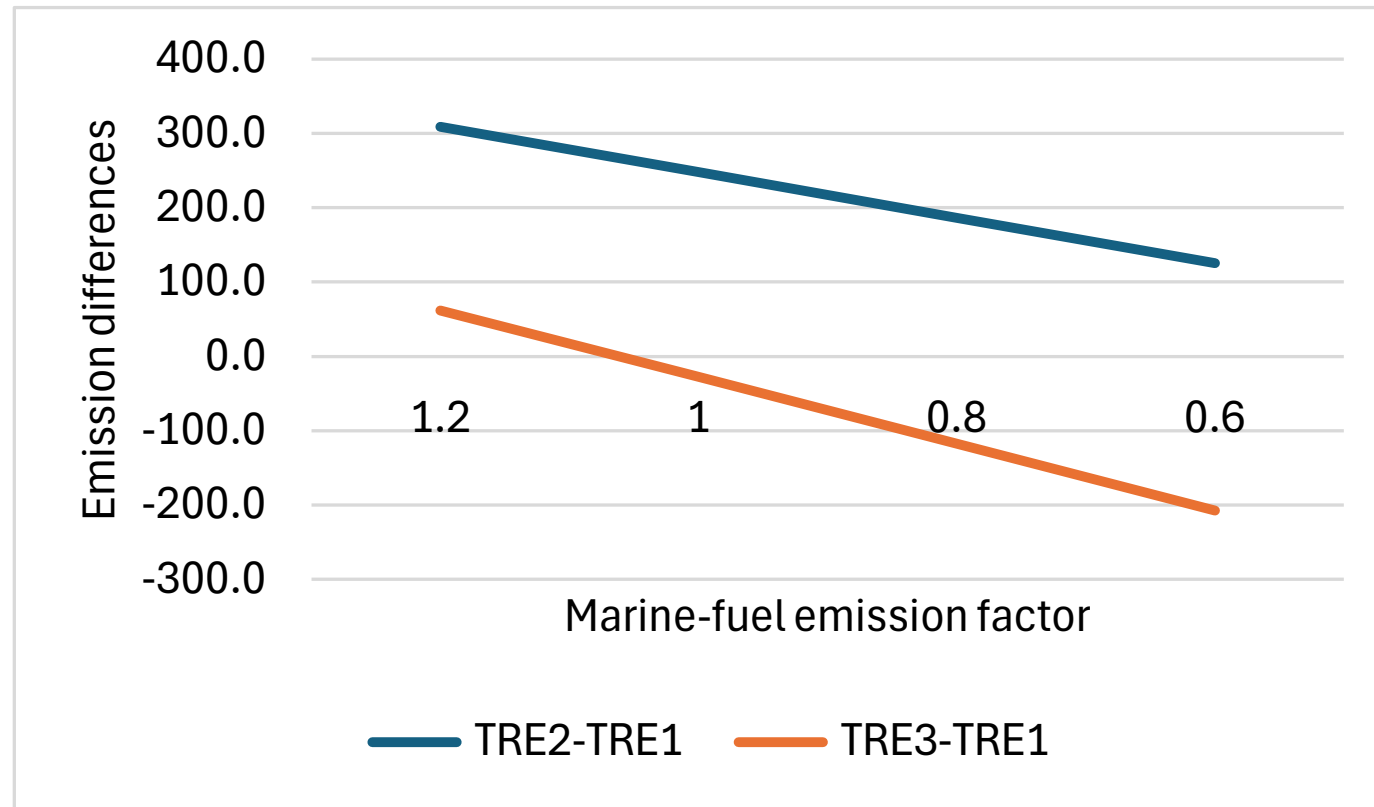
The round-trip distance in deep-sea service



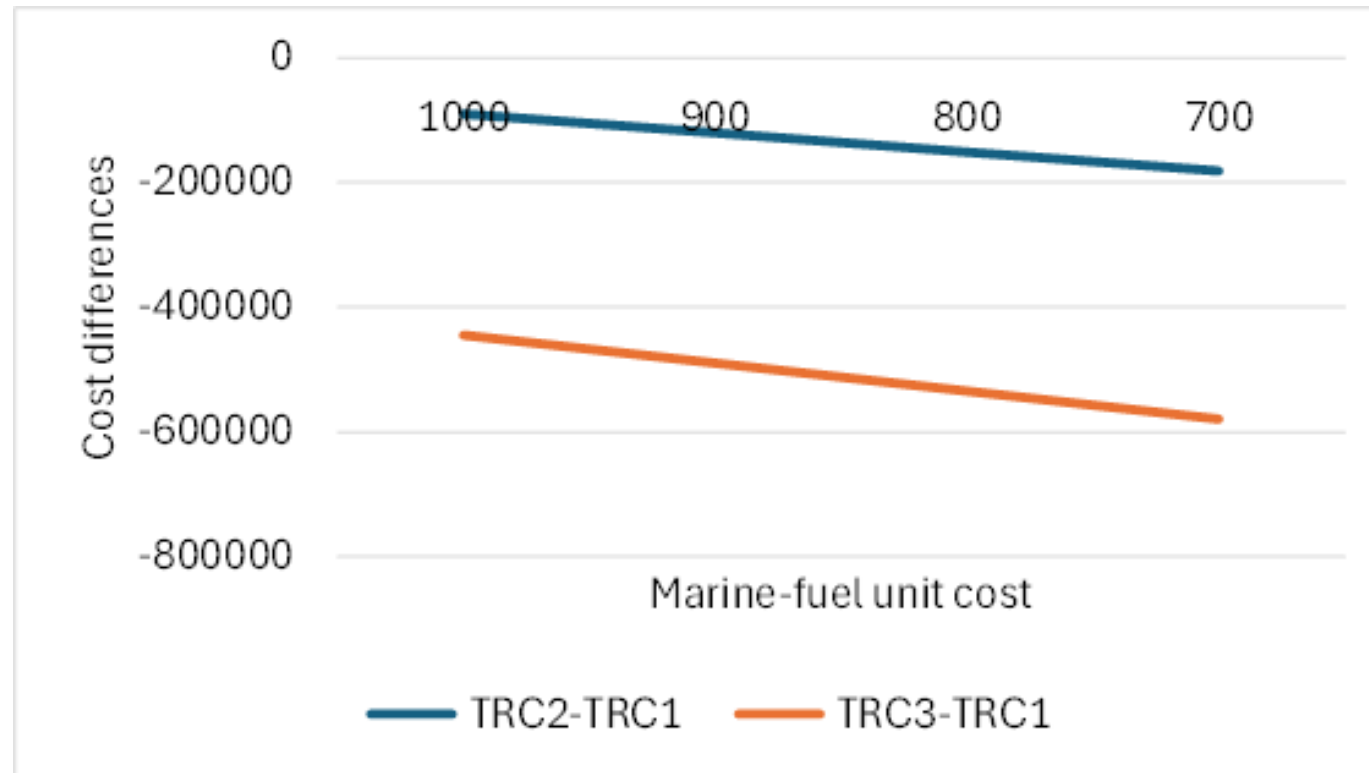
The hinterland shipment volume



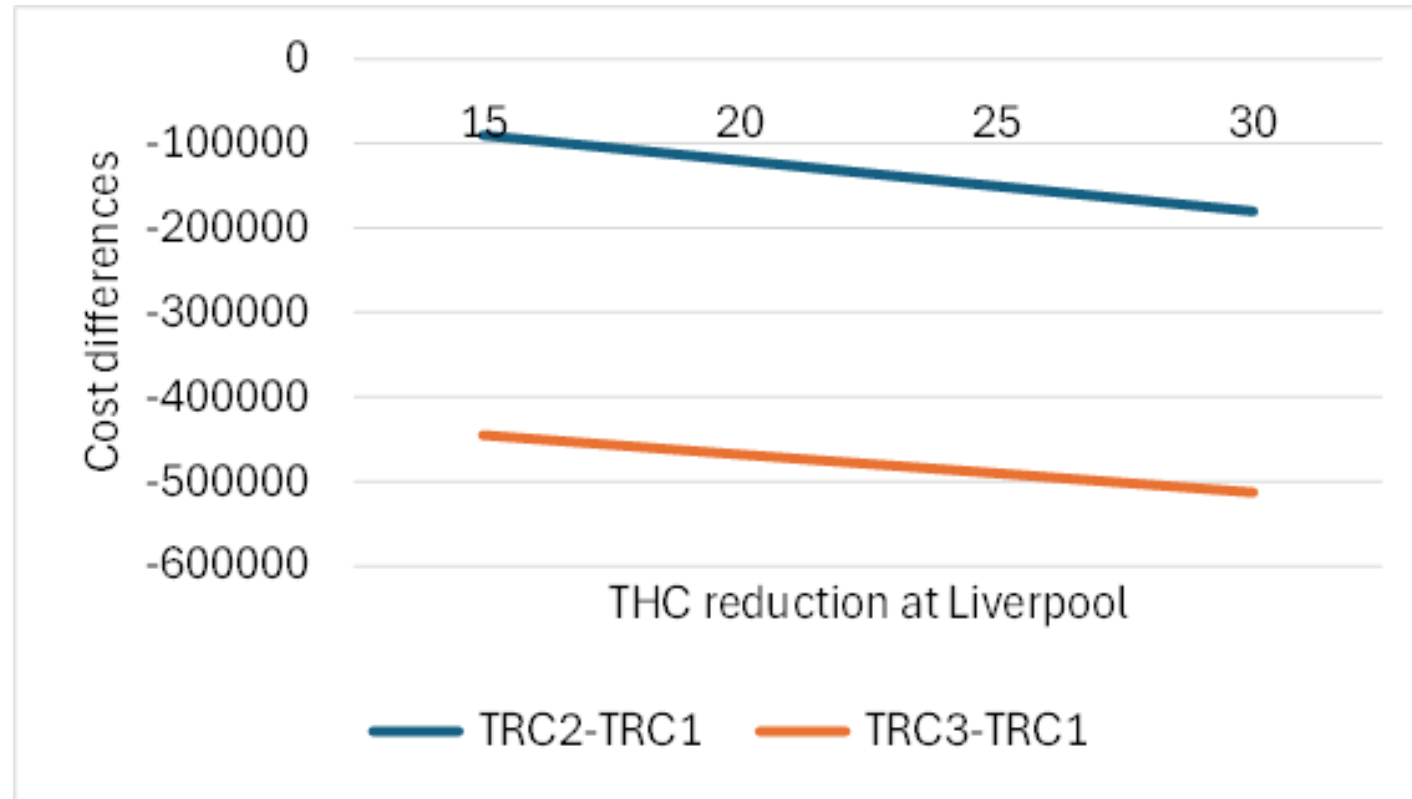
The CO₂ emission factor of marine fuel



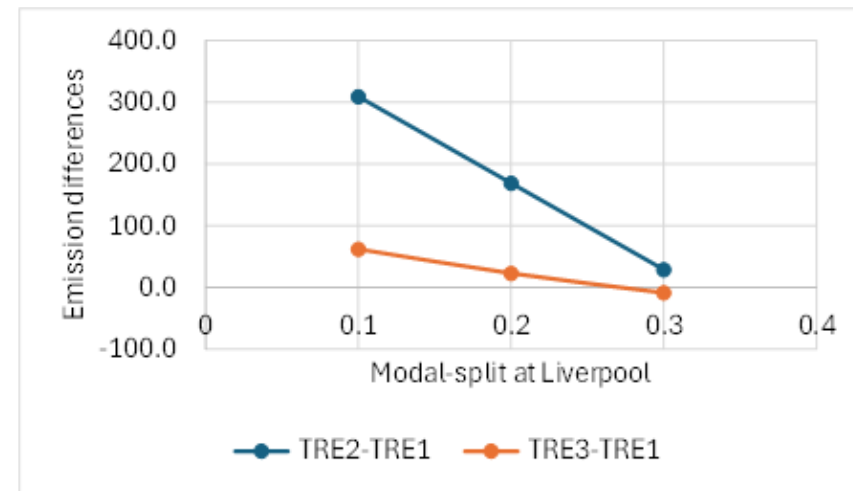
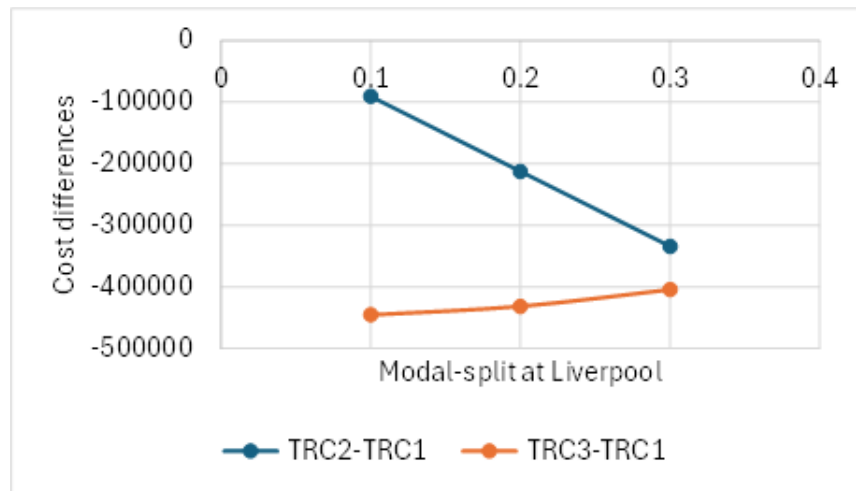
The marine fuel cost per tonne



The reduction of THC at Liverpool



The modal split at Liverpool



Key findings under baseline parameters

- ***Economic viability***: Rerouting to Liverpool yields significant cost savings under both scenarios, saving cost by \$90,201 in Scenario 2 and \$445,060 in Scenario 3.

