Imperial College London

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System-level comparison of ammonia, compressed and liquid hydrogen as fuels for polymer electrolyte fuel cell powered shipping

H2FC Supergen Research Conference

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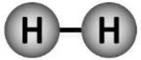
Background

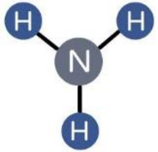
- The NO_x, SO_x and CO_2 emissions from the marine traffic contributed to around 15%, 13% and 2.5% of global emissions; CO_2 emissions from the marine sector are expected to grow up to 250% by 2050 if no measure is taken
- Using alternative fuel could reduce emissions

Hydrogen:



- Carbon-free
- High mass energy density
- Directly used in PEMFCs
- Low volumetric energy density: store as compressed gas at 350 bar or 700 bar at 293.15 K or as liquid at 20.28 K under atmospheric pressure

Ammonia:



- Carbon-free hydrogen carrier
- Mature supply chain
- Higher volumetric energy density than hydrogen: could store as liquid at 298.15 K and 10 bar

PEMFC: polymer electrolyte membrane fuel cell

Nature Communications, vol. 9, no. 1, Art. no. 1, Feb. 2018, doi: 10.1038/s41467-017-02774-9

Methodology

Design gaseous hydrogen (GH_2), liquid hydrogen (LH_2), liquid ammonia (LNH_3) marine propulsion systems powered by PEMFCs

Develop scalable **thermodynamic models** based on mass, energy and exergy balances for the designed GH_2 system, LH_2 system and LNH_3 system

Applied the thermodynamic models on the two case studies:

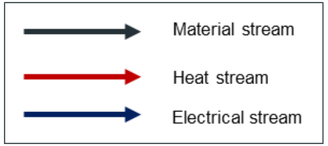
12-passenger water taxi

2600TEU container ship

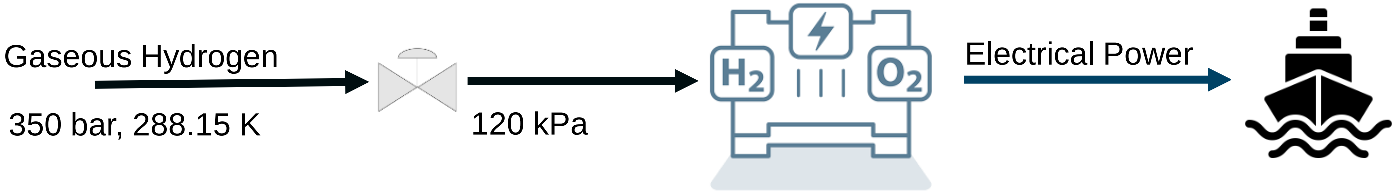
Based on the modelling results, **assess and compare** the performance of the **systems** with respect to the following **performance** indicators: system energy and exergy efficiency, fuel consumption, mass and volume occupation, environmental impacts, and the costs

International Journal of Hydrogen Energy, *47*(13), 8565-8584. doi: 10.1016/j. ijhydene.2021.12.164

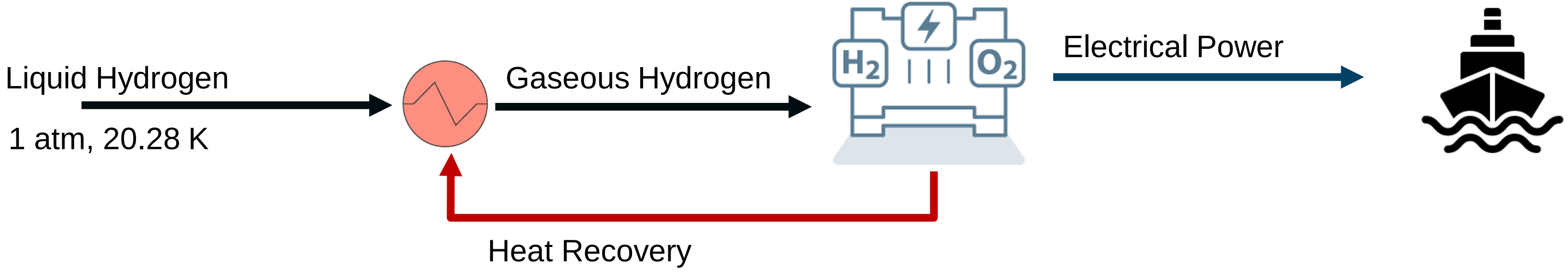
System Design



Gaseous Hydrogen Propulsion System (GH_2 PEMFC system)

