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UNIVERSITY OF CAMBRIDGE Department of Engineering

From Emissions to Solutions

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Input from:

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Many post-docs (see posters)

Acknowledgements to many industry partners

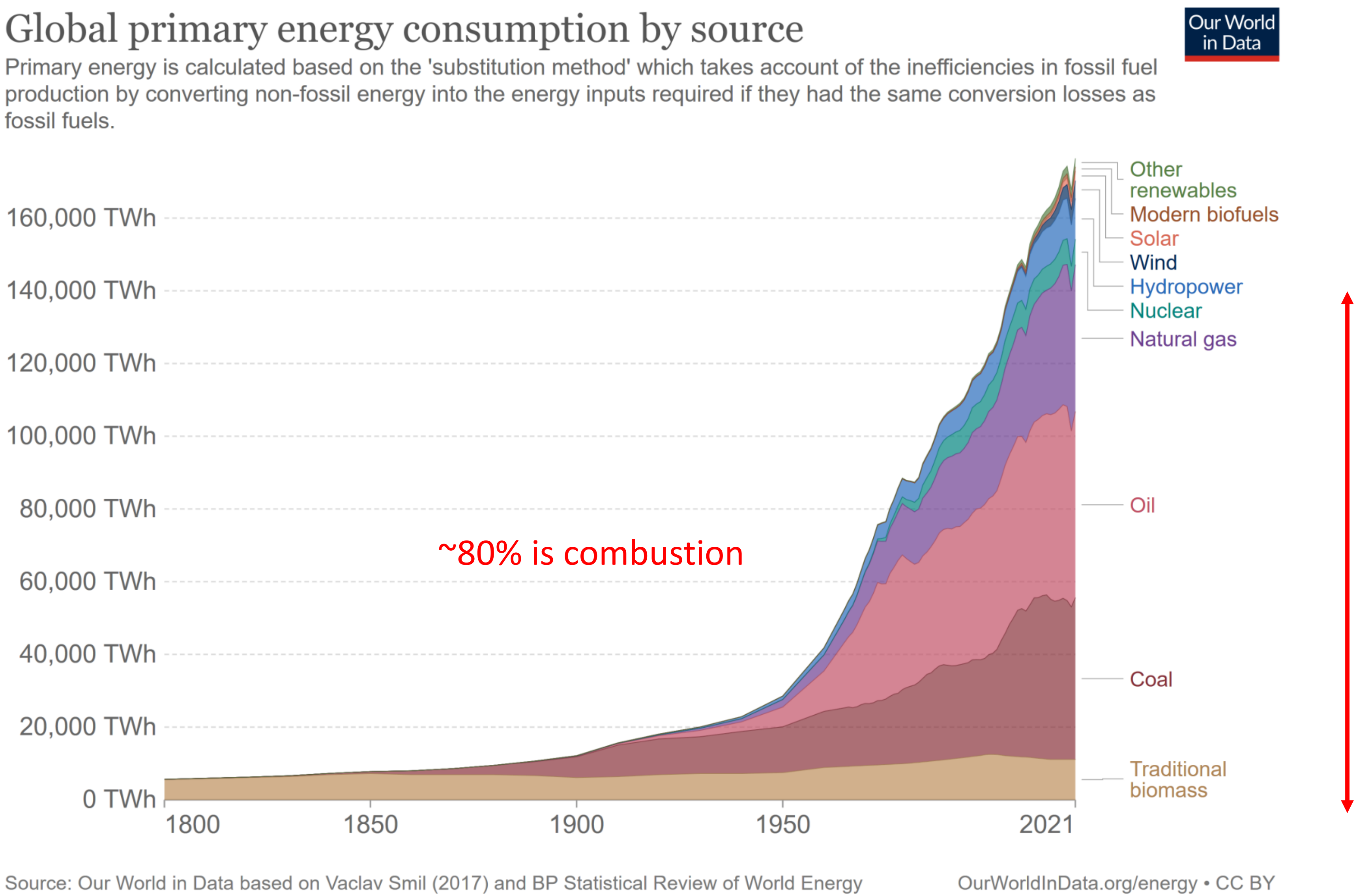
Outline

The problems we are trying to solve

A sampler of research results

Future steps

Primary energy sources -



The "big picture" of a part of C4T project

Emissions:

If you use fossil fuel, you produce **CO_2**.

If you use fossil fuel in a combustion process, you also produce **NOx**, **Particulate Matter (PM)**, and other species. They may be toxic, carcinogenic, respiratory irritants etc.

Solutions:

Use less fuel per unit of output ("efficiency", "waste heat utilisation")

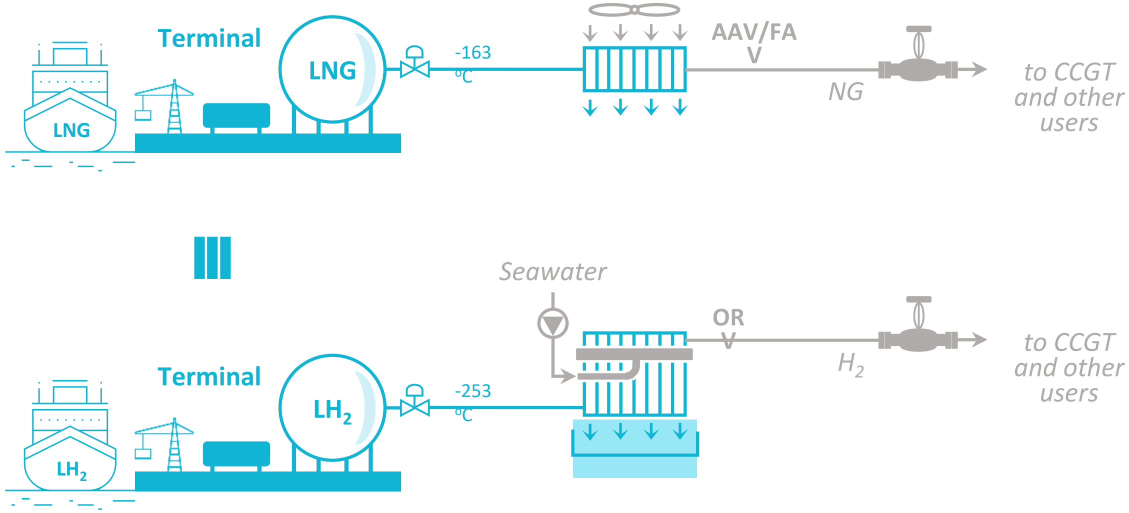
Burn well ("emit less per unit of heat released")

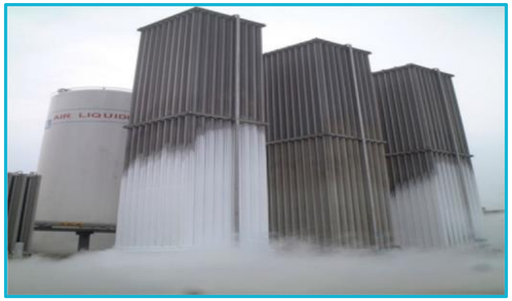
Burn zero-C fuel ("emit no CO_2") or C-neutral ("synthesize the hydrocarbon" or use "biofuel")

In parallel: Know what happens to the pollutant in the atmosphere

LNG and LH_2 Cold utilization strategies

- *The **regasification** of LNG or LH_2 is based on current **LNG terminal technologies** (e.g. Ambient or Forced Air Vaporizers, Open Rack Vaporizers using seawater)*