Show commercial viability under current market conditions

- ***Environmental trade-off***: Rerouting increases total supply chain CO₂ emissions by 309 tonnes and 62 tonnes more for Scenario 2 and Scenario 3 respectively.

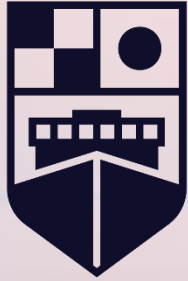
Create a cost-emissions trade-off for decision-makers

Strategic levers for enhancing rerouting viability

Factor	Economic impact on rerouting	Environmental impact on rerouting
Slower steaming	Positive	Positive
Higher hinterland volume	Positive	Positive
Increased rail use at Liverpool	Positive	Positive
Lower fuel emission factor	Neutral	Positive
Lower fuel unit cost	Positive	Neutral
Lower THC at Liverpool	Positive	Neutral
Longer distance deep-sea route	Minor Positive	Minor Positive

Managerial insights and implications

- **Prioritize dual-benefit levers:** Investing in rail infrastructure, adopting slower steaming, and fostering hinterland cargo consolidation
- **Accelerate greener fuel adoption:** Policy support (subsidies, mandates) for near-zero emission marine fuels is essential to resolve the emissions trade-off
- **Optimize port economics:** Regional ports should strategically improve efficiency and offer competitive THC to attract deep-sea services.
- **Implement a consolidated UK service route:** An alternative rerouting scenario can be designed by introducing a rotating call pattern alternating between SOU and LIV.



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Clean Maritime
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Thank you for your attention!

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CLEAN MARITIME ASSEMBLY 2026 · ACADEMIC INSIGHTS

Energy-aware scheduling and berth allocation for ferries under phased cold ironing upgrades

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Presented by Asefe Forghani

Research Fellow for Leading Co-innovation Methodology & Maritime Decarbonisation

Funded by UKRI National Clean Maritime Research Hub · EPSRC
EP/Y024605/1

Transportation Research Part E, 210 (2026) 104800

Motivation

Ports must reduce at-berth hotelling emissions, with ferries among the strongest early candidates

Vessel manoeuvring, anchoring and berthing drive local air pollution and public-health risk in densely populated port areas. **Cold ironing** (shore-side power) lets a berthed vessel switch off its auxiliary diesel engines and draw electricity instead. Ferries - fixed routes, small size, high call frequency - are the strongest early candidates, reinforced by green-corridor commitments such as the **Clydebank Declaration** (at least six UK corridors by 2026).



200+

ports

now offer cold ironing worldwide,
serving roughly 2,500 vessels



~5%

of shipping CO₂

from RoPax / Ro-Ro ferries -
concentrated near populated coasts



25–57%

berthing CO₂ cut

reported from cold ironing across
UK, Turkish and Taiwanese ports

The problem

Limited shore power forces hybrid ferries back to diesel

When several hybrid ferries berth in close succession, their combined cold-ironing demand can exceed what the grid and on-site battery (BESS) can supply.

A BESS needs time to recharge and degrades with every charge–discharge cycle, so it cannot absorb synchronised peaks on its own. Some vessels then revert to auxiliary diesel engines, eroding both the emission benefit and the return on shore-power investment.



The two operational levers - vessel schedules and berth assignments - are tightly coupled in ferry terminals, so they must be optimised together, not in sequence.

Why peaks cause diesel fallback



Several hybrid ferries berth at once

Synchronised, high-frequency shuttle calls



Combined demand exceeds grid + BESS

Battery cannot recharge fast enough between peaks



Some ferries revert to diesel

Lost emission savings and stranded investment

What existing scheduling and berth-allocation models miss



Uniform shore power assumed

Most models assume every berth has adequate cold ironing. Partial, phased upgrades - the real early-transition state - are rarely represented.



Energy constraints overlooked

Many berth-allocation and scheduling models ignore grid-capacity limits and BESS charge–discharge dynamics altogether.



Container-terminal assumptions

RoRo ferries operate on cyclic and predictable schedules and usually berth immediately upon arrival, unlike the assumptions typically used for container terminals.



Decoupled, single-operator view

Scheduling and berth allocation are treated separately, and multi-operator terminals with mixed diesel–hybrid fleets are under-studied.

An integrated, energy-aware model for ferry terminals



Energy-aware ferry model

Berth allocation and scheduling tailored to ferries: cold-ironing limits, interdependent crossing schedules, and mixed fixed/flexible ticketing across multiple operators in a single formulation.



Enables a phased diesel-to-hybrid shift

A tri-objective MIP that cuts CO₂, limits grid exceedance to protect the BESS, and reduces berth activation - extracting maximum benefit at every phase without large up-front infrastructure spend.

Structural observation: in cyclic short-sea ferry operations, fixing the initial berthing time may largely determine the downstream sequence of arrivals, suggesting that scheduling and berth allocation are difficult to treat as fully separable decisions.

Three competing objectives, in strict priority order

1



Minimise CO₂ emissions

Prioritise electric (hybrid) berthing over diesel and eliminate unnecessary crossings.



2



Minimise grid exceedance

Limit periods where demand exceeds grid capacity, cutting BESS cycling and extending battery life.



3



Minimise berth activation

Avoid switching on berths - especially costly cold-ironing berths - that are not needed, lowering maintenance cost.



Robustness: sensitivity analysis confirms the ordering is stable under realistic demand - re-ordering the objectives changes the schedule only on unusually low-demand days, when spare vessels can be idled.

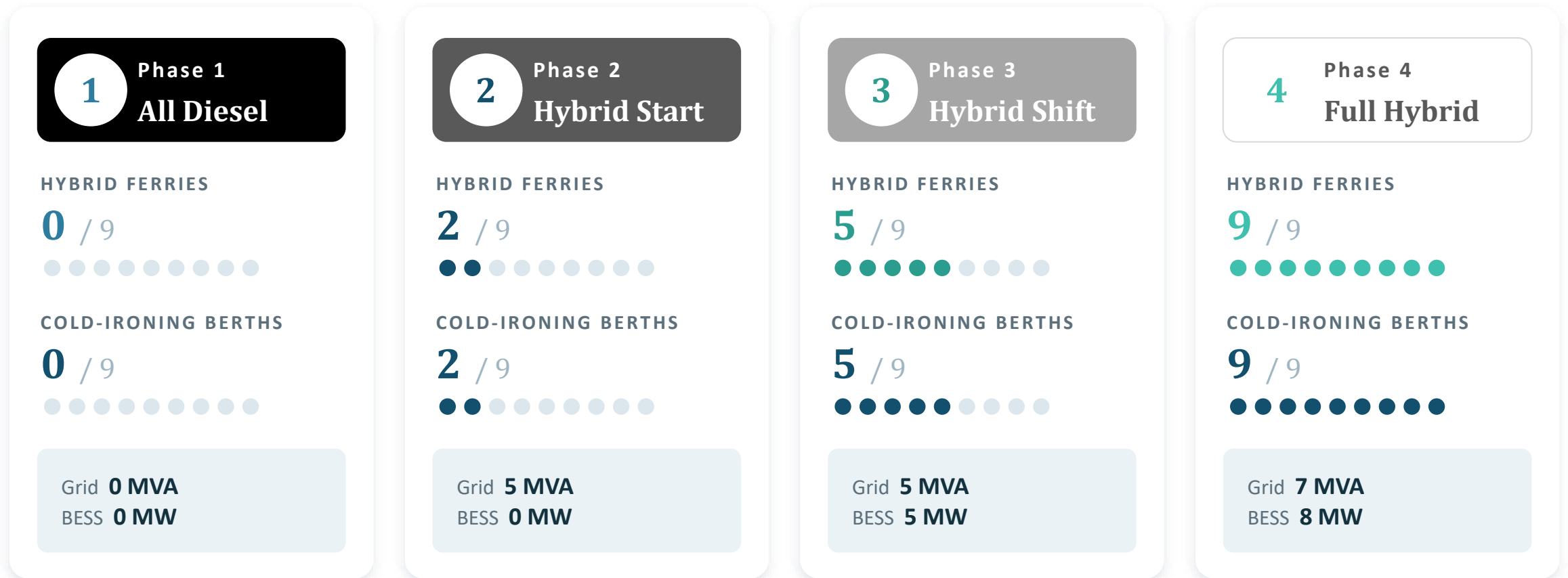


Why lexicographic, not weighted

The objectives are non-compensatory: a gain on a lower priority must never offset a loss on a higher one. Each is optimised in turn, only after the one above has reached its best attainable value.

CASE CONTEXT

A four-phase pathway from all-diesel to full-hybrid



A major Western European ferry port (Port A)



The binding constraint on a real green corridor

Port A faces limited grid capacity and ageing infrastructure - full upgrades are roughly a decade away - while the partner port has already upgraded.

Three operators each run three ferries. Cars buy operator-specific tickets; freight uses flexible multi-operator tickets and boards any ferry with space.

Arrivals are modelled with Poisson fits to eight years of historical demand (2016–2023).

