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The Marine Decarbonisation Challenge

Transport Energy Network Workshop

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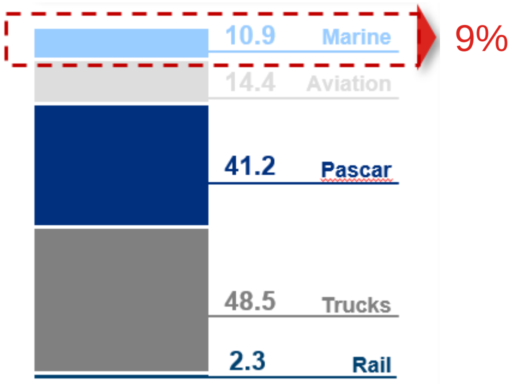
www.ricardo.com

Agenda

- **The Marine Decarbonisation Challenge**
- Some Thoughts on Alternative Fuels
- Marine Application Requirements
- Conclusions

Marine is a significant energy user and today almost exclusively powered by oil, thus a significant carbon emitter

World Transport Sector
2018 Energy Use
117 Exajoules ($1x10^{18}$ J)



Source: BP Energy Outlook 2018

- Transport uses 20% of the world's energy
- **Marine represents 9% of Transport**
  - That's 2% of the world's energy
- Today almost all of that Marine energy is from oil derived fuels of which it uses **240 million tonnes annually** split as follows:
  - 80% residual oils (Heavy Fuel Oils)
  - 20% distillate oils (Marine Gas/Diesel Oils)
  - LNG is used but only in relatively small quantities
- This oil is globally available with a well developed ship supply infrastructure and efficient engine technologies to use it
- It's also a relatively cheap fuel, with a typical residual oil available to a ship at $380/tonne which is ~£0.27/litre
- The challenge is that residual oil emits circa 3kg CO_2 per kg fuel, around **740 million tonnes CO_2 per year**

The International Maritime Organisation (IMO) has mandated a 50% reduction in Marine carbon emissions by 2050, i.e. “50 by 50”

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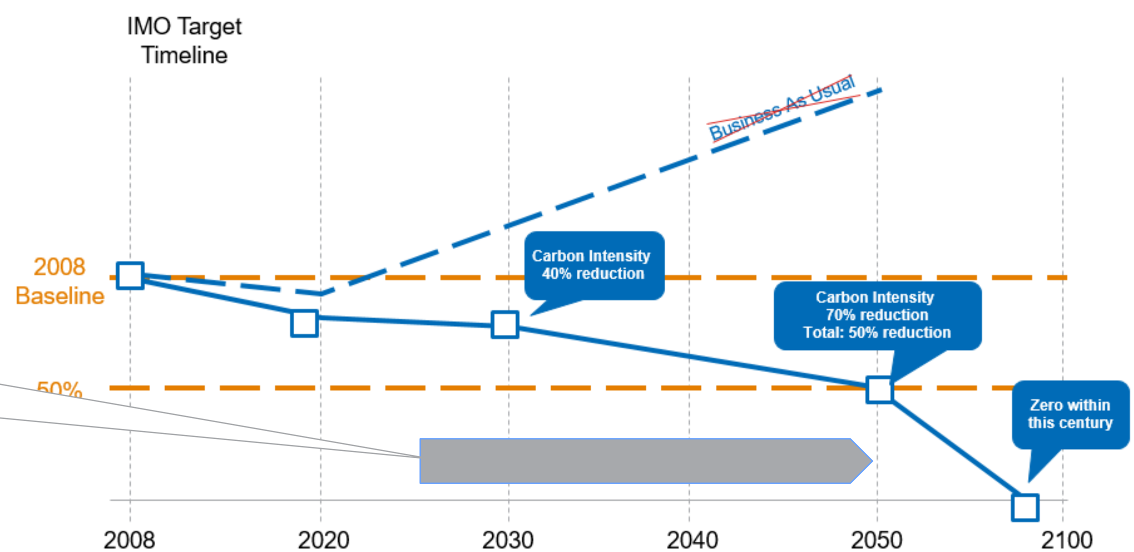
- The IMO target is a **50% reduction in total Marine GHG emissions in 2050**, relative to a 2008 baseline
  - Thereafter, full decarbonisation (a 100% reduction) as soon as possible within this century
- ‘GHG’ definition also includes methane (attributed a 25 GWP) and nitrous oxide (attributed a 298 GWP)
  - It is not yet confirmed if this is Well-to-Wake or Tank-to-Wake, i.e. if carbon containing fuels are allowed
- ‘Total’ means the absolute amount of Marine GHG emissions so, if there is a continued growth in world trade and associated increase in the amount of shipping, the individual ships will have to reduce carbon emissions more than the 50% in order to reach a total 50% reduction
- Thus IMO have also introduced a **Carbon Intensity measure, defined as Tank-to-Wake* CO_2 per tonne-mile**, with targets for each ship to reduce 40% by 2030 and then **70% by 2050**