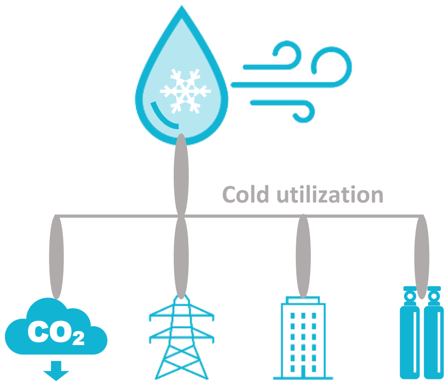
Frost generated in AAV

ORV by Kobelco

- *The **high-grade cold energy** released during regasification of LNG or LH_2 can instead be recovered for various utilization opportunities*

A. Romagnoli , NTU

LNG and LH_2 Cold utilization strategies



- Development and assessment of large-scheme strategies, by considering:

  1) multiple utilization opportunities, including **carbon capture**, **power generation**, **district cooling**, **gas production**;

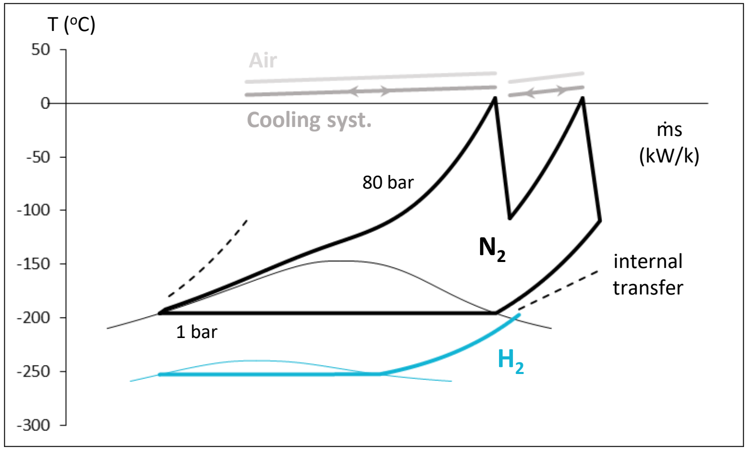
  2) synergy with a potential LH_2 import scenario.

- Up to **2.8 Mtons/year** of LCO_2 with LNG cold utilization and **4.1 Mtons/year** of LCO_2 with both LNG and LH_2 cold utilization.

- A **Nitrogen- or Helium**-based cryo-cogeneration system appears to have the adequate properties for LH_2 cold utilization

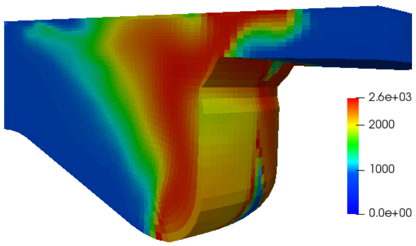
- Up to **10%** of the liquefaction energy consumed prior to shipment is recovered and utilized

- A **1,000-tpd** LH_2 terminal would lead to **15.7 MW** of power and **50 MW** of cooling

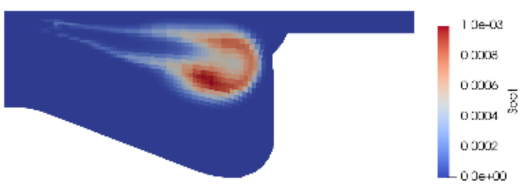


A. Romagnoli , NTU

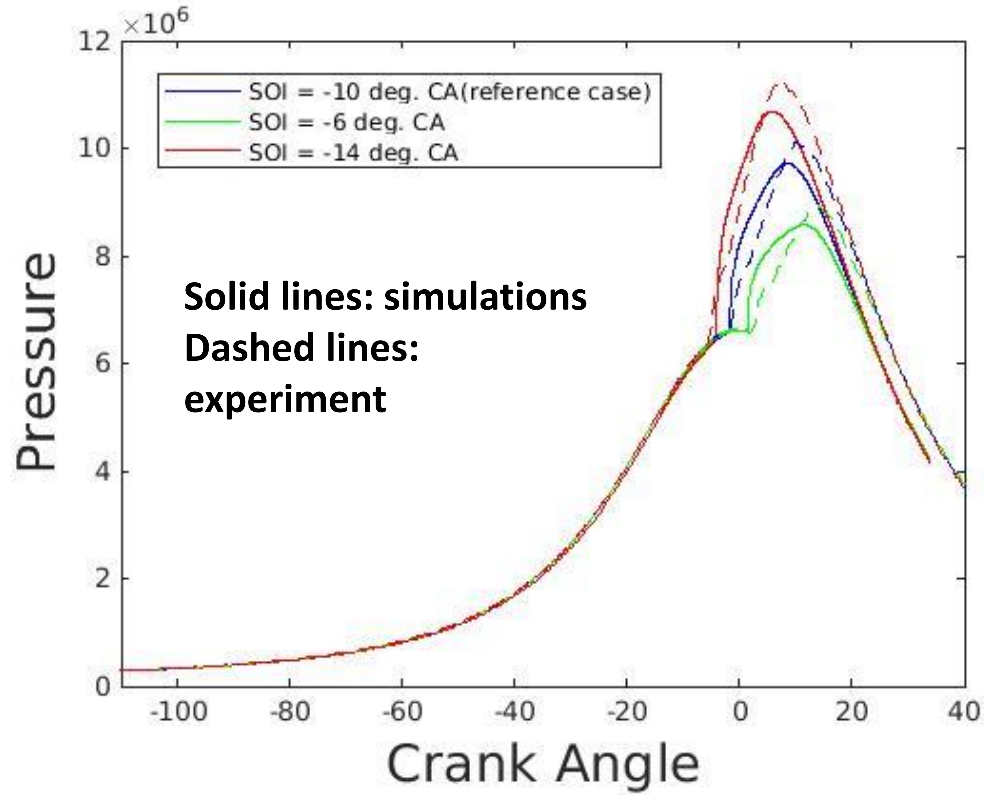
Marine engine Computational Fluid Dynamics