24 h

Scheduling horizon
(6 h round trip, 4
trips/ferry)

1 h / 5 h

Berthing / sailing time

5 MW

Hourly charging load
per ferry during
berthing

2.0 / 6.7

Berthing CO₂ (t/h)
hybrid / diesel

4 × 200

Demand scenarios
× instances

2016–23

Years of demand data

Mixed-integer programming, solved to optimality in under two seconds



minimise
CO₂ emissions



minimise
Grid exceedance



minimise
**Berth-activation
penalty**



Three decision levers

- Initial berthing time of each ferry (within a flexibility window)
- Berth assignment in each time period
- Service-termination time of each ferry



Key constraint groups

- Demand coverage within time windows (fixed & flexible tickets)
- Cyclic round-trip timing and continuous service
- Berth occupancy, exclusivity and operator-specific compatibility
- Energy balance: grid import + BESS charge/discharge



Computational performance

0.94 s

average solve time

1.37 s

slowest of 200 instances

200 / 200 solved to proven optimality

Gurobi 12.0 · Python 3.12

Result (experiment 1)

Planned infrastructure is sufficient, with one modest top-up

Phase	Grid · BESS (planned)	CI berths active	Reinforcement needed
1 All Diesel	0 · 0	0	None
2 Hybrid Start	5 · 0	1	None
3 Hybrid Shift	5 · 5	2	None
4 Full Hybrid	7 · 8	3	+1 MVA grid or +6 MW BESS

3

cold-ironing berths

are enough to serve all demand without any ferry waiting



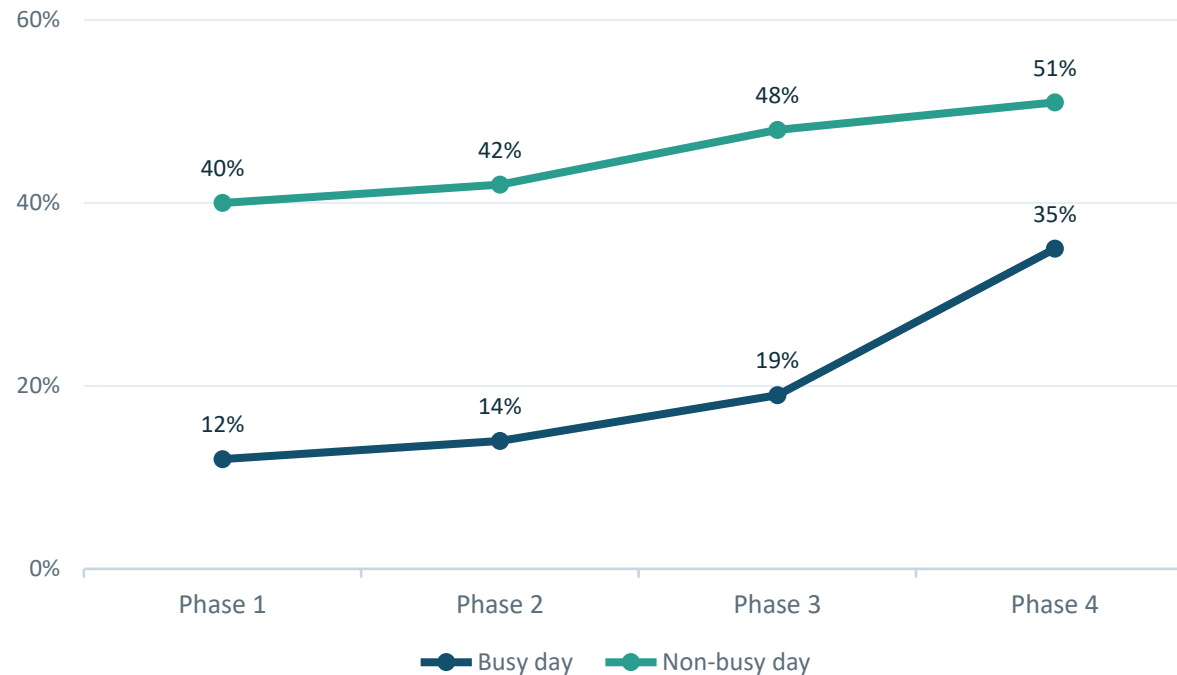
Only Phase 4 needs more. A small top-up - +1 MVA grid or +6 MW BESS - restores feasibility under simultaneous peak demand. Phases 1–3 need nothing.

Extra berths beyond these three remain valuable for resilience, maintenance and future growth - this is an activation benchmark, not a case for decommissioning.

Result (experiment 2)

Energy-aware scheduling beats business-as-usual - even before hybridisation

CO₂ reduction vs business-as-usual (%)



Fewer, fuller crossings

Busy day 41→36 · non-busy 40→24 - redundant sailings removed



Higher capacity efficiency

+12% on the busy day, +40% on the non-busy day



No diesel fallback while berthed

Energy-aware scheduling keeps every hybrid ferry on shore power

Zero-investment win: even with no hybrids, EAS cuts CO₂ by 12–40% vs BAU just by removing redundant crossings.

Result (experiment 3)

Up to 70% lower at-berth hotelling CO₂ emissions as the fleet transitions to hybrid propulsion

70%

maximum berthing CO₂ reduction (Full Hybrid)



At-berth hotelling electricity consumption increases in each phase

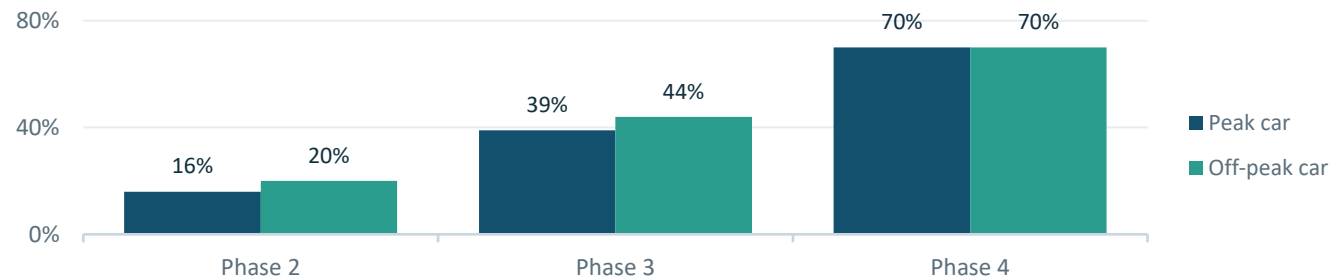
22% → 56% → 100% of berthings powered by electricity (peak-car case)



Grid exceedance only in Full Hybrid

And only under simultaneous peak car + peak freight - a deliberate worst-case stress test. These are controlled BESS peak-shaving events, not service failures.

Berthing CO₂ reduction vs all-diesel (%)



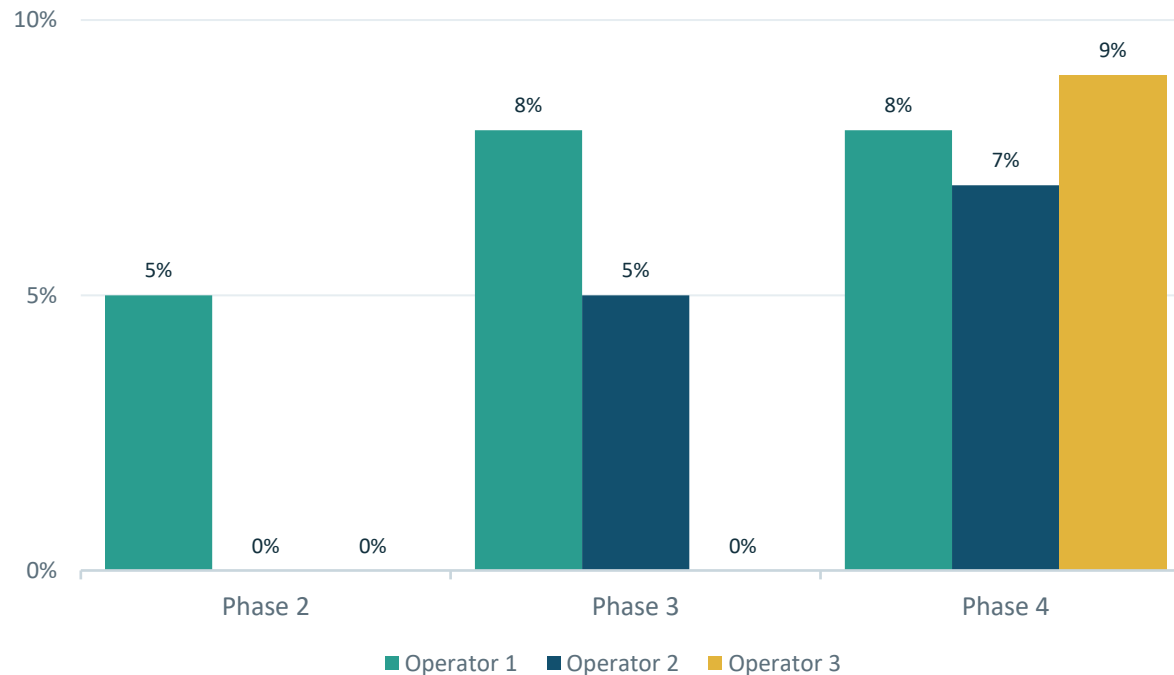
Freight flexibility optimises the timetable

Total crossings stabilise at 36 in the peak-car-demand case and 24 in the off-peak-car-demand case, regardless of freight timing. This suggests that freight flexibility supports more efficient allocation without adding redundant sailings.

Result

Operators benefit too, with stable at-berth energy-system performance

Operator CO₂ reduction vs all-diesel (% , total daily)



Diesel fallback eliminated

Every hybrid ferry stays on shore power, in all phases and demand scenarios.



Flatter load profile

EAS smooths BAU's demand spikes, cutting grid-exceedance events and protecting the BESS.



Longer battery life

Less charge–discharge cycling; the BESS stays near full and serves mainly as backup.

Operator-level cuts of 5–9% are bounded because crossings remain diesel-powered - the saving is on berthing only.

Optimise before you build, and coordinate across the corridor



Operational optimisation first

Substantial cuts are achievable with limited cold ironing - defer capital-heavy grid and BESS expansion and preserve investment flexibility.



Coordinate the operators

Central, energy-aware scheduling plus flexible freight tickets remove redundant crossings and overlapping demand peaks.



Corridor-wide benefit

Fixing the berthing schedule at the constrained port automatically smooths hybrid-ferry arrivals at the partner port.



Operational levers

Energy constraints should shape both strategic and operational decisions and must therefore be embedded in operational optimisation.

Smart scheduling is a low-cost lever for ferry decarbonisation



What we show

- Scheduling and berth allocation must be optimised jointly for ferries - they are structurally inseparable.
- Up to 70% lower berthing CO₂, and 12–40% versus BAU even with no hybrids, with little or no new infrastructure.
- A phased diesel → hybrid transition is feasible with only modest, well-timed top-ups.
- Decision support for ports, operators and policymakers across the whole corridor.



Where next

-  Full electrification requires shore power for main propulsion during crossings, beyond at-berth hotelling demand
-  Operator alliances and coordinated service planning
-  Diesel-fallback modelling for capacity shortfalls and outages
-  Scalable methods: rolling-horizon, decomposition, tailored heuristics
-  Landside traffic interactions at busy terminals



Thank you · Questions welcome

Energy-aware scheduling and berth allocation for ferries under phased cold ironing upgrades