Typical ship lifetime 25yrs. Fleet ordered now will be around in 2050



* This may change subject to future review

Ships efficiency improvements to reduce CO_2 will not be enough – need to decarbonise the energy source, i.e. the fuel

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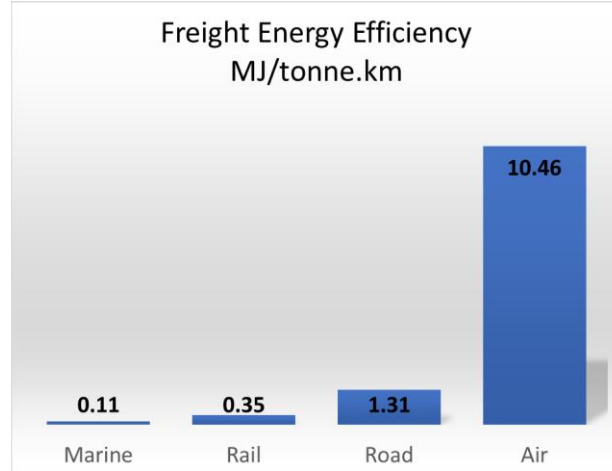
- Remember that ships are already well developed to efficiently move cargo: ~10 times more efficient than a truck
- There are a range of **efficiency improvement** technologies but their **potential is limited to achieve a Carbon Intensity reduction of 70%,** e.g.
  - ~5% from sails (kite or flettner rotor)
  - ~5% from hull air lubrication
- Speed reduction is an option with significant potential, e.g.
  - ~40% carbon reduction from ~25% speed reduction
  - But reducing speed is problematic for passenger services like ferries and in all cases has commercial impacts
- Needs energy source decarbonisation to hit 70% reduction
  - i.e. **the fuel needs to decarbonise**
  - (a switch to battery electric with renewable electricity is an option to decarbonise the energy source but more on that later)
  - Note LNG might deliver 10-20% CO_2 reduction (excluding Well-to-Tank emissions) that might be sufficient short term but mid to long term has no transition pathway