Temperature



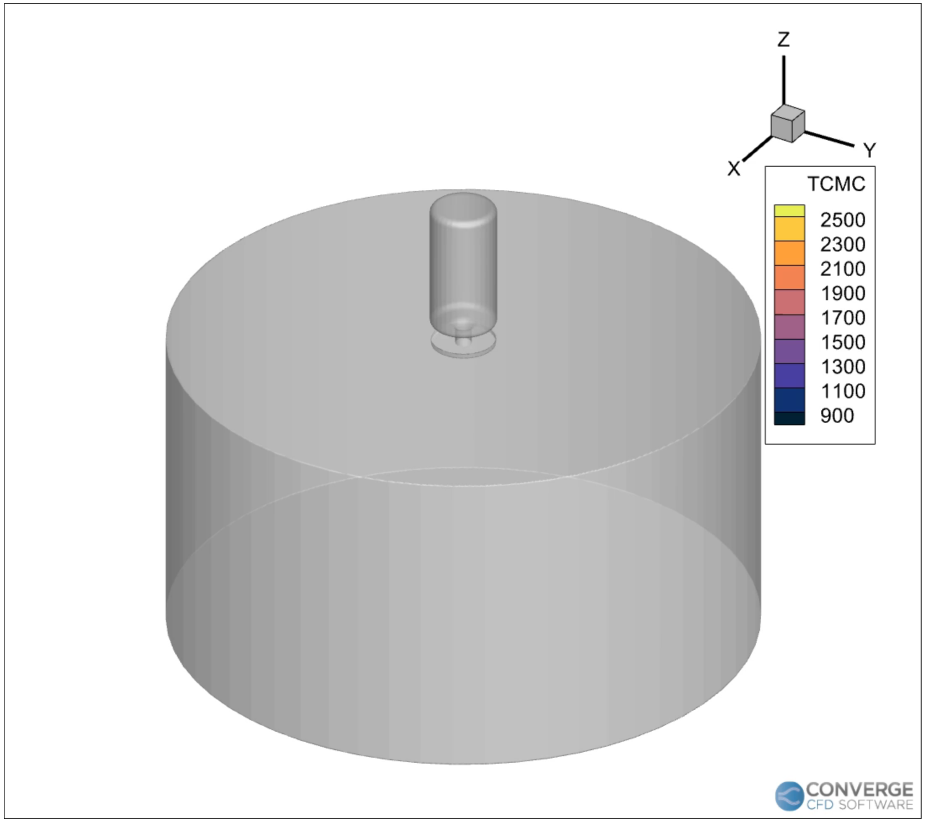
Soot



Detailed CFD codes are used by industry to design cleaner engines. Imperative for new engine development for new fuels (biofuels, NH_3, H_2 etc).

Trivedi et al, 2021: https://doi.org/10.4271/2021-24-0041

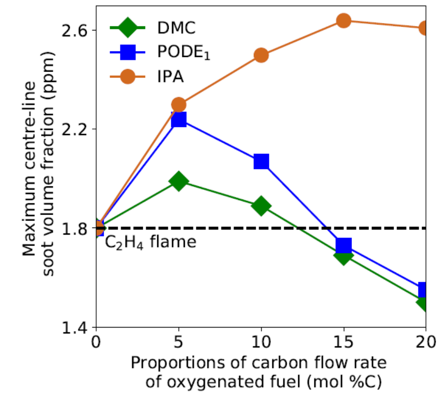
Jet ignition of LNG engines (and NH_3 and CH_3OH)

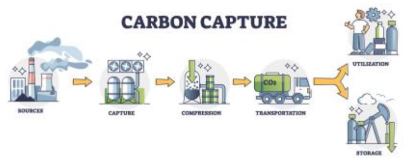
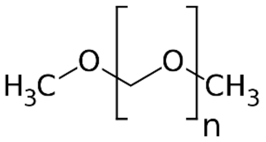
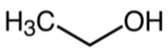
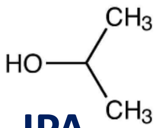
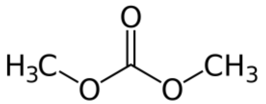


New fuels need new combustion modes which need new combustion models

Harikrishnan et al, 2024: AIAA SciTech

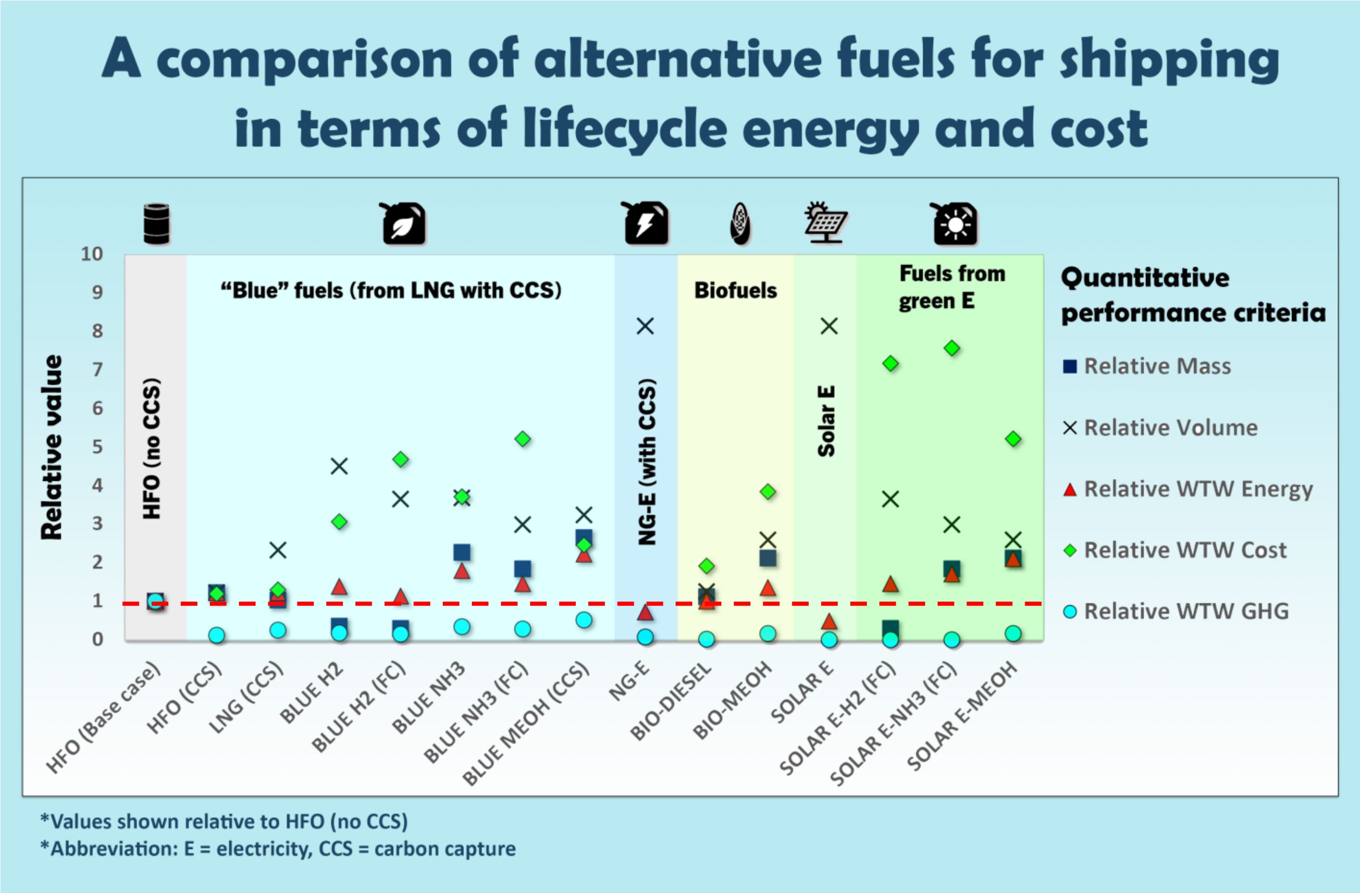
Biofuel structure, chemistry, and soot emission



	POLY-ETHERS	ALCOHOLS	CARBONATES
Sourcing		 	
Chemical structure	 **PODE$_n$**	 **EtOH**  **IPA**	 **DMC**
Oxygen content	42 - 48%	27 - 35%	53%

Each biofuel is different; research developed chemical mechanisms and understanding on PM emissions from various biofuels