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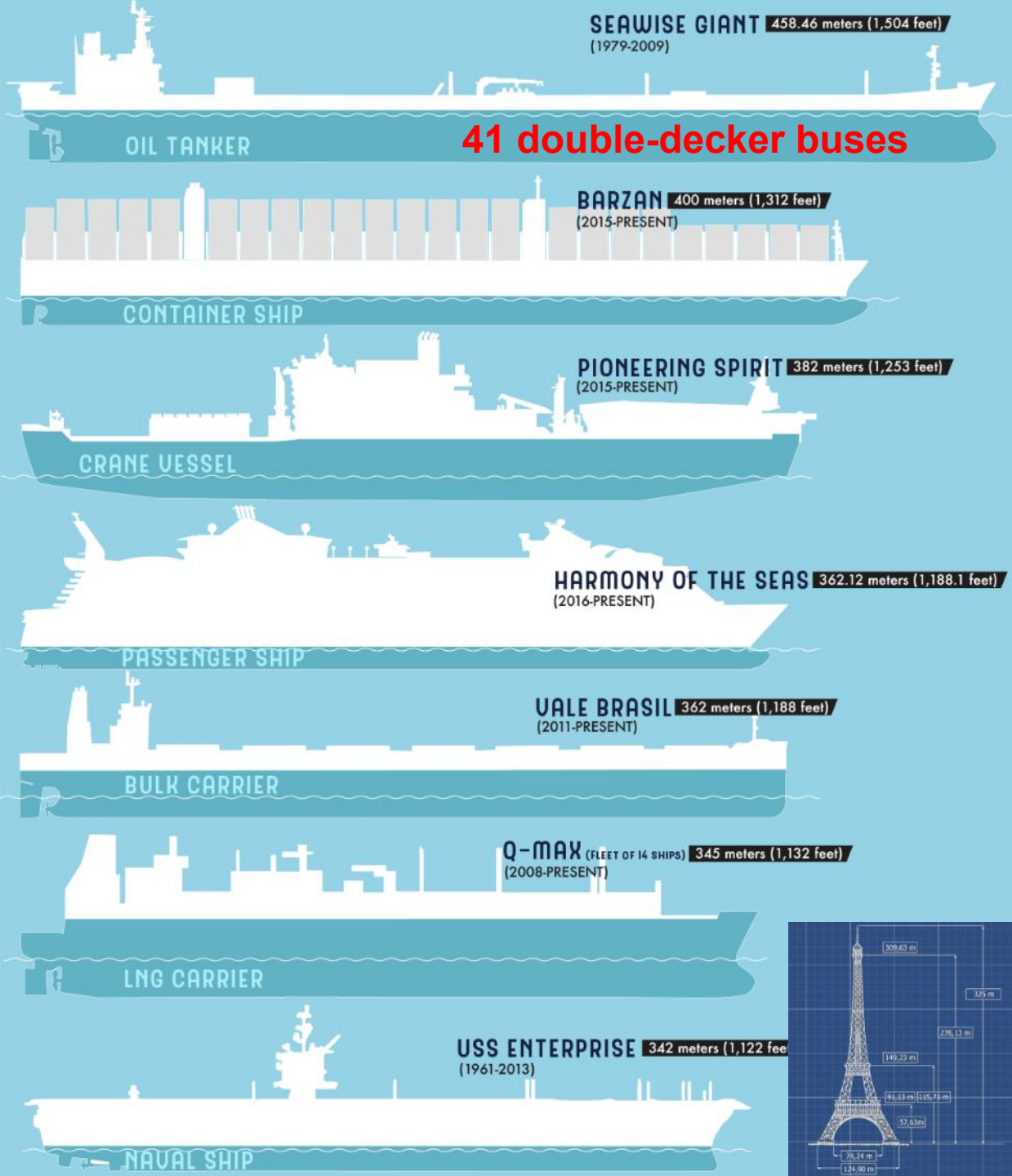


BIRMINGHAM CITY
University

Wind-Assisted Ship Propulsion

Clean Maritime Assembly 2026





“Hull length”

24 m

“96% of the waterline length
at 85% of the moulded depth”

TEU = Twenty-foot Equivalent Unit



Evergreen = 1250 x 747

Maritime Decarbonisation

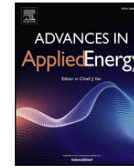
Advances in Applied Energy 20 (2025) 100255



Contents lists available at ScienceDirect

Advances in Applied Energy

journal homepage: www.elsevier.com/locate/adapen



A systematic review of technologies, measures, and CO₂ emission reduction potential for maritime transport decarbonisation

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ARTICLE INFO

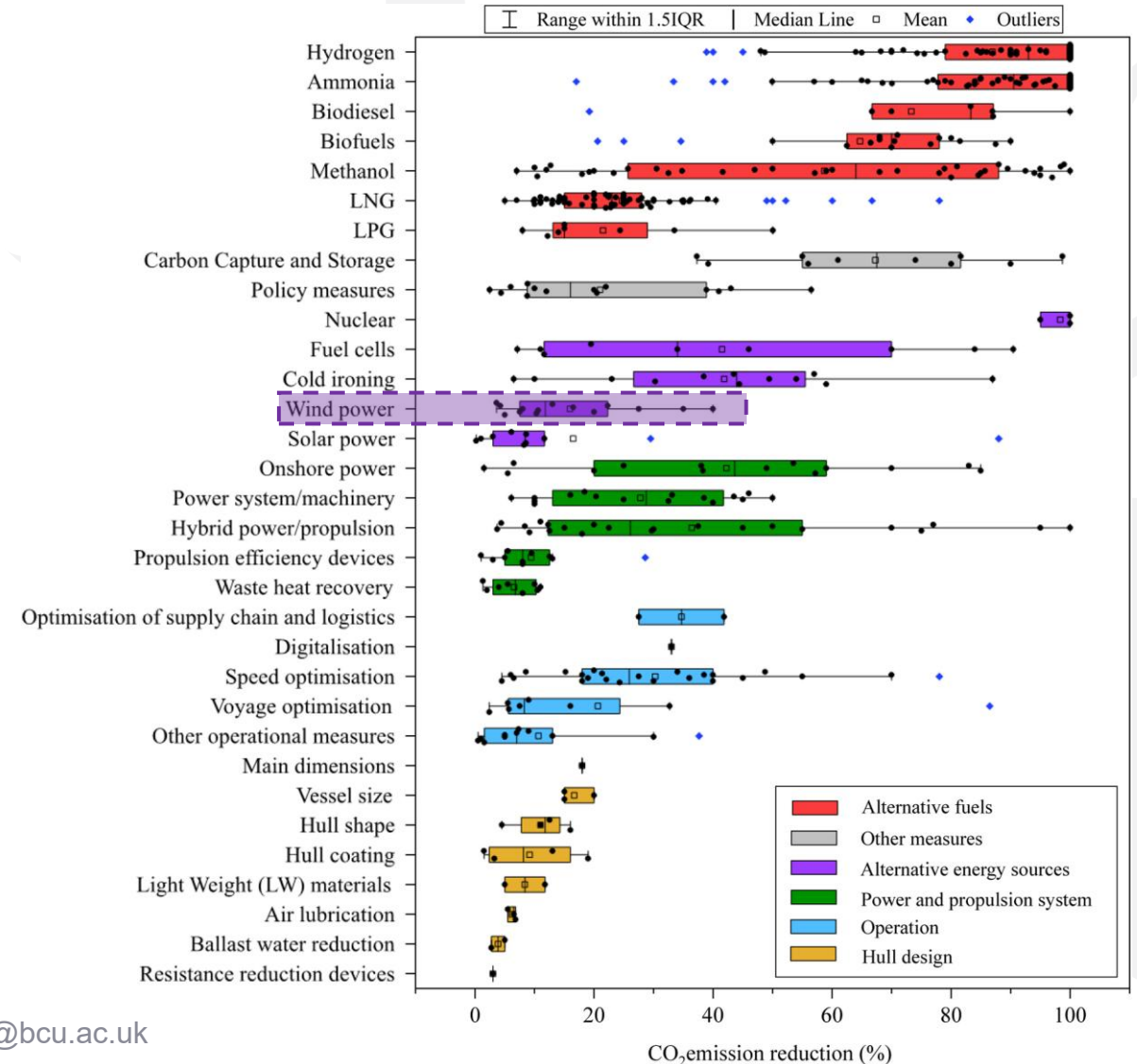


ABSTRACT

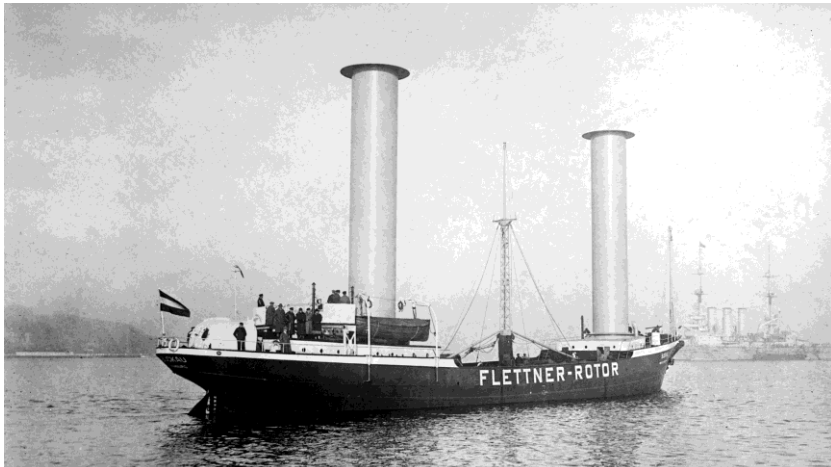
The maritime shipping sector is a significant contributor to global carbon dioxide (CO₂) emissions, accounting for approximately 2.7%-3% of global emissions. In response, the International Maritime Organization (IMO) has set ambitious targets: a 30% reduction in emissions by 2030, 80% by 2040, and net-zero by 2050, relative to 2008 levels. Meeting these goals requires a comprehensive understanding of the full range of viable decarbonisation measures. Therefore, this study conducts a systematic review of maritime decarbonisation measures, applying the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. Unlike previous studies, this paper not only provides an updated overview of CO₂ reduction measures but also maps them to specific vessel types based on data reported in the literature. Furthermore, the findings are compared with literature to highlight shifts in mitigation potential. A case study is also included to schematically demonstrate how these measures can be applied in practice. Following a rigorous analysis: (i) thirty-two individual CO₂ mitigation measures were identified and classified into six categories, (ii) alternative fuels shown the highest long-term potential (5–100 % CO₂ emission reduction), whereas hull design improvements show the lowest (1–20 %), (iii) the wide disparity in reported abatement values is attributed to inconsistent system boundaries, variability in fuel origin, partial-blend scenarios, and differing assumptions across studies, (iv) combinations of measures provide the most practical and realistic pathway to phased emissions reduction. These findings are expected to assist decision-makers in selecting effective, context-appropriate strategies to support global maritime decarbonisation and ensure long-term sectoral sustainability.

<https://doi.org/10.1016/j.adapen.2025.100255>

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Wind-Assisted Ship Propulsion



Journal of Sailing Technology 2025, volume 10, issue 1, pp. 258 - 278.
The Society of Naval Architects and Marine Engineers.

State of the Art in Wind Assisted Ship Propulsion for Maritime Decarbonisation and Sustainable Shipping: A Systematic Review

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Manuscript received May 8, 2025; revision received August 11, 2025; accepted August 21, 2025.



Abstract. The advent of modern wind propulsion systems (WPS) to answer contemporary and forthcoming regulatory requirements to reduce shipping emissions has prompted the development of multiple technologies, ranging from sails to rotating cylinders, to kites. However, as the benefits of WPS for wind-assisted ships are still based on predictions due to the lack of operational, on-water data, the most promising technologies and areas of future research remain unclear. Moreover, the lack of consistent research methodologies and test conditions has led to large reported divergences in the potential of WPS in the literature. Consequently, to ascertain the comparative potential of WPS to reduce shipping emissions and present the state of the art in wind propulsion for ships, a systematic review is undertaken, with the aim to quantify the carbon dioxide (CO₂) emission reductions associated with each type of WPS. The systematic literature review methodology ensures unbiased results, while accurately reporting the latest research developments in the field. Here we quantify the benefits of WPS, with an average 17% reduction in CO₂ emissions, with an interquartile range from 7.5% to 22.5%. Moreover, we identify Flettner rotors as both the most studied and most commonly installed WPS, and note a discrepancy for suction wings, with a large share of installed WPS, but only very little published research. Additionally, we critically appraise current practices in the analysis of WPS, ranging from true wind and ship speed to the vessel type and size. These findings provide a novel and holistic overview of wind propulsion of ships, as well as the first systematic review on the topic, allowing an unbiased assessment of wind propulsion for ships. It is anticipated that these results may inform future research directions in sustainable shipping, and inform policymakers on the benefits of wind propulsion to meet emission regulations. Moreover, recommendations for more consistent reporting of WPS studies have been provided to support future global research and enable quantitative comparison across all published work.

Keywords: wind propulsion for ships; clean maritime; shipping; decarbonisation; aerodynamics.