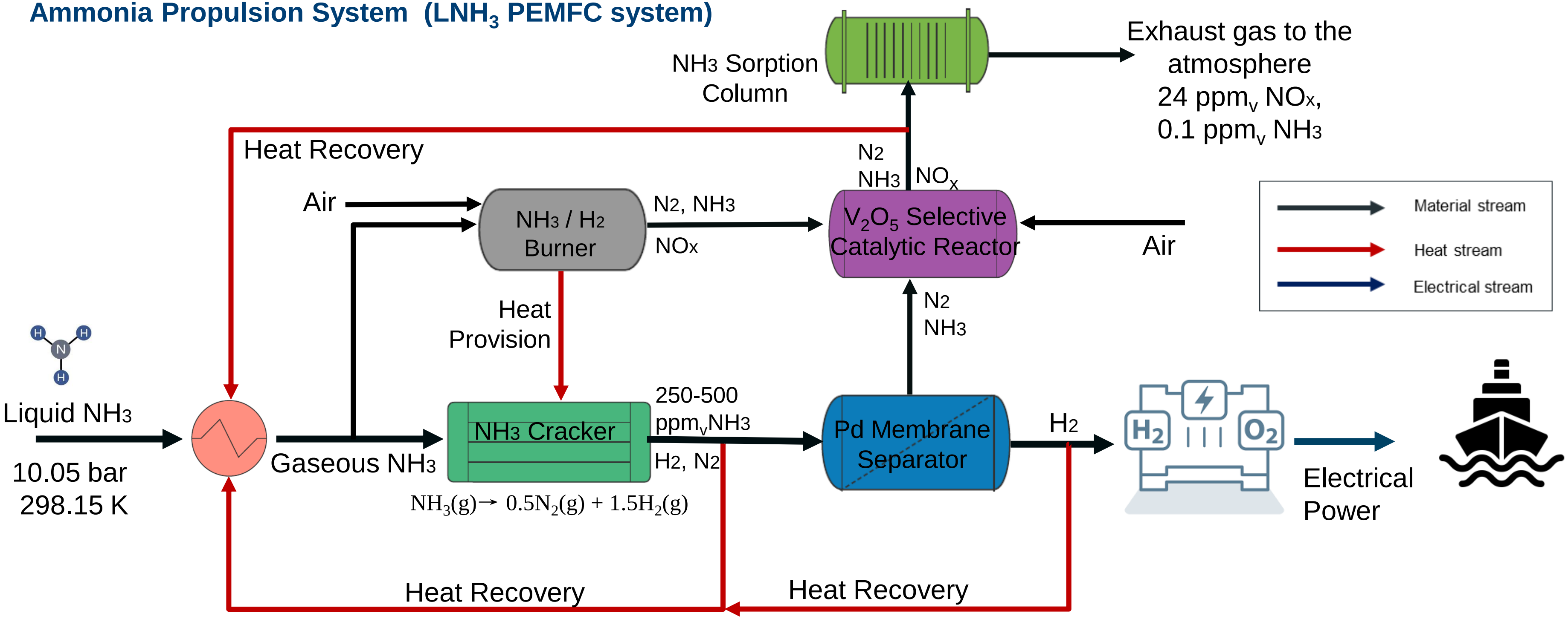


Liquid Hydrogen Propulsion System (LH_2 PEMFC system)



System Design

Ammonia Propulsion System (LNH_3 PEMFC system)



Methodology

Design gaseous hydrogen (GH_2), liquid hydrogen (LH_2), liquid ammonia (LNH_3) marine propulsion systems powered by PEMFCs

→

Develop scalable **thermodynamic models** based on mass, energy and exergy balances for the designed GH_2 system, LH_2 system and LNH_3 system

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Applied the thermodynamic models on the two case studies:

12-passenger water taxi

2600TEU container ship

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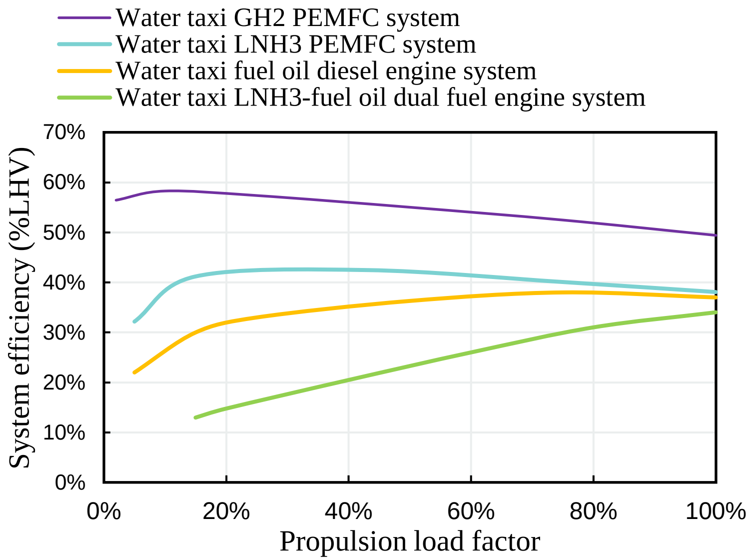
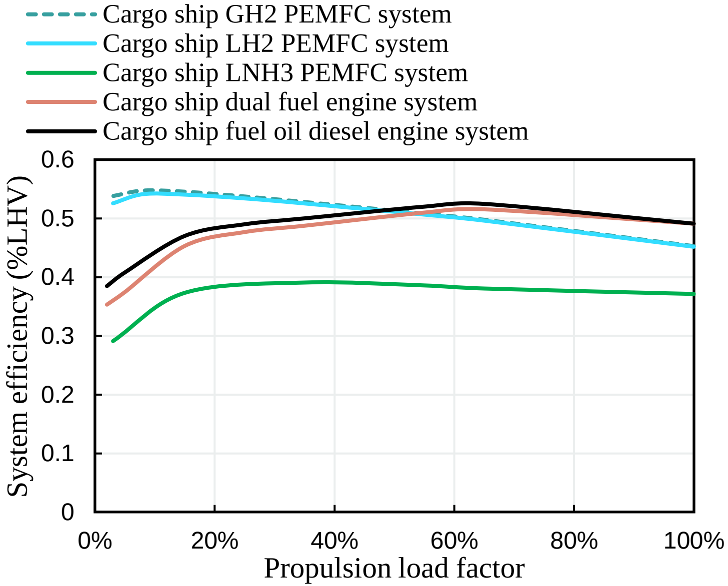
Results – Energy efficiency analysis

Water Taxi Case Study



Cargo Ship Case Study



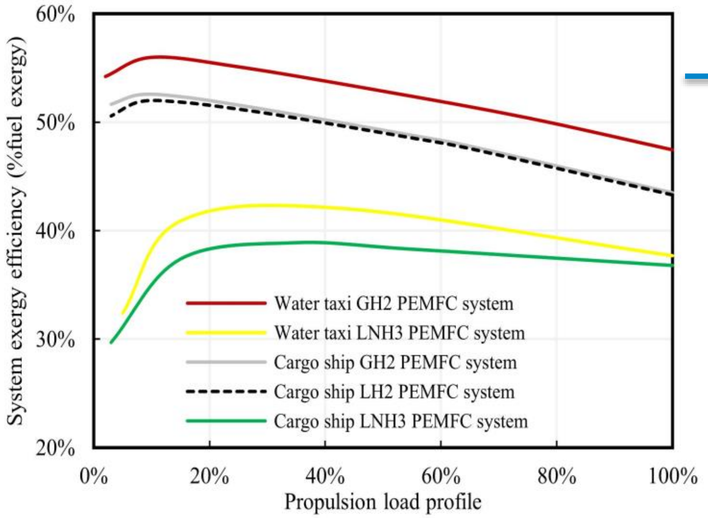
$$\eta_{en,system} = \frac{Power_{propulsion\ shaft} + Power_{maneuvering} + Power_{hotel}}{\dot{m}_{fuel} \cdot \mathrm{LHV_{fuel}}}$$

Load factor: the actual propulsion power output relative to the maximum rating; Dual fuel engine: LNH_3-fuel oil engine;
LHV: Low Heating Value

Applied Sciences, vol. 2, no. 4, Art. no. 4, Dec. 2012, doi: 10.3390/app2040726.