Comprehensive evaluation of alternative maritime fuels

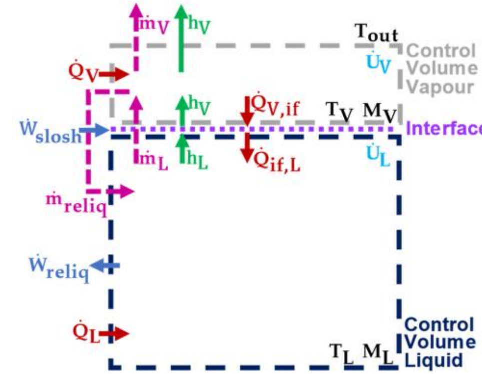


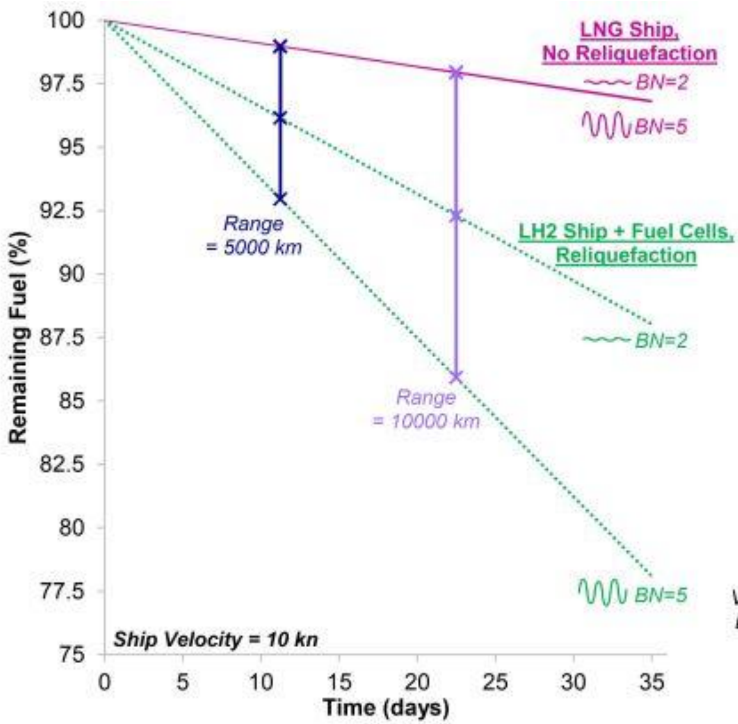
All good options consume a lot of energy, on a Well-To-Wake lifecycle basis.

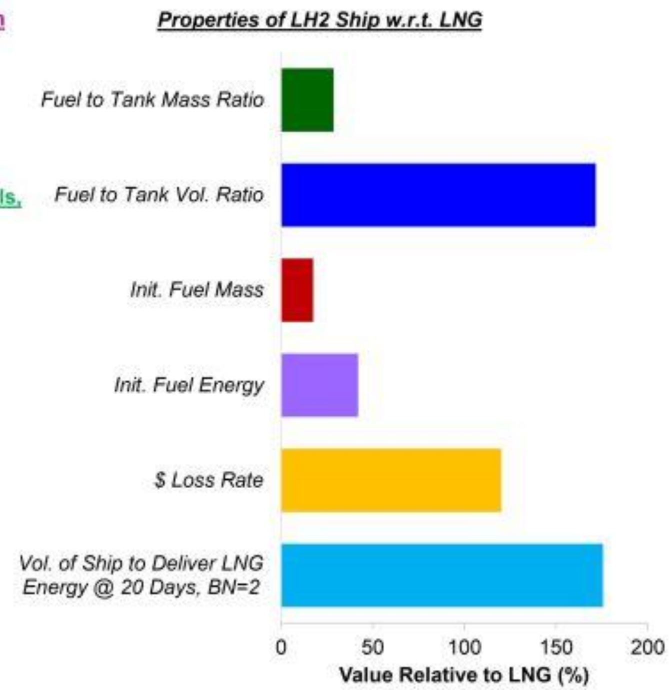
On-line calculator: https://lowcarbonship.com

Law et al, 2021: https://doi.org/10.3390/en14248502

Hydrogen ship : thermodynamics of boil-off (sloshing, effects of weather, tank properties etc)



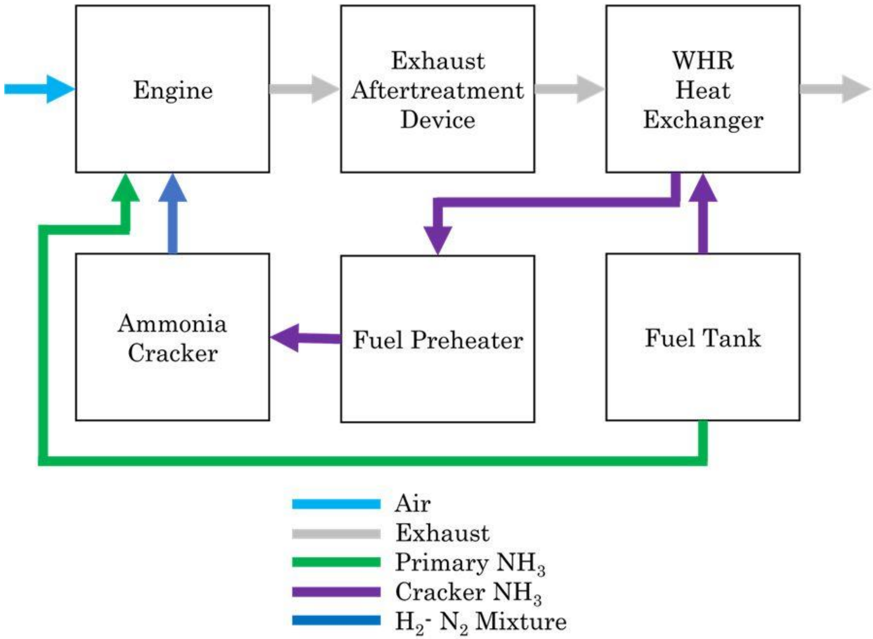


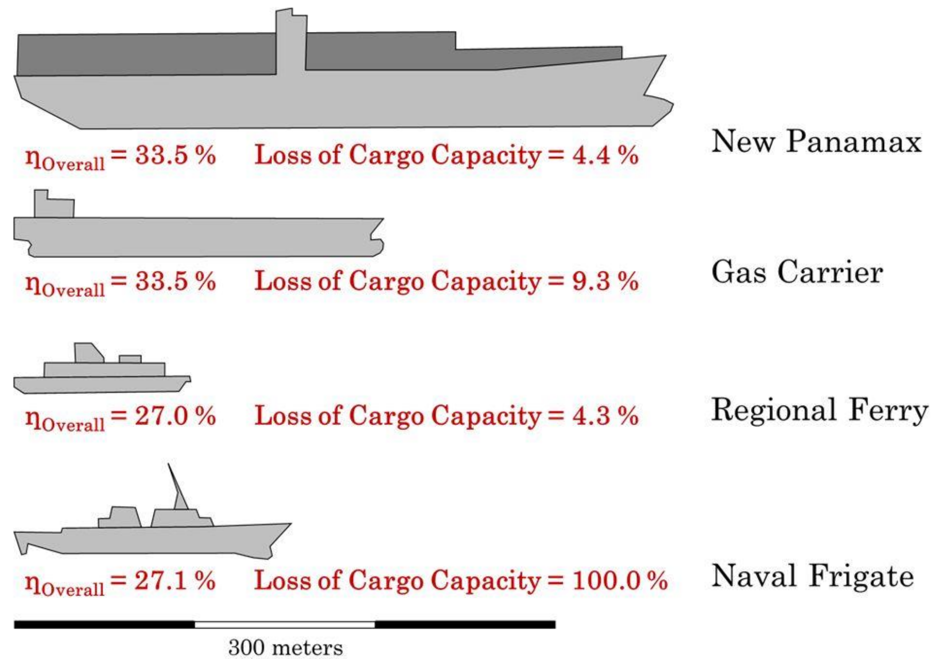


LH2 ship very sensitive to sloshing, causing high boil-off rates; significant extra energy needed to re-liquefy the evaporated hydrogen.