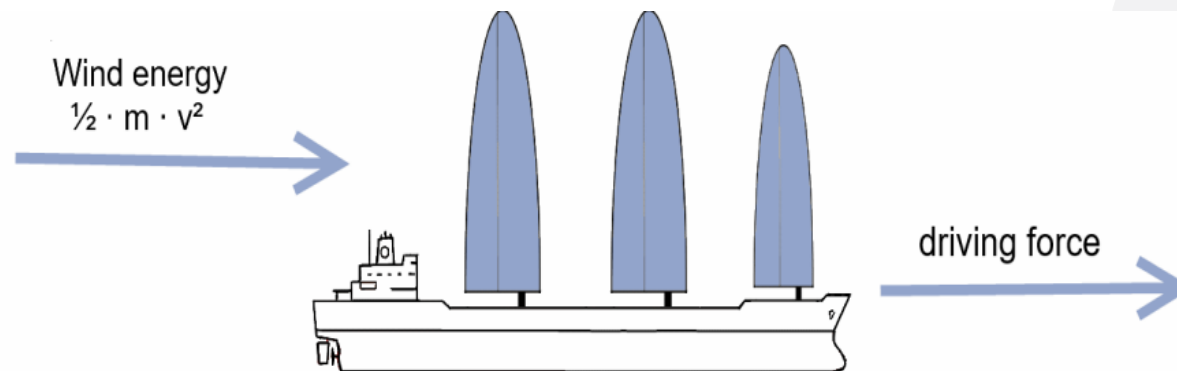
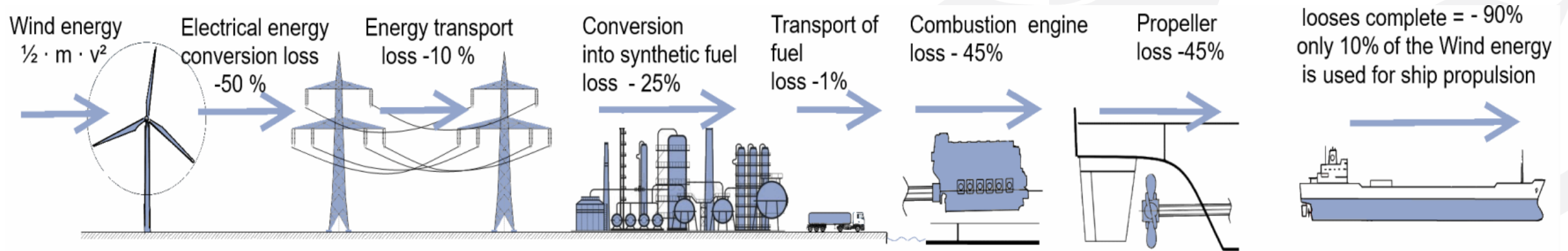
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<https://doi.org/10.5957/jst/2025.10.1.258>

Why wind?



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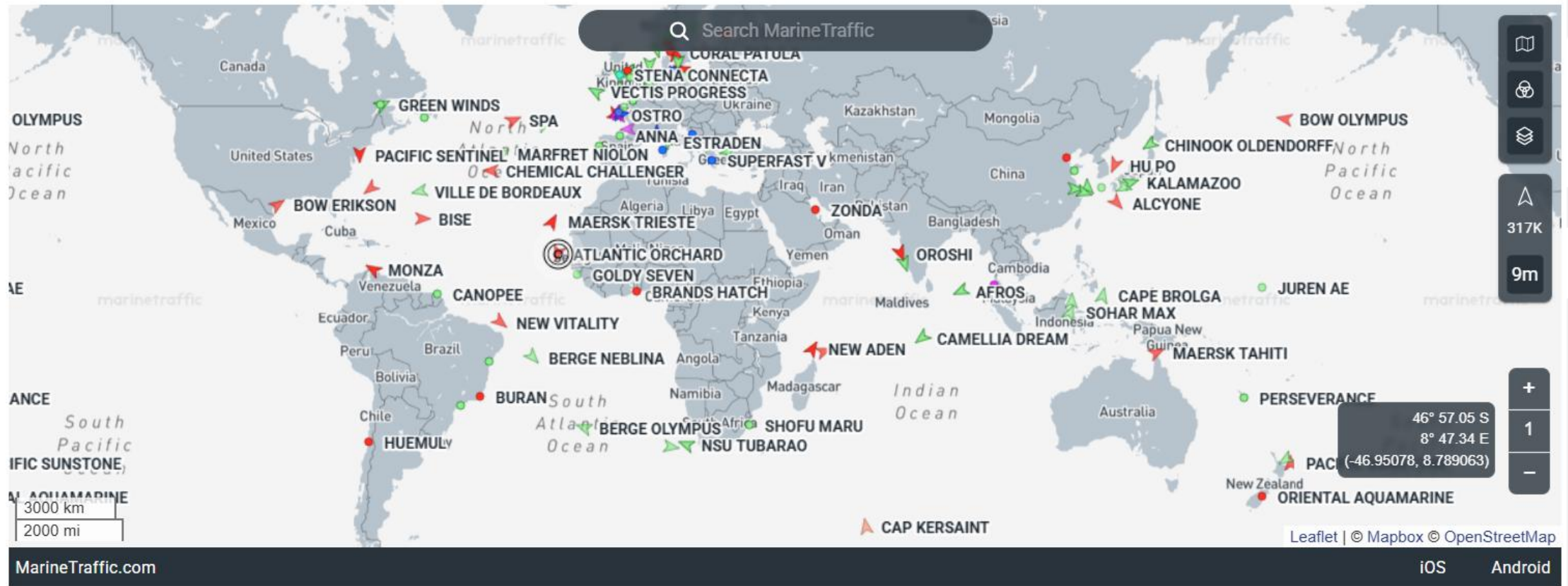


advantages of a sailing ship:

- uses high wind potential on the open sea
- No losses due to energy conversion
- No losses due to energy transport
- No land-based infrastructure necessary
- One sailing ship replaces 10 land based wind power plants
- No fuel costs for the shipping company (wind is for free)
- less dependency of shipowners on fuel producers

Herbert Blümel ,2019

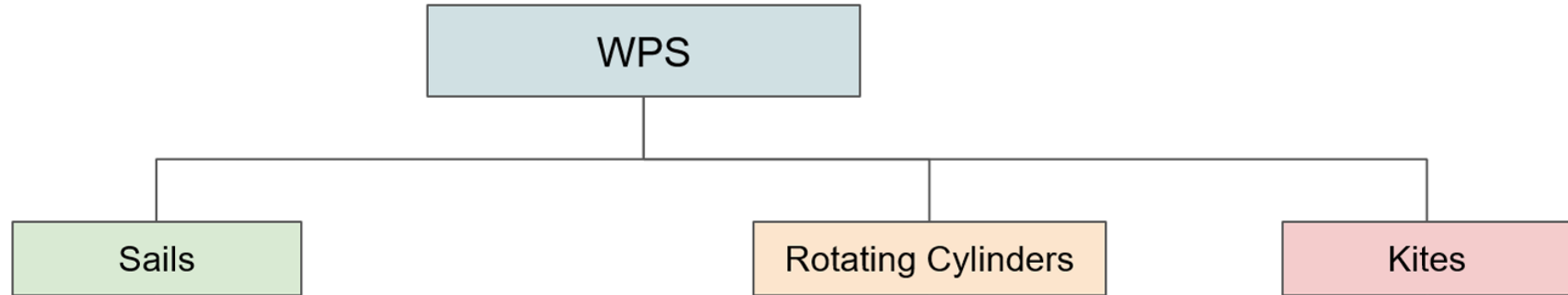
Wind-Assisted Ships at Sea



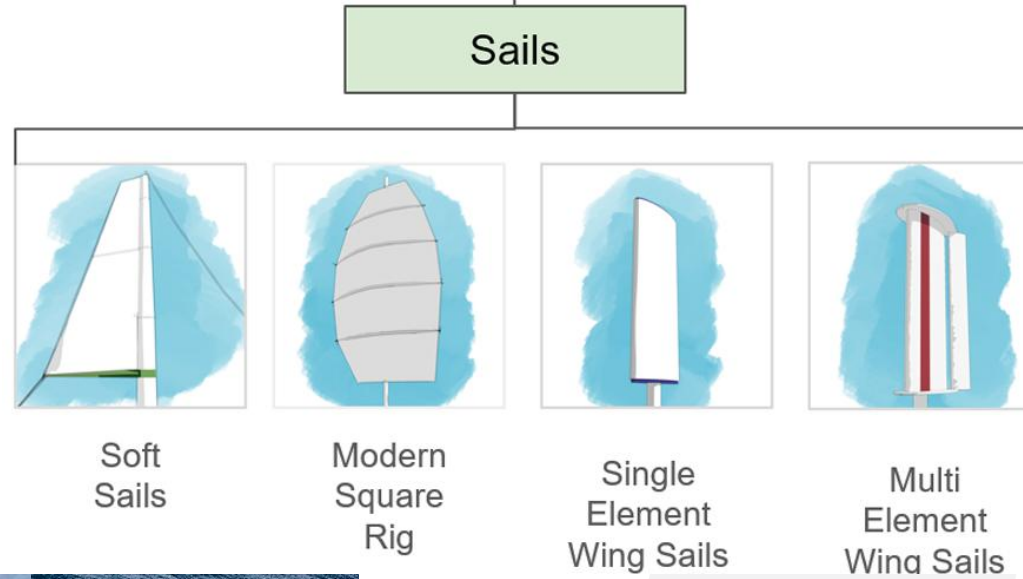
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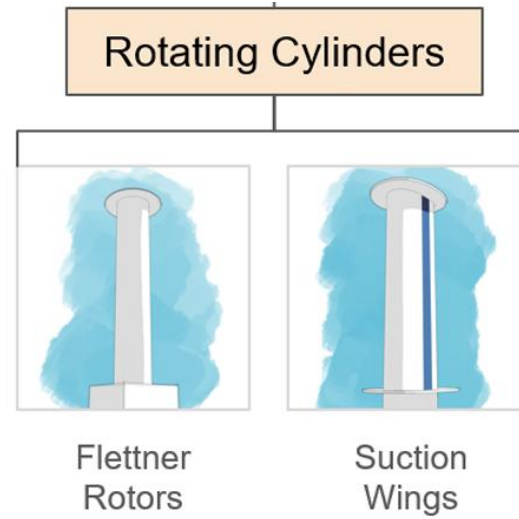
Wind Propulsion Systems (WPS)



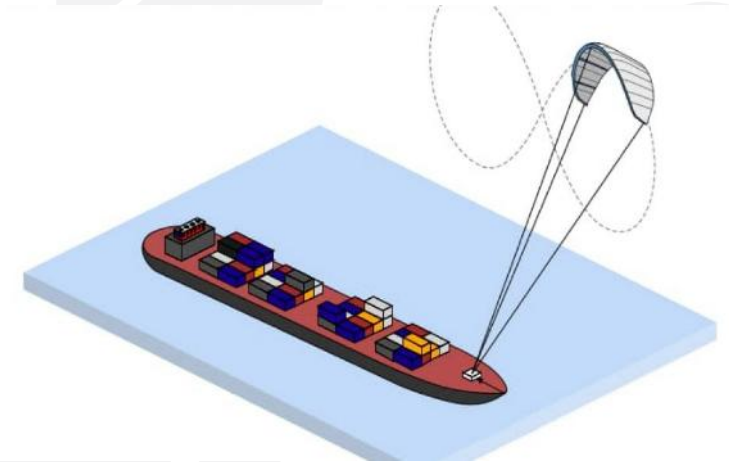
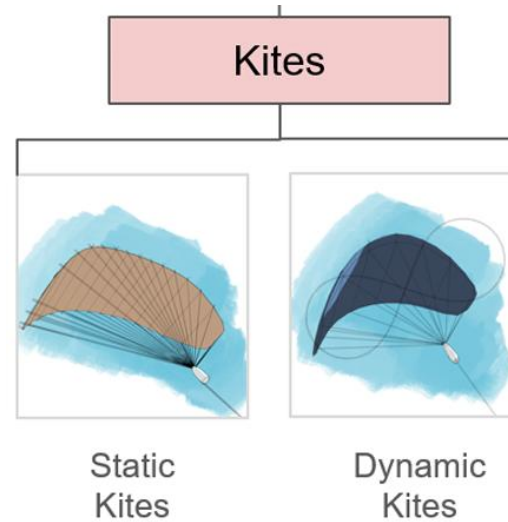
Wind Propulsion Systems (WPS)