Results – Exergy analysis

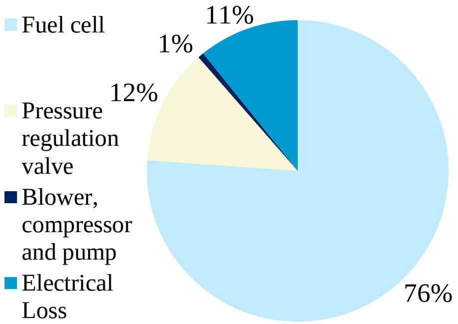
Exergy efficiency



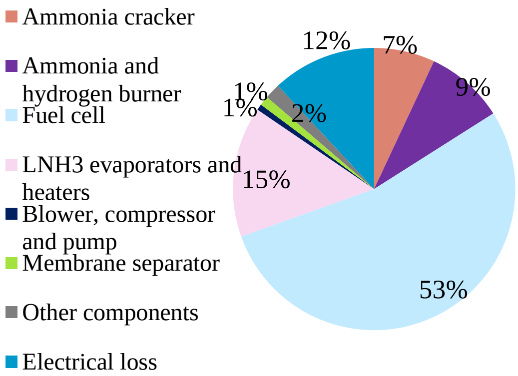
Exergy destruction rate distribution (Cargo ship)

The exergy efficiencies and the system energy utilization could be improved by reducing exergy destruction rates