Smith et al, 2022: https://doi.org/10.3390/en15062046

Ammonia-fuelled ship model

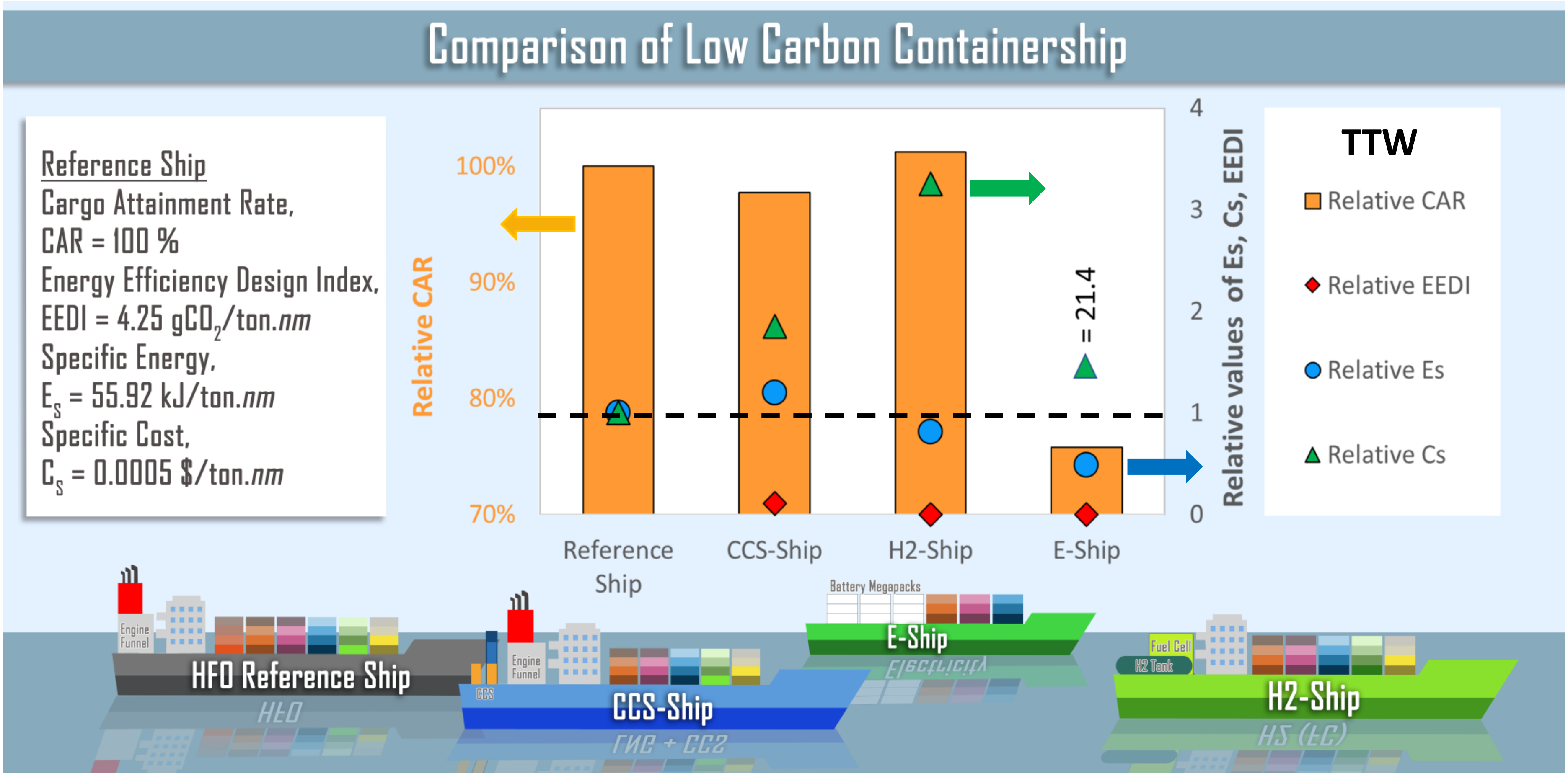




NH_3 ship must include many new sub-systems – this means extra cost, weight, volume, cargo loss

Imhoff et al, 2021: https://doi.org/10.3390/en14217447

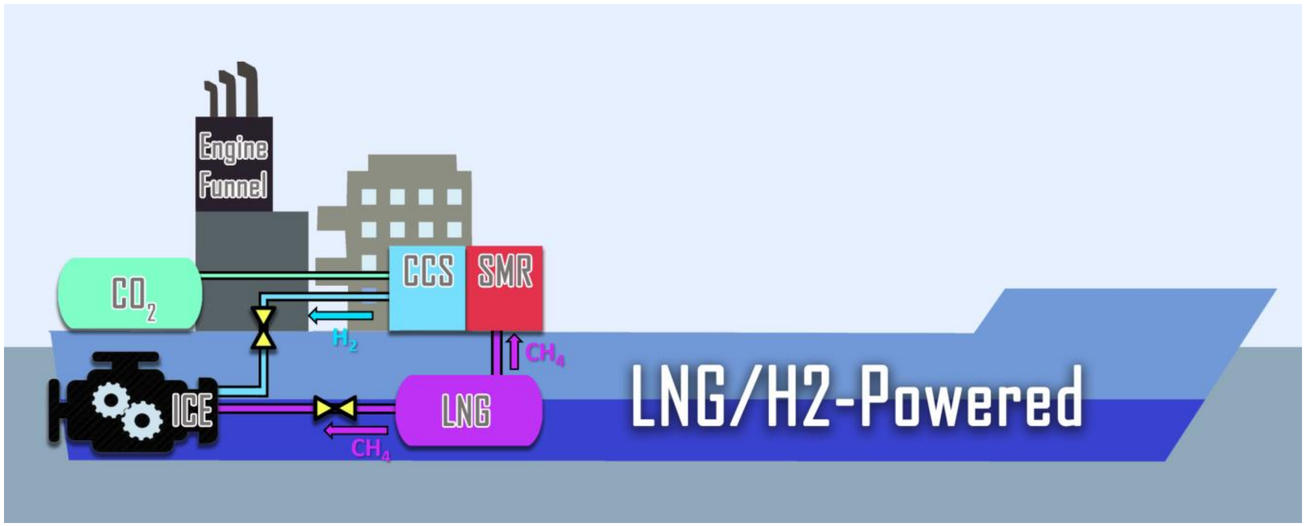
Containership with post-combustion on-board Carbon Capture and Storage, comparison with battery & LH2 ship