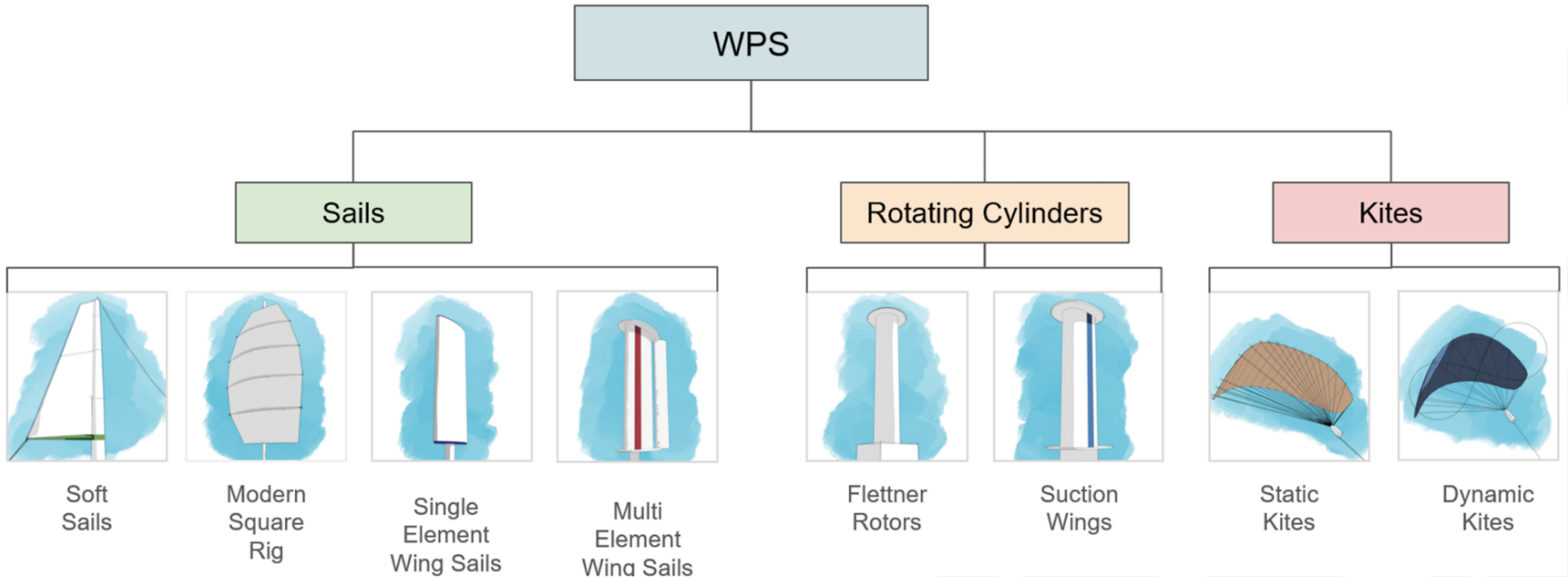
Wind Propulsion Systems (WPS)



Wind Propulsion Systems (WPS)



Wind Propulsion Systems (WPS)



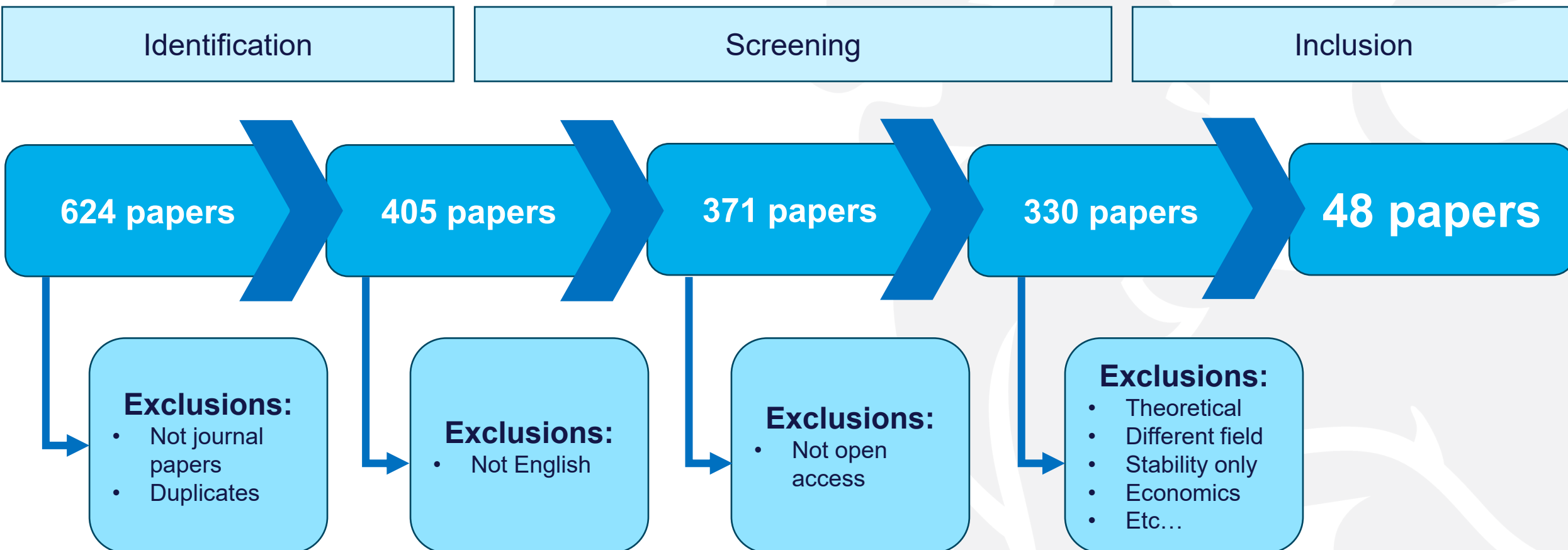
Low power requirements and simpler than rotating cylinders
BUT
Generates less thrust