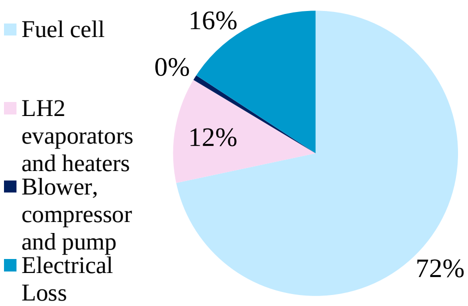
GH_2 PEMFC system



LNH_3 PEMFC system

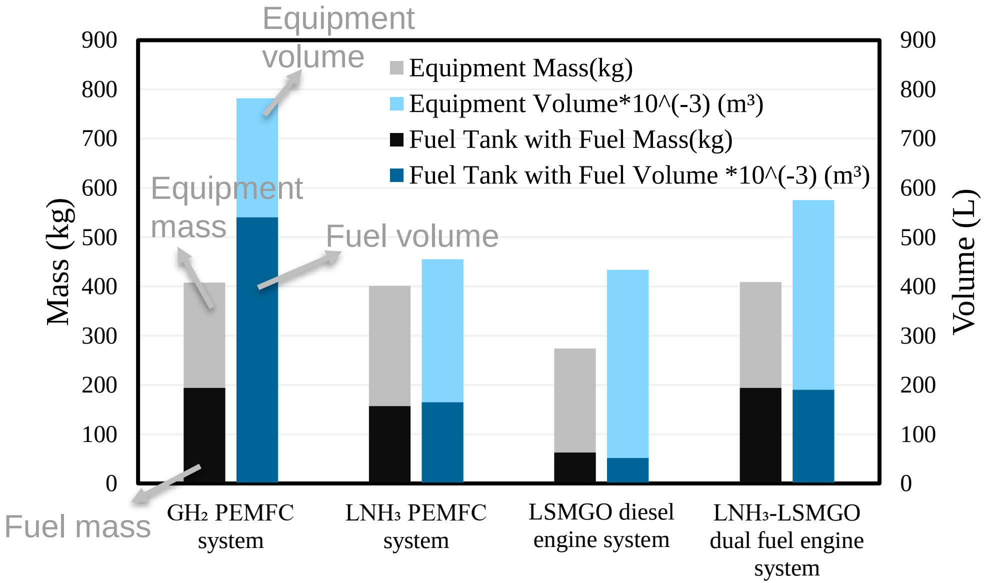


LH_2 PEMFC system



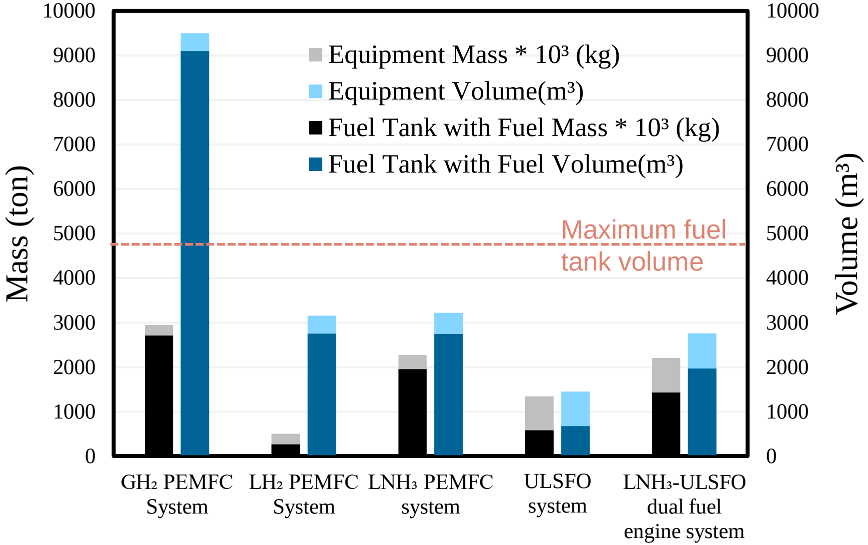
Results – Volume and mass analysis

Water Taxi Case Study



- Both GH_2 and LNH_3 PEMFC systems could meet the mass and volume constraint of the water taxi , but LNH_3 PEMFC system is preferable in term of volume.

Cargo Ship Case Study



- The fuel tank volume limit for the 2600TEU cargo ship is around 4700 m^3, therefore, only LH_2 (liquid hydrogen) and LNH_3 systems can be applied for the cargo ship in term of volume and mass.

LSMGO: low-sulfur marine gasoil (0.1 mass % S); ULSFO: ultra-low sulfur fuel oil (0.1 mass % S)

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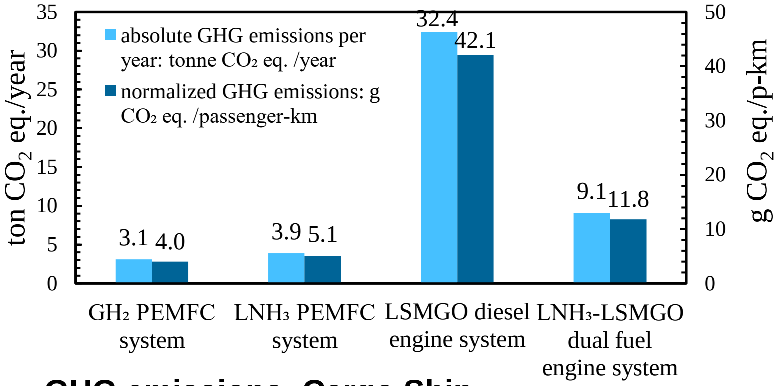
Results – Environmental analysis

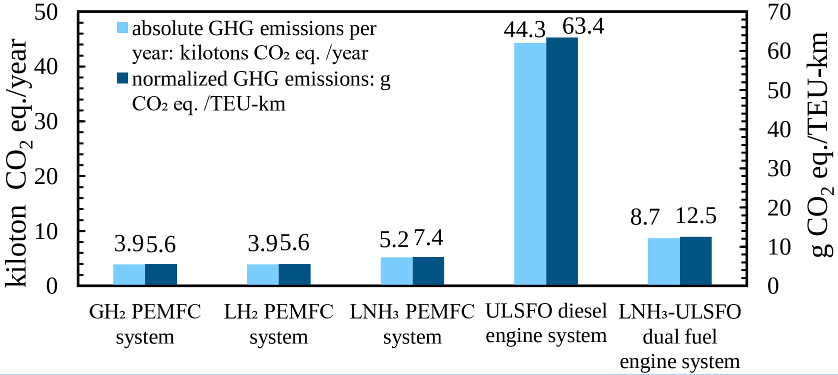
	Emissions during operation	Lifecycle greenhouse gas (GHG) emissions
GH_2/LH_2 PEMFC system	Zero emission	91% GHG reduction compared with the fuel oil system
LNH_3 PEMFC system	Zero PM, SO_x, CO_2 emission; 95-98 % NO_x reduction compared with the fuel oil system	88% GHG reduction compared with the fuel oil system

Note: The hydrogen and ammonia are assumed to be produced from the electrolysis with the renewable energy