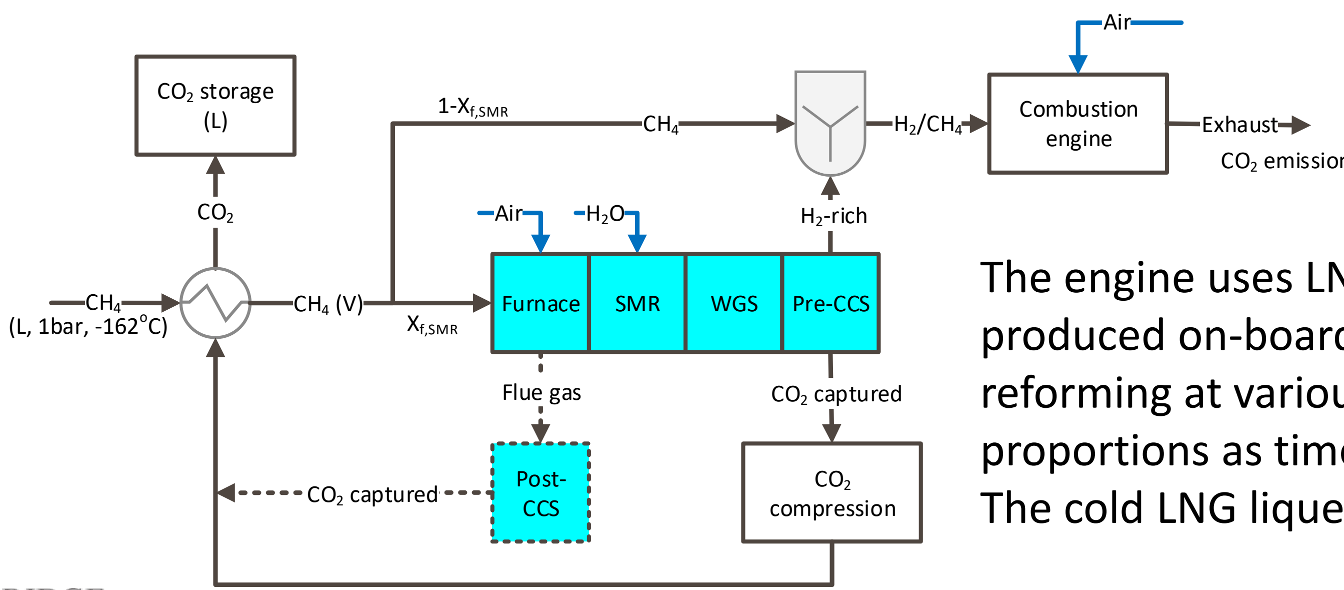


On-board CCS seems a reasonable proposition; "the devil is in the detail" however

Law et al, 2023: https://doi.org/10.1016/j.egyr.2023.02.035

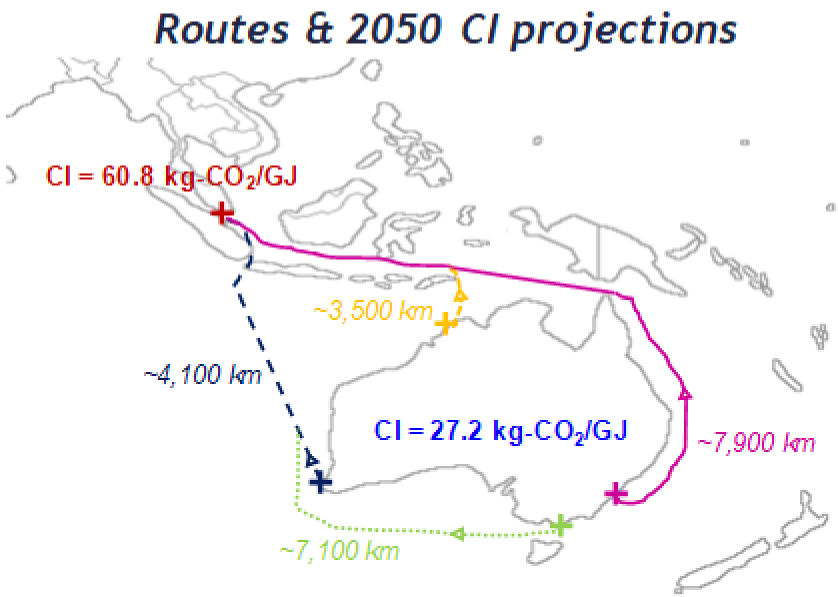
On-board partial LNG reforming (engine fed by LNG + H2), pre-combustion Carbon Capture and Storage

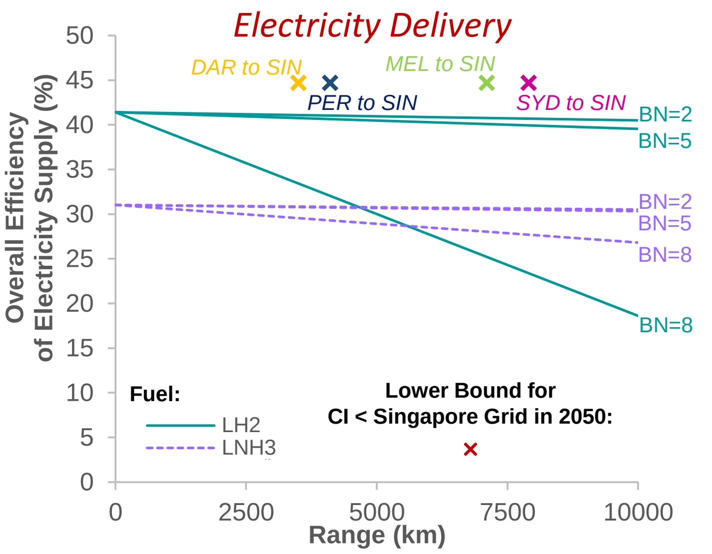


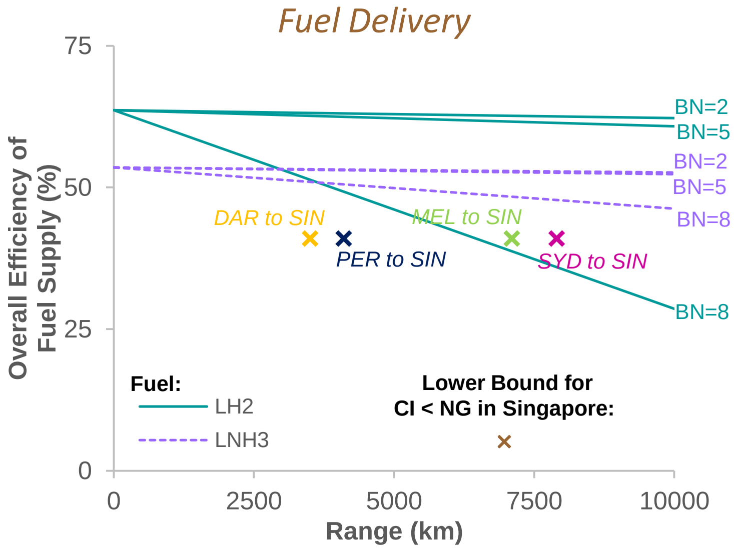


The engine uses LNG + H_2 produced on-board by LNG reforming at various proportions as time evolves. The cold LNG liquefies the CO_2.