Higher lift and good wind angles
BUT
Expensive and power requirement

Higher altitude = more wind
BUT
Limited wind angles

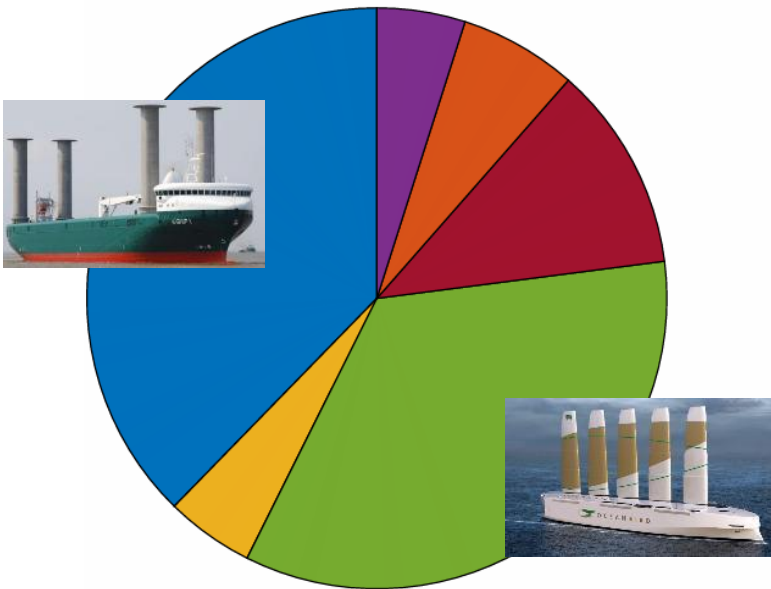
Systematic Literature Review

(wind OR sail) AND assisted AND (ship OR propulsion OR vessel)*

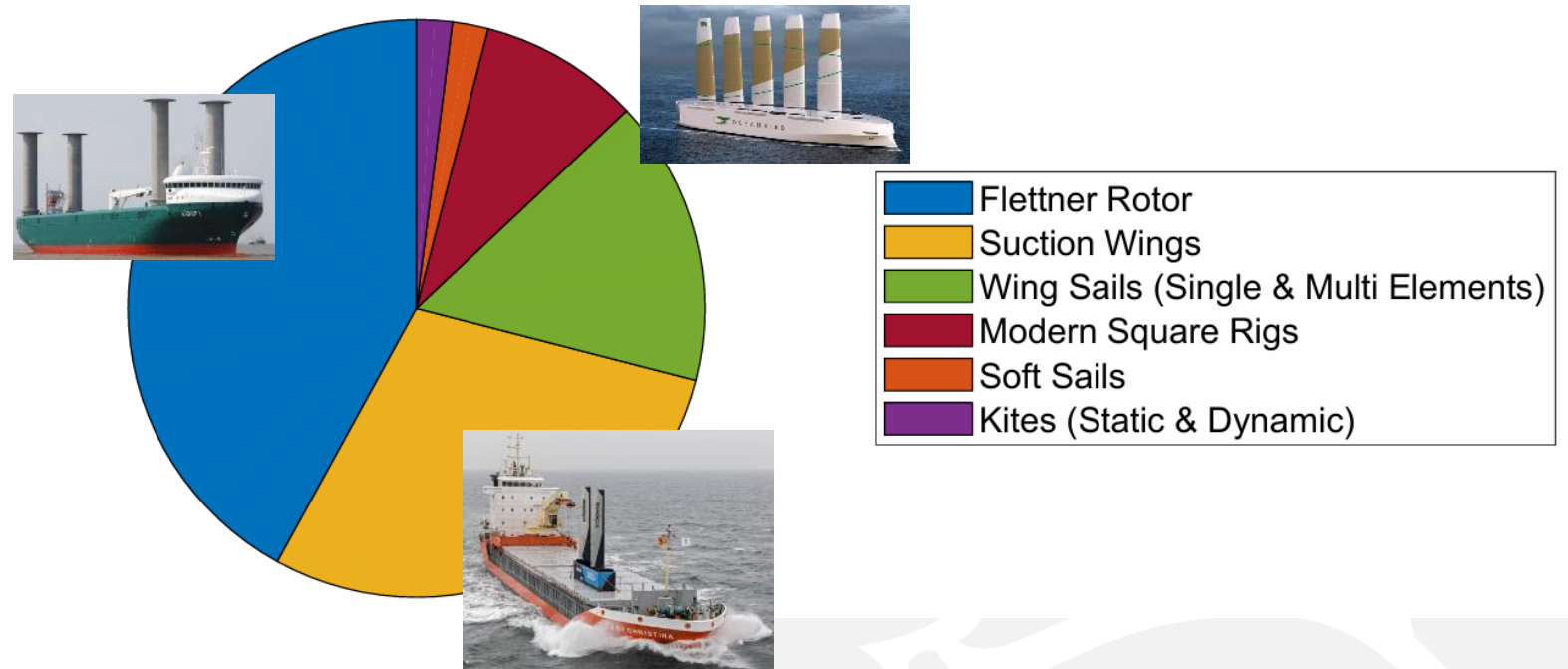


Results: WPS

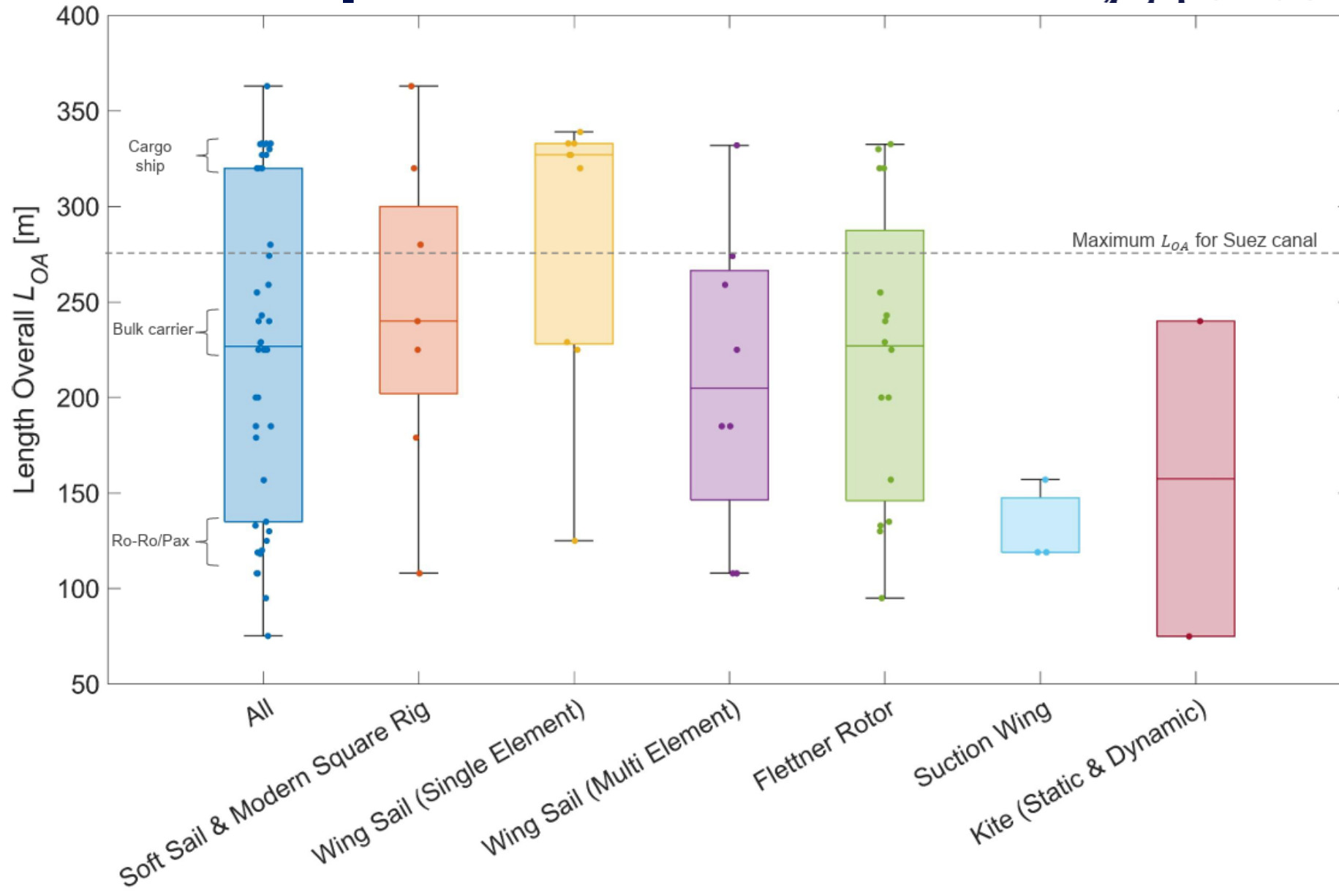
(a) WPS in the literature



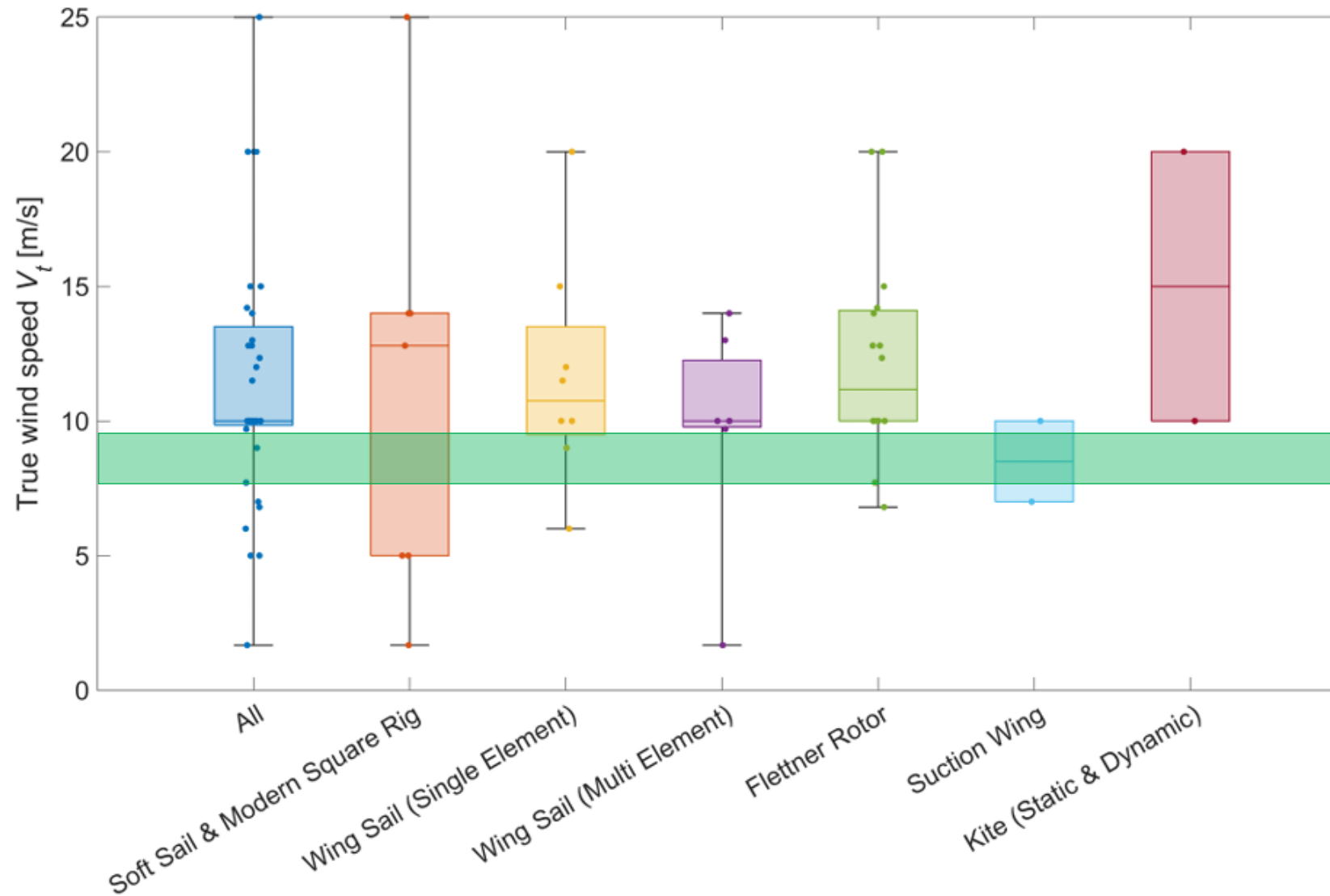
(b) WPS on ships



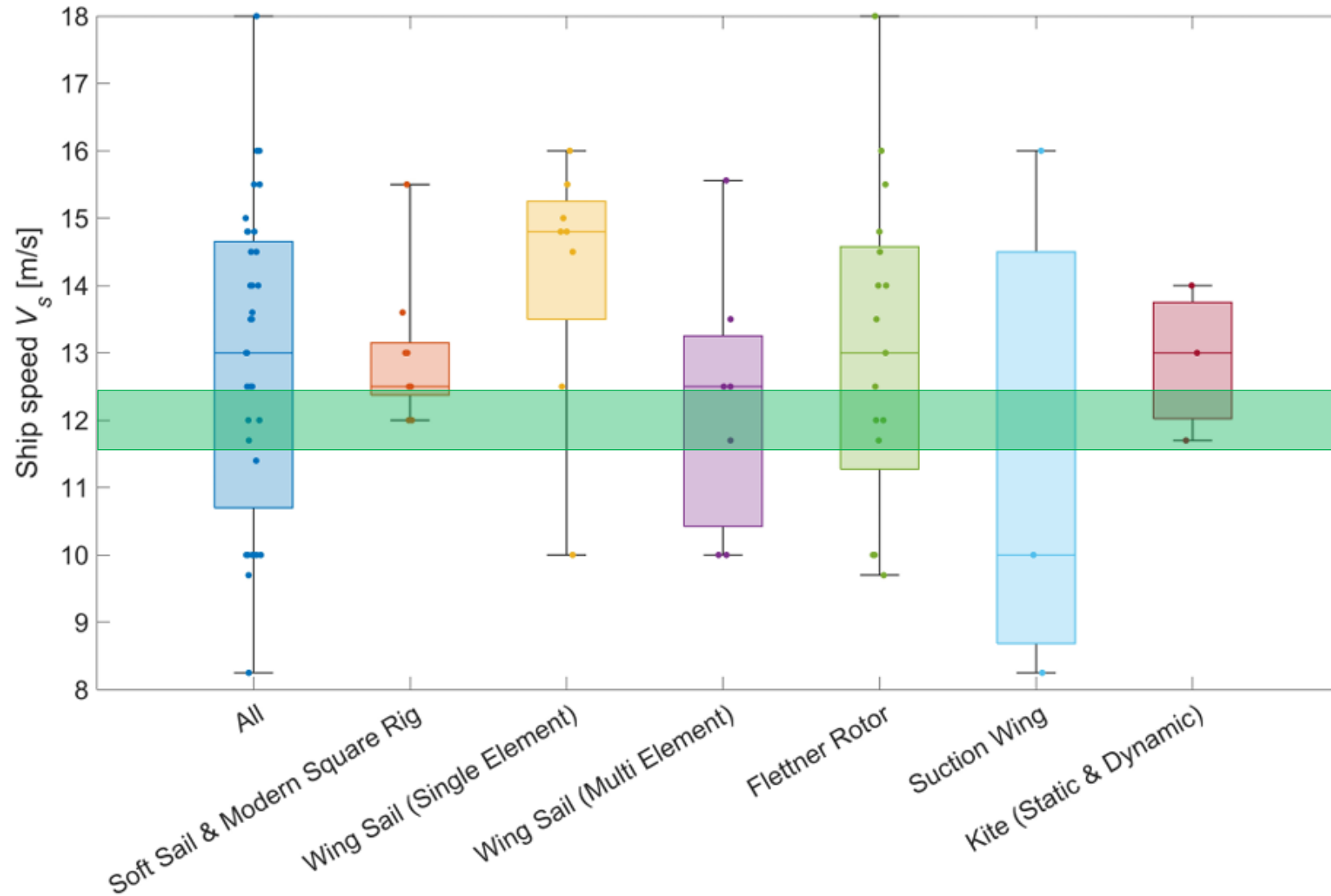
Results: Ship Size



Results: Wind Speed



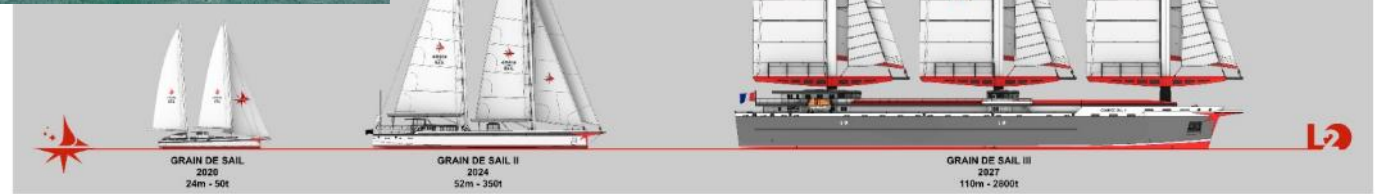
Results: Ship Speed



Results: CO₂ Reduction

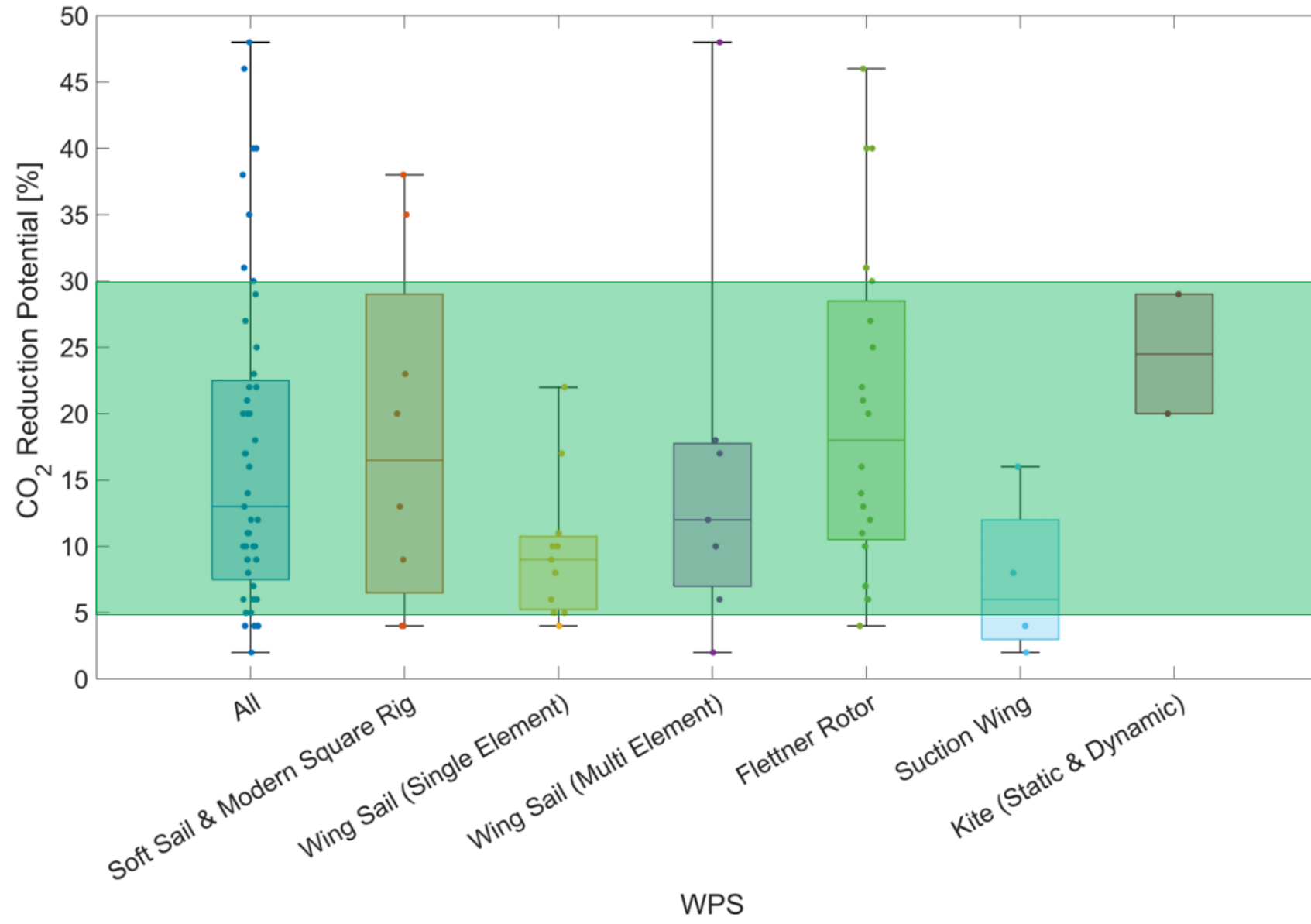
What does the industry rule of thumb say?

- Retrofitting with no change to operations: 5%-20%
- Retrofitting with wind optimisation (e.g. routing): 25%-30%
- New build designed for wind propulsion: 50%+



What does the *literature* say?

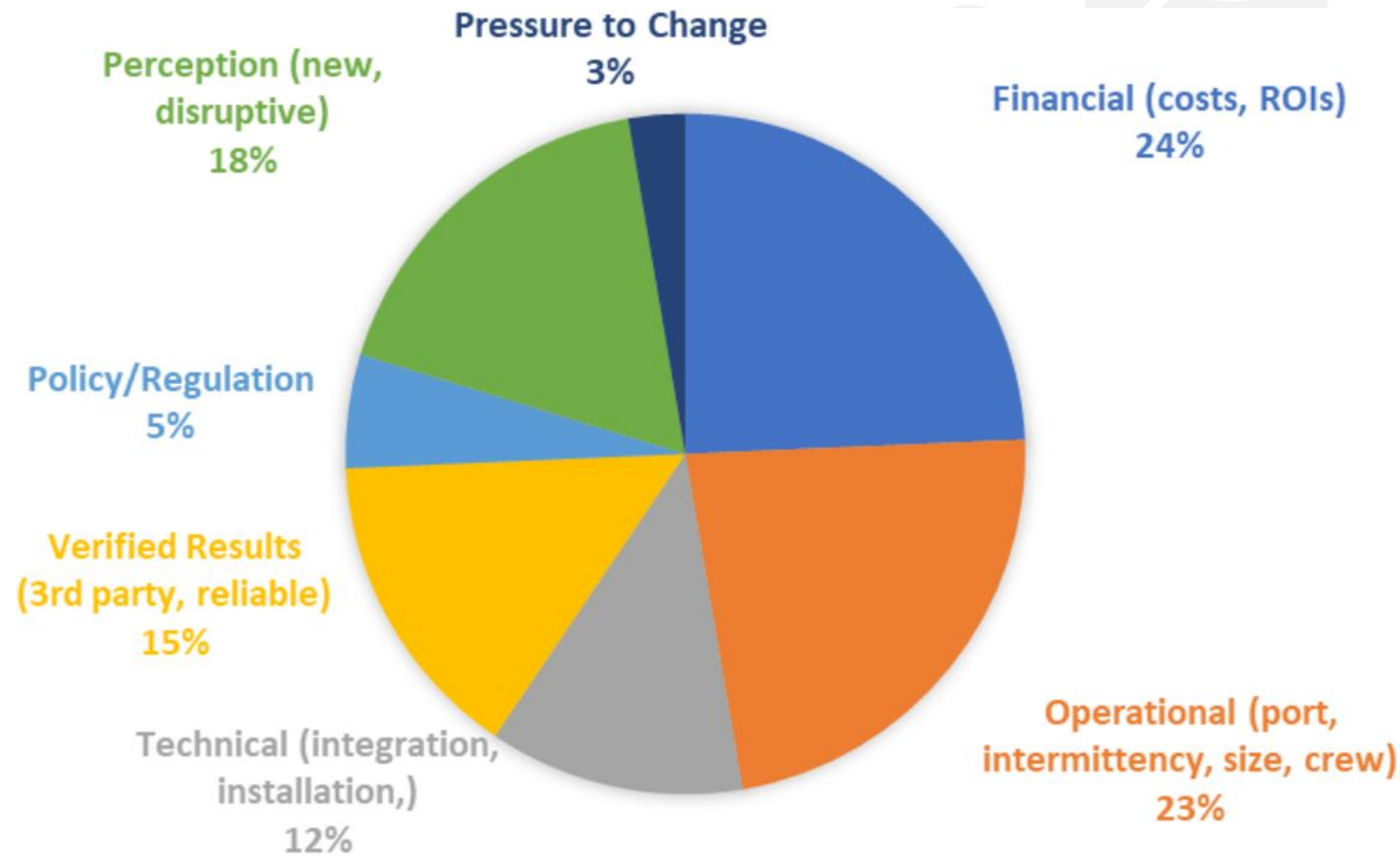
Results: CO₂ Reduction



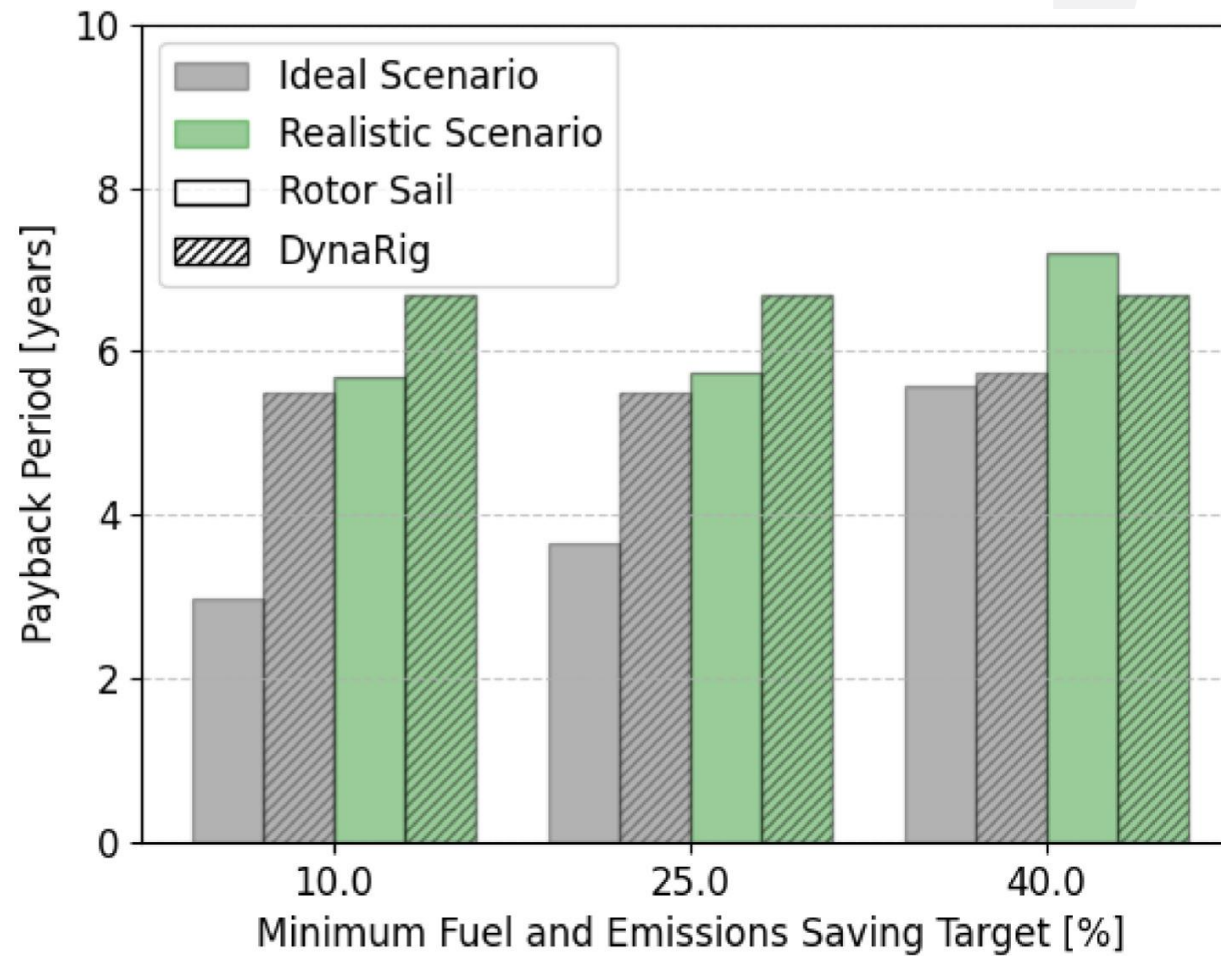
Barriers to Uptake (IWSA, 2023)



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ROI (Reche Vilanova, 2025)



Conclusions

- Historically proven technology
- Multiple Wind Propulsion Systems available
- 5-30% reduction in CO₂ emissions for retrofits
- Up to 100% reduction in CO₂ emissions for new builds
- ~ 6-8 years ROI
- Continued growth forecast
- Pushback against fuel-centric regulations



<https://doi.org/10.5957/jst/2025.10.1.258>

A wide-angle shot of a modern lecture hall. The room features a complex, geometric ceiling with white and grey panels. The seating consists of blue upholstered benches arranged in a semi-circle, each with a wooden desk in front of it. Each desk has a small laptop on it. The floor is dark grey with white circular markers. The walls are white with vertical slats. Two large white screens are visible on the left and right sides of the room.

Thank you



Prof. Jean-Baptiste R. G. Soupez

Professor of Mechanical Engineering and STEAM Education
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Clean Maritime
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Thank You

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