GHG emissions- Water Taxi



GHG emissions- Cargo Ship



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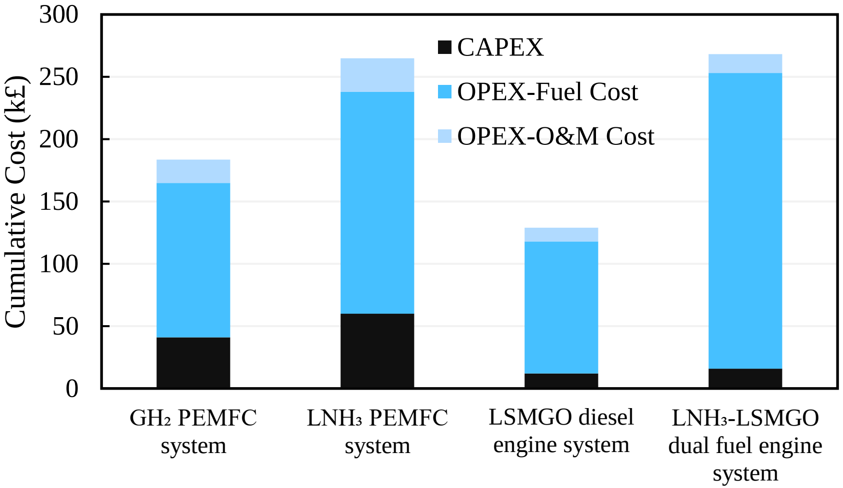
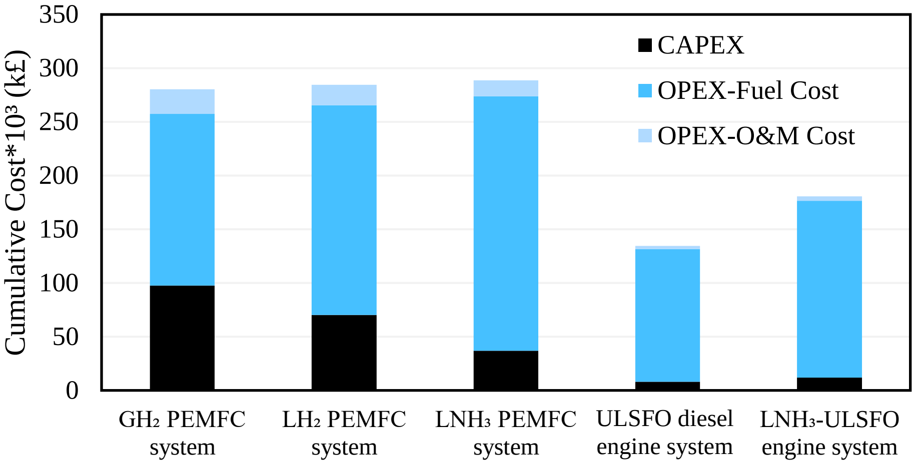
Results – Economic Analysis

Water Taxi Case Study



Cargo Ship Case Study



- The GH_2 , LH_2, LNH_3 PEMFC systems are 43% -116% more expensive than the conventional fuel oil engine system
- A carbon tax of 75-191 £/tonne would need for the low carbon options to become cost competitive with the high carbon fuel oil engine system

Current carbon price in UK: 50 £/tonne

Note: Cumulative costs for hydrogen and ammonia systems are analyzed with lifetime of 25 years and discount rate of 5%
LSMGO: low-sulfur marine gasoil (0.1 mass % S); ULSFO: ultra-low sulfur fuel oil (0.1 mass % S)

Conclusions

- The system LHV energy efficiency of the GH_2 PEMFC system is 45% - 58 %, which is around 18%-46% more energy-efficient than the LNH_3 PEMFC system depending on the ship scale and the load factor.
- Improving the stack exergy efficiency would lead to a significant improvement in the system energy utilization.
- All three hydrogen sources fit within the volume and mass constraints of the water taxi, but only the LH_2 and LNH_3 solutions could meet the constraints of the cargo ship.
- Compared to conventional fuel oil system, the proposed GH_2, LH_2 and LNH_3 systems could deliver 91%, 91% and 88% greenhouse gas (GHG) reductions, respectively.
- Further carbon policy measures and cost reduction in green fuels and fuel cells are required to bring the designed PEMFC systems down by 31%-54% to make them cost competitive to the fuel oil engine system.

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