Source: Deutsche Bahn AG

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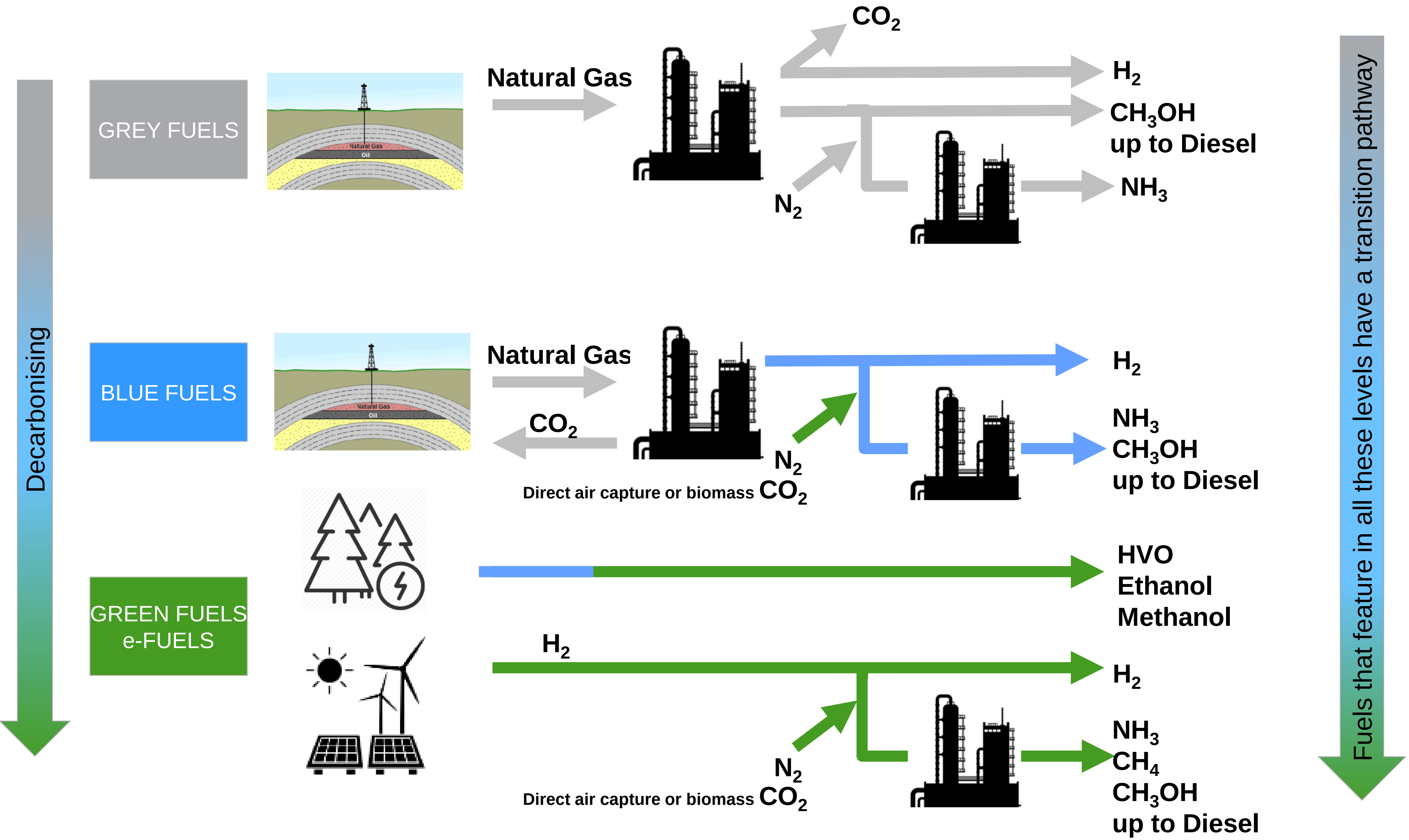
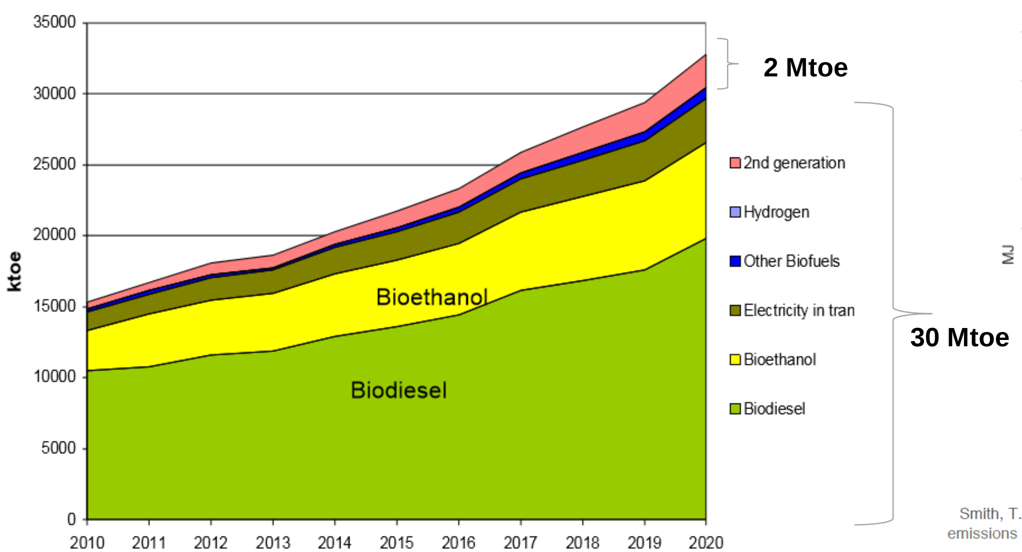
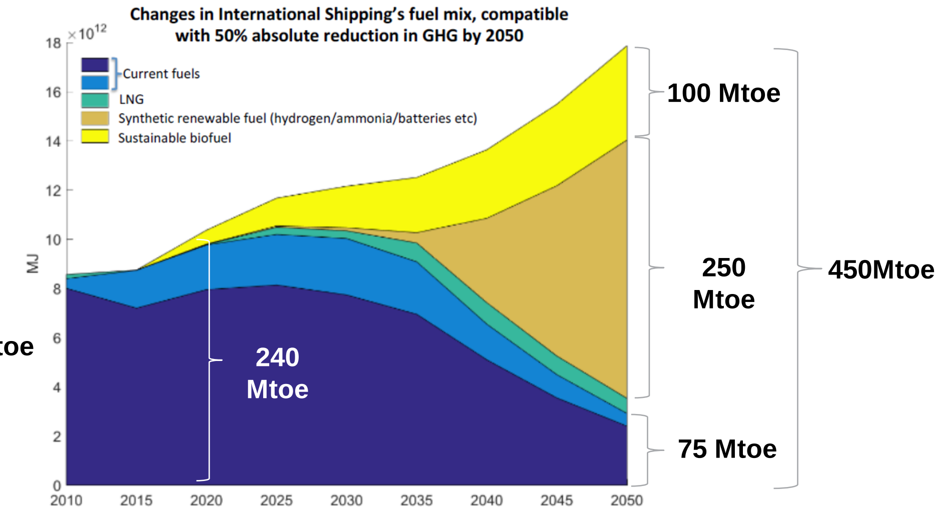
There is a dizzying array of sources for 'Alternative Fuels' with different levels of decarbonisation (this is a simplistic overview)