Round-trip efficiency for green electricity imports to SG through LH2 and NH3



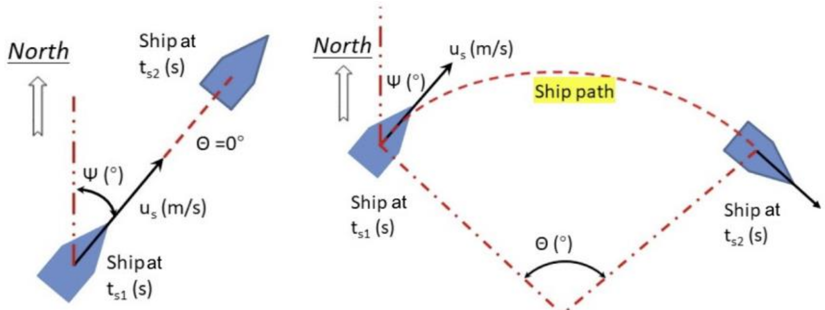




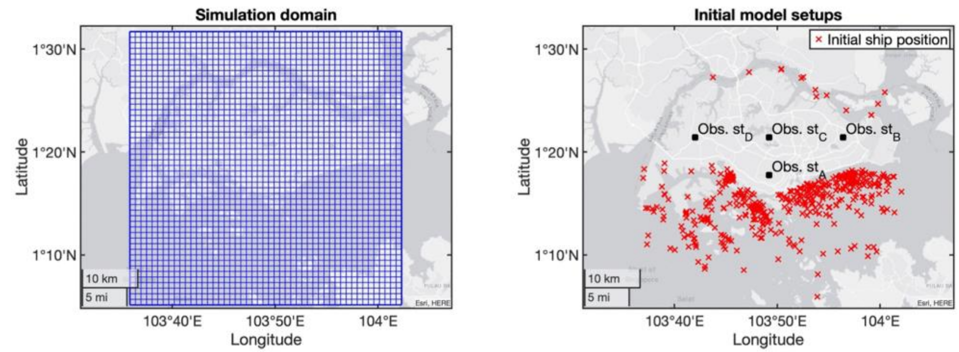
Round-trip efficiency with LH2 and LNH3: not too attractive

Jessie Smith, PhD, Univ of Cambridge 2023:
https://doi.org/10.17863/CAM.94654

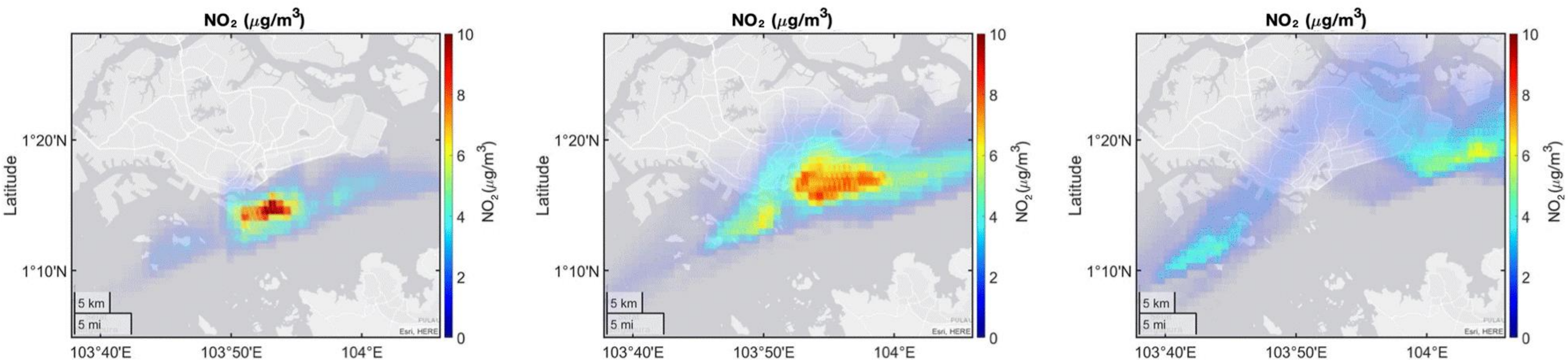
Moving sources in atmospheric dispersion CFD (“Air Quality Modelling” AQM)



(a) Moving straightly (θ=0°) (b) Moving in a curve ($\theta \neq 0°$)



(a) 50 km × 50 km domain (1 km resolution) (b) Initial ship positions for 1^{st} hour



(a) At $t = 60$ min (b) At $t = 120$ min (c) At $t = 180$ min

Model development to better include ship emissions

Pan et al 2021: https://doi.org/10.5194/gmd-14-4509-2021

Particulate emissions from shipping in ports (drone with sensors)

http://www.eng.cam.ac.uk/news/monitoring-maritime-emissions-land-and-sea-using-drones-and-handheld-particle-sensors

Haugen et al 2022: 10.1016/j.atmosenv.2022.119384

Multi-parameter PM emissions monitoring

- **AethLab AE51** for black carbon/mass (ng/m^3)
- **TSI P-traks** for particle number (PN/cm^3)
- **Naneos Partector 2** for lung-deposited surface area (μm^2/cm^3)
- Probe sampling from outside downwash

Area, number, mass evolve differently as plume mixes. Important input in AQM.
Vertical distribution of pollutants: important for residents of high-rise buildings.

Haugen et al 2022: [10.1016/j.atmosenv.2022.119384](https://doi.org/10.1016/j.atmosenv.2022.119384)

Drone sensing for methanol bunkering

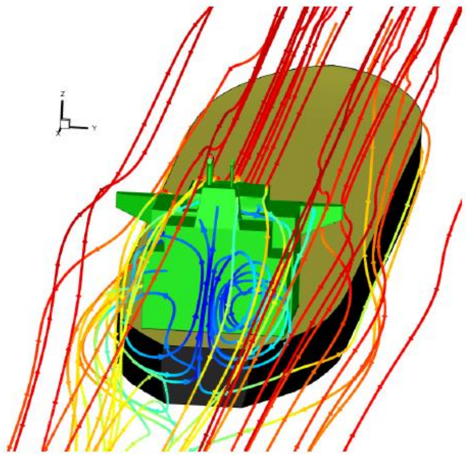
CARES LinkedIn post: https://www.linkedin.com/posts/cambridge-centre-for-advanced-research-and-education-in-singapore-cares-_cares-drone-at-mpa-methanol-bunkering-operation-ugcPost-7092334900187451392-VIcM?utm_source=share&utm_medium=member_desktop

High-res movie:
https://www.dropbox.com/scl/fi/pj69hu76zyrqtaaoxhh07/Highlight-reel-for-external-use_high-quality.mp4?rlkey=yhrs2uat8ml8ky6fbo227xkdc&dl=0

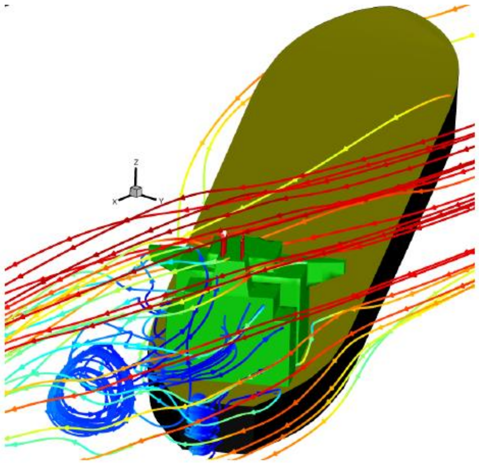
World's first ship-to-containership methanol bunkering; CARES drone with CH_3OH sensor to detect leaks. (Raffles Anchorage, 27 July 2023)

Ship-scale CFD for plume dispersion

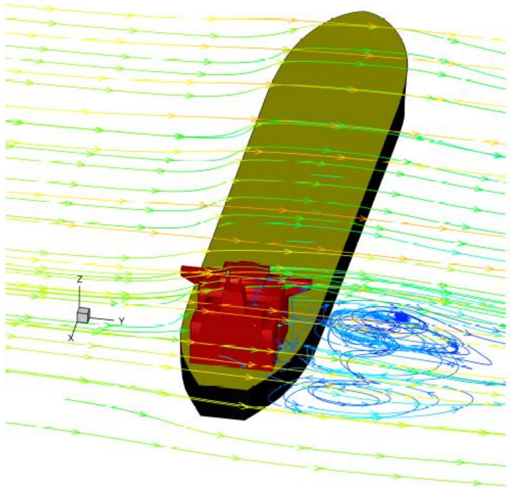
- CFD of plume dispersion at various wind directions: used to explore quick near-field transformations and the validity of standard practices used by regulators.



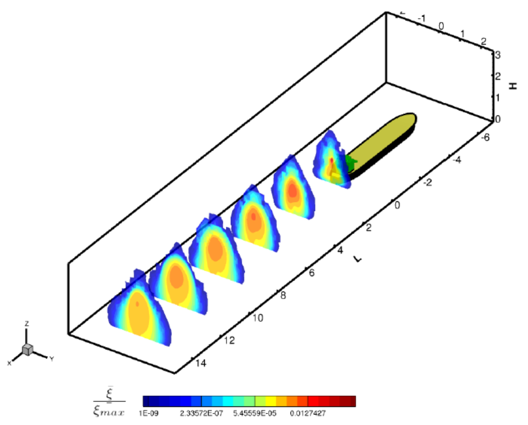
Headwind case

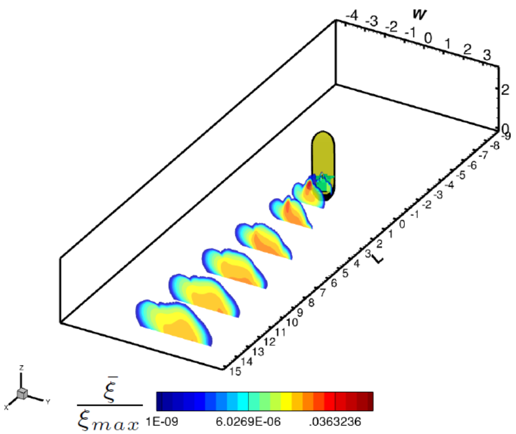


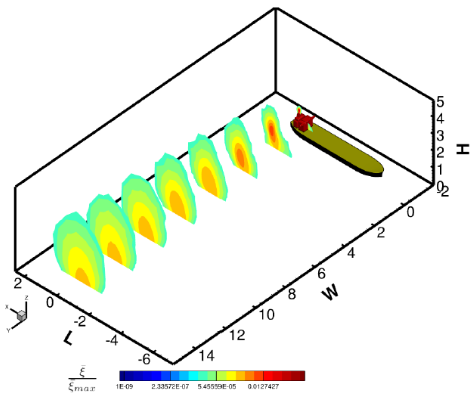
Inclined Wind Case



Cross Wind Case

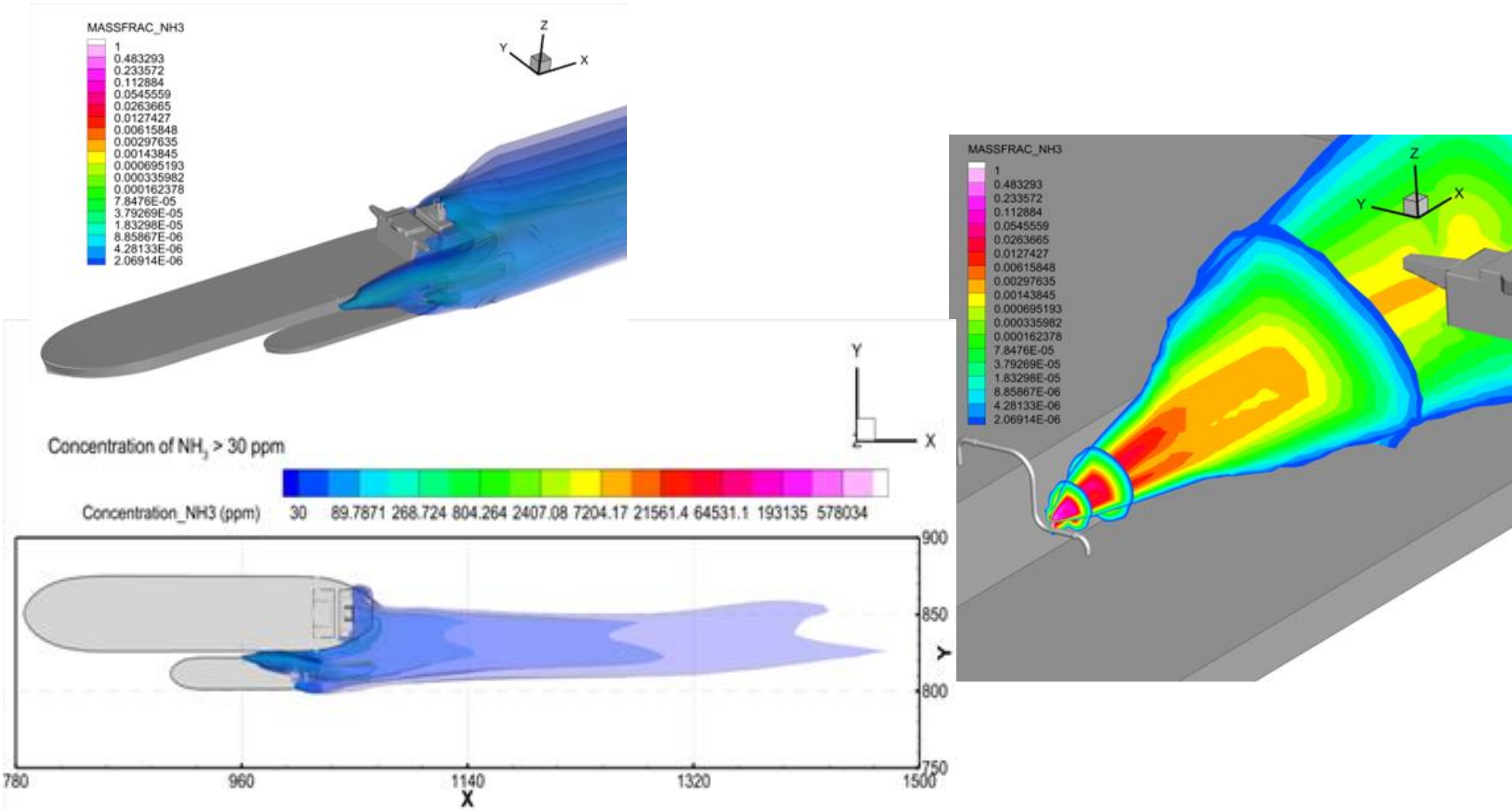






CFD for NH_3 leak dispersion during ship-to-ship bunkering

- CFD of NH_3 dispersion from connecting pipe: used to explore physical range where concentrations are dangerous.



Future steps:

Continue researching the production and combustion of biofuels, SAFs, H_2, NH_3, CH_3OH.

Continue thinking of ways to integrate waste heat and cryogenic systems.

Continue thinking of “where the pollutant goes” in the atmosphere – important for policy-making, H&S, penetration of zero-C fuels etc.

Develop a direct dialogue with policy-makers, regulators, propulsion and power generation system manufacturers: the standard innovation pathway is too slow for the rate of CO_2 reduction we need.

NATIONAL RESEARCH FOUNDATION
PRIME MINISTER'S OFFICE
SINGAPORE

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