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 -

Global primary energy consumption by source

Primary energy is calculated based on the 'substitution method' which takes account of the inefficiencies in fossil fuel production by converting non-fossil energy into the energy inputs required if they had the same conversion losses as fossil fuels.

~80% is combustion

Source: Our World in Data based on Vaclav Smil (2017) and BP Statistical Review of World Energy

OurWorldInData.org/energy • CC BY
The “big picture” of a part of C4T project

Emissions:

If you use fossil fuel, you produce $\text{CO}_2$.

If you use fossil fuel in a combustion process, you also produce $\text{NO}_x$, 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 $\text{CO}_2$”) or C-neutral (“synthesize the hydrocarbon” or use “biofuel”)

In parallel: Know what happens to the pollutant in the atmosphere
LNG and LH₂ Cold utilization strategies

- The regasification of LNG or LH₂ is based on current LNG terminal technologies (e.g. Ambient or Forced Air Vaporizers, Open Rack Vaporizers using seawater)

- The high-grade cold energy released during regasification of LNG or LH₂ can instead be recovered for various utilization opportunities
LNG and LH₂ 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 LH₂ import scenario.

- Up to 2.8 Mtons/year of LCO₂ with LNG cold utilization and 4.1 Mtons/year of LCO₂ with both LNG and LH₂ cold utilization.

- A Nitrogen- or Helium-based cryo-cogeneration system appears to have the adequate properties for LH₂ cold utilization.

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

- A 1,000-tpd LH₂ terminal would lead to 15.7 MW of power and 50 MW of cooling.

A. Romagnoli, NTU
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$_3$OH)

New fuels need new combustion modes which need new combustion models

Harikrishnan et al, 2024: AIAA SciTech
Biofuel structure, chemistry, and soot emission

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

<table>
<thead>
<tr>
<th>POLY-ETHERS</th>
<th>ALCOHOLS</th>
<th>CARBONATES</th>
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<tbody>
<tr>
<td>PODE&lt;sub&gt;n&lt;/sub&gt;</td>
<td>EtOH</td>
<td>DMC</td>
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<tr>
<td>Chemical structure</td>
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<td>H&lt;sub&gt;3&lt;/sub&gt;C&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;n&lt;/sub&gt;</td>
<td>H&lt;sub&gt;3&lt;/sub&gt;C&lt;sub&gt;2&lt;/sub&gt;OH</td>
<td>H&lt;sub&gt;3&lt;/sub&gt;C&lt;sub&gt;2&lt;/sub&gt;COOCH&lt;sub&gt;3&lt;/sub&gt;</td>
</tr>
<tr>
<td>Oxygen content</td>
<td>42 - 48%</td>
<td>27 - 35%</td>
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</tbody>
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Sourcing

Proportions of carbon flow rate of oxygenated fuel (mol %C)

Maximum centre-line soot volume fraction (ppm)

C<sub>2</sub>H<sub>4</sub> flame
All good options consume a lot of energy, on a Well-To-Wake lifecycle basis.

On-line calculator: [https://lowcarbonship.com](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

NH₃ 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](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](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 + H2 produced on-board by LNG reforming at various proportions as time evolves. The cold LNG liquefies the CO2.
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)

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

Model development to better include ship emissions
Particulate emissions from shipping in ports (drone with sensors)


Haugen et al 2022: 10.1016/j.atmosenv.2022.119384
Multi-parameter PM emissions monitoring

- **AethLab AE51** for black carbon/mass (ng/m³)
- **TSI P-traks** for particle number (PN/cm³)
- **Naneos Partector 2** for lung-deposited surface area (μm²/cm³)
- 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.

Drone sensing for methanol bunkering


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 CH3OH 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.
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, H₂, NH₃, CH₃OH.

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 CO₂ reduction we need.
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