Biomass supply scalability is heavily limited by Land Usage, Land Usage Change and Forestry and competition from other sectors

- Significant portion of existing Biofuels comes from 1st Generation Biofuels (crops grown specifically for fuel production), which has Land Usage, Land Usage Change and Forestry (LULUCF) impacts
  - LULUCF impact varies significantly based on fuel type and route to production
  - The EU has pledged to have a ‘zero-debit’ LULUCF effect, meaning any LULUCF impacts must be offset by equivalent reforestation or support for sustainable forestry
  - **European commission has proposed not supporting 1st Gen biofuels from 2020 onwards**
- **2nd Generation biofuels are currently only available in small amounts ~2Mtoe**
  - **Just 0.8% of the global shipping fleet 2020 fuel consumption of ~240Mtoe**
- **Competition for 2nd generation biofuels** from other transport sectors will be strong with aviation likely to be able to pay more. Global political leadership may be necessary for a high level decision to avoid multiple modes choosing the same fuel option to decarbonise
- **Conclusion is that biofuels are unlikely to be sufficiently scalable**





Smith, T., Raucci, C., Haji Hosseinloo S., Rojon I., Calleya J., De La Fuente. S., Wu P., Palmer K. CO2 emissions from international shipping. Possible reduction targets and their associated pathways. Prepared by UMAS, October 2016, London.

Source: European Commission https://ec.europa.eu/clima/news/regulation-land-use-land-use-change-and-forestry-2030-climate-and-energy-framework-adopted_en
European Commission http://www.ieabioenergy.com/wp-content/uploads/2014/10/P02-iLUC-Status-of-EU-legislation-Marques.pdf

Development and industrialisation of Direct Air Carbon Capture and Storage is critical to carbonaceous eFuel scalability = risk

- In order to produce sustainable carbon dioxide, one of the key technologies is Direct Air Carbon Capture and Storage (DACCS)
  - Industrial sources of CO_2 are tending to be concentrated in industrial areas where it is expected renewables will not be co-located
  - In fact, renewables are likely to be off-grid, therefore the CO_2 has to either be transported from an industrial source
  - This is why Ricardo consider Direct Air Capture as the most appropriate technology for eFuel scalability across the globe
  - Ricardo are however not yet convinced of Carbon Storage schemes, with long term storage integrity and auditability uncertain
- Different mechanisms for DACC exist at varying levels of viability and technology readiness levels (implied from Royal Society source) ➔ **requires significant development and upscaling. Risk for eFuels requiring DACC**

'Artificial Trees'

CO_2 passively adsorbed onto large surface area until saturated → Adsorbent is humidified or soaked in water at low pressure → CO_2 released and the adsorbent can be reused

TRL 7-8 (at low scale)

Supported amine absorption

Amines held on porous material with high surface area → Air passes through, whereby CO_2 reacts with amines → Absorbent is heated releasing CO_2 once again (heat can come from waste heat recovery)

TRL 7-8 (at small commercial plant scale)

Lime-soda Process

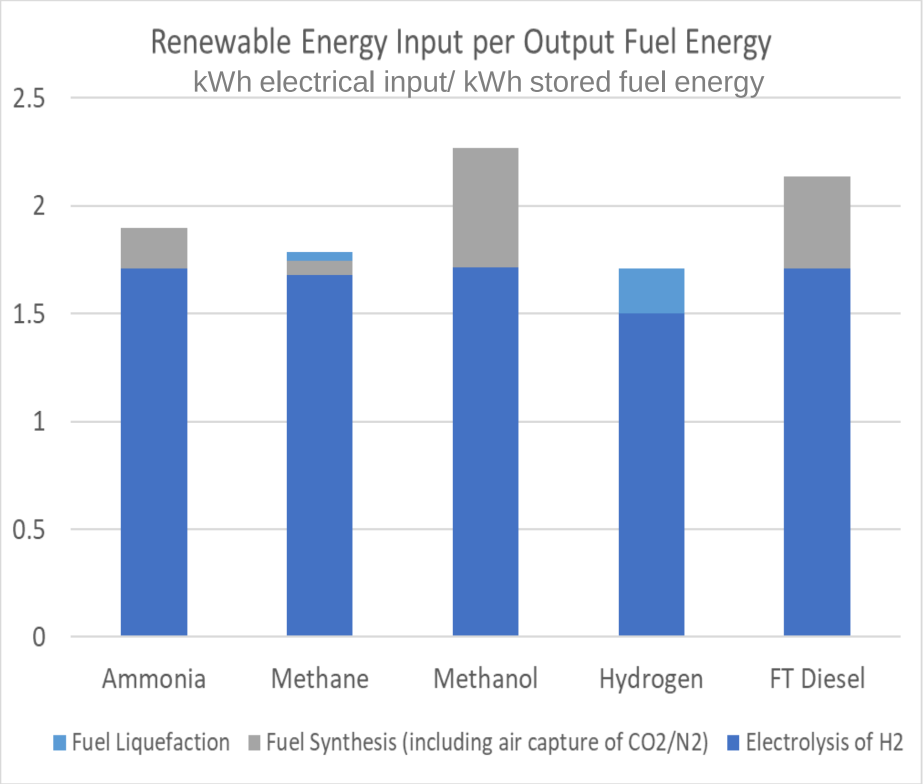
Sodium Hydroxide reacts with CO_2 in atmosphere. Creates Na_2CO_3 for storage → CaO added to regenerate Sodium Hydroxide and leave $CaCO_3$ deposit → $CaCO_3$ heated to regenerate CaO and release CO_2

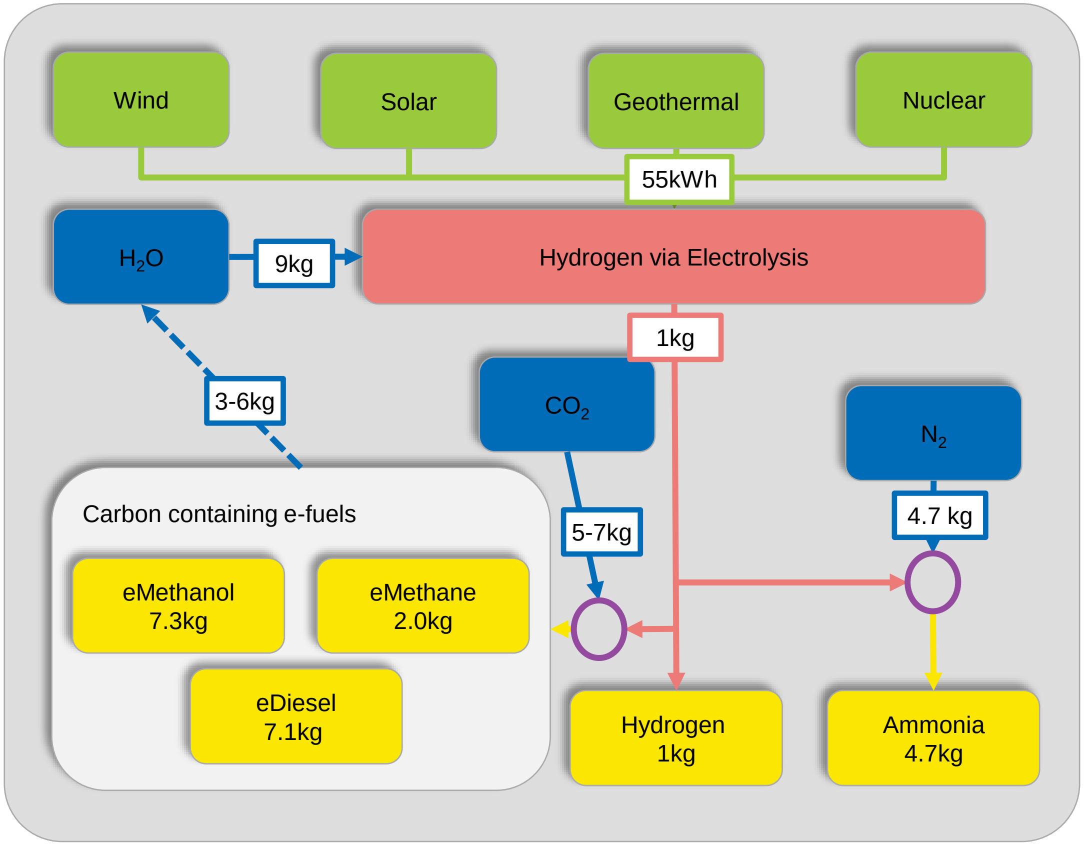
TRL 7-8 (demonstration plants produced)

Source: Royal Society, Greenhouse Gas Removal 2018

Cost competitiveness, important for shipping, of eFuels is sensitive to the amount of renewable electricity they need

- Electrolysis is an energy intensive process, accounting for the majority of energy input to making eFuels
  - The **amount of renewable energy required to store a unit of fuel energy is a key differentiator of eFuels**
  - As renewable energy becomes cheaper, the **cost of Green/eFuels will reduce and compete** with 'Blue' sources, expected to be 50/50 Blue/Green by 2050
- **Clean water**, needed in large quantities to produce fuel via the electrolysis route, is a scarce resource in some geographies (desalination likely to be required)



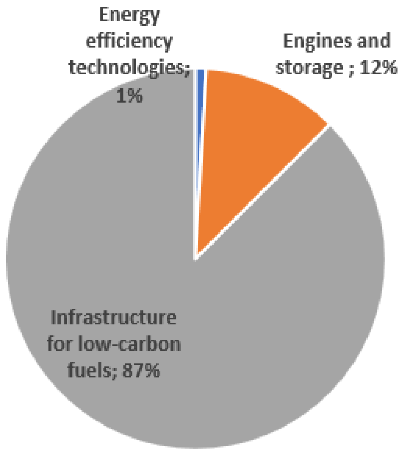


Source: Adapted from: "Alternative Fuels" – Jorn Karl, Shell International, 2019
Energy breakdown calculated from FVV data found in: Defossilising the Transport Sector

It's not just the ships. Studies show that ~87% of the investment cost to decarbonise is attributed to on-shore fuel infrastructure

- **Fuel infrastructure is a key piece of the puzzle for a marine decarbonisation strategy**. Many believe that current "land-based infrastructure is lagging behind the development of zero-carbon ships" (Nick Brown director of Lloyd's Register Marine & Offshore). **Ship technologies will make-up a fraction of the investment required compared to infrastructure.**
- **Widespread uncertainty that underpins the sector is equally prevalent portside** – in particular ports face tough decisions regarding **'which alternative fuels to back and what infrastructure to develop / invest in'.**

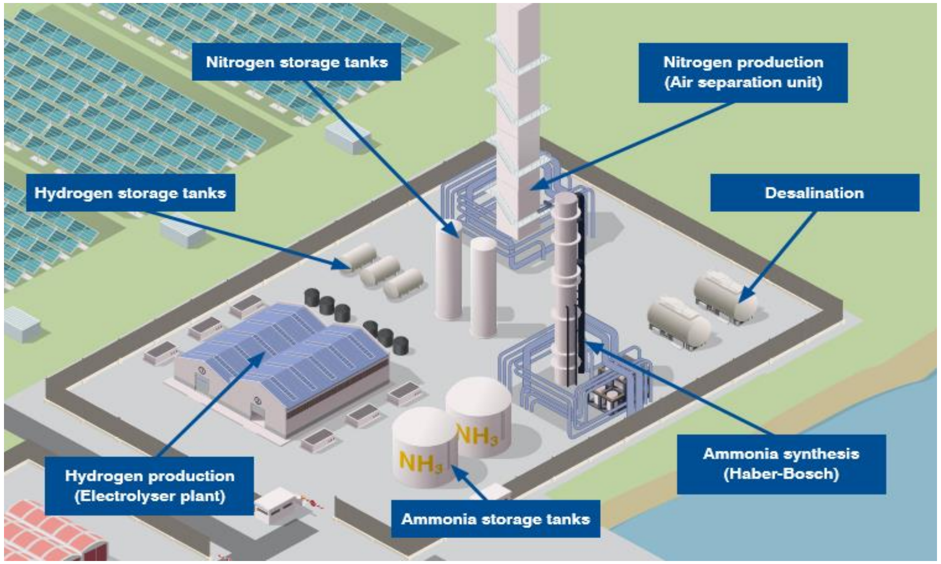
Aggregate investment costs (%)



SMR, CCS and / or electrolysis will be a strong focus…

A recent study by UMAS estimated that 87% of future marine decarbonisation investment is required to develop <u>infrastructure</u> (~$1.4 trillion by 2050).

Conceptual layout of hypothetical green NH_3 plant



UMAS' analysis suggested NH_3 could have a 'leading role' in marine decarbonisation, Ricardo's 'Sailing on Solar' report provided a schematic for a conceptual green NH_3 plant. `

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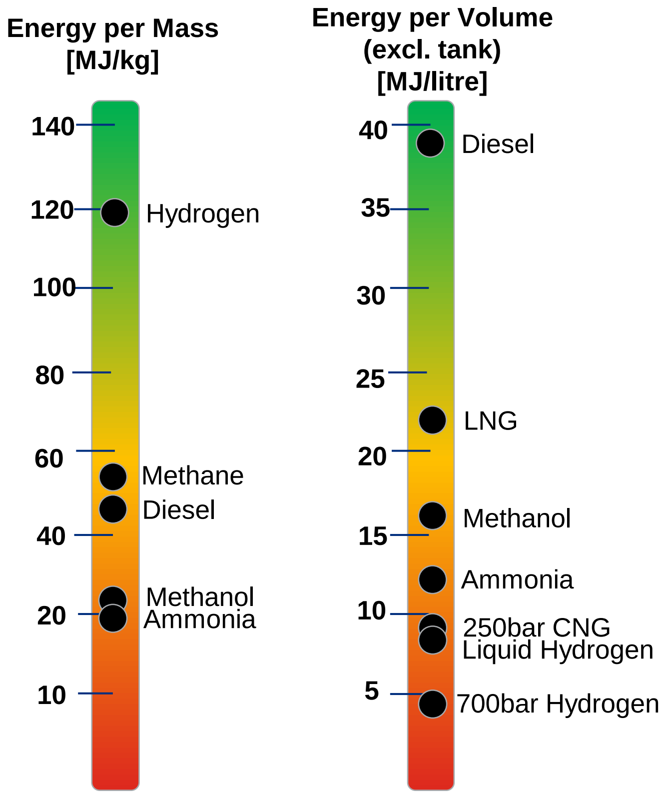
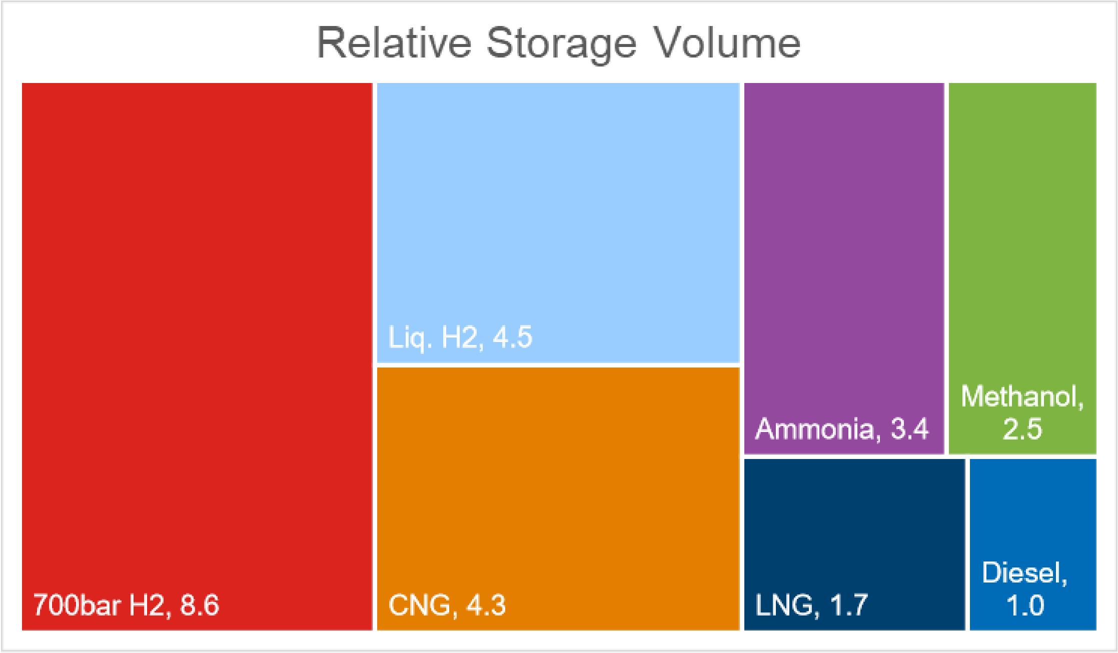
Ships that cross oceans need to store a lot of energy. Fuel volume matters as it takes cargo and passenger space





- Additional volume of tank insulation required for cryogenic temperature of liquid hydrogen will be significant
- Additional effective volume required for high pressure tanks due to cylindrical shape (~33% on top of fuel volume)
- Boil off gas volumes for cryogenic fuels not considered but could be significant factor on some applications for liquid hydrogen (anticipated ~0.4% per 24hrs for H_2 relative to ~0.2% for LNG)

➔ Hydrogen not suitable for long range applications, ammonia and methanol similar to LNG

	Diesel (liquid)	Hydrogen (gas)	Hydrogen (liquid)	Ammonia (liquid)	Methanol (liquid)	Methane (gas)	Methane (liquid)
Stored Condition	Ambient	700bar ambient	<10bar -253degC	20bar ambient	Ambient	200bar ambient	<10bar -163 degC
Density [kg/m3] at Stored Condition	846	38	71	618	792	168	414
LHV [MJ/kg]	46	120	120	19	20	54	54
LHV [MJ/litre] at Stored Condition (excluding tank system)	39	4.5	8.5	12	16	9.0	22
Storage Volume relative to Diesel (excluding tank system)	1.0	8.6	4.5	3.4	2.5	4.3	1.7

Battery Technology is only practical/feasible and commercially viable for short voyages close to renewable grid supply, e.g. ferries, leisure and port vessels

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A Li-ion battery system* compared to a Diesel fuel tank:

System Volume:
Diesel equivalent**
x92

System Weight:
Diesel equivalent**
KG x108

A Container Ship illustration:

Post-Panamax
container ship energy use on a 14 day voyage

Cargo capacity
Volume: 10,000 TEU (twenty foot container equivalent)

Mass: 120,000 tonnes *:**

Diesel Fuel Tank
Volume: 140 TEU = 1.4% of capacity
Mass: 3,920 tonnes / 3% of capacity

Battery
Volume: 13,000 TEU = **130% of capacity**
Mass: 420,000 tonnes / **350% of capacity**

Not Feasible

TEU – Twenty foot Equivalent Unit
DWT – Deadweight tonnage = cargo capacity

Source: * https://corvusenergy.com/products/corvus-blue-whale/, **Diesel assumed 46MJ/KG / 39MJ/l *** https://www.morethanshipping.com/fuel-costs-ocean-shipping/,

A one page overview on the suitability of the different alternative fuels for marine application

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	BioFuels	eDiesel	eHydrogen	eMethane	eMethanol	eAmmonia
Well to Wake Carbon Potential	Zero to Medium	Zero	Zero	Zero but methane slip	Zero	Zero
Tank to Wake Carbon Potential (as well as legislation and emissions trading risks)			Zero			Zero
Scalability	Unlikely	Yes, but air carbon capture long way off maturity	Yes	Yes, but air carbon capture long way off maturity	Yes, but air carbon capture long way off maturity	Yes. Global commodity already, shipped today
Renewable Electricity Cost (MJ/MJ stored)	Low (depends on process)	2.1	1.7	1.8	2.3	1.9
Storage Volume (relative to Diesel, exc. tank and boil off)	~1	1.0	4.5 – 8.6	1.7 – 4.3	2.5	3.4
Application Development	Drop-in	Drop-in	Retrofit/New Build First ships running with fuel cells Engines under development	Drop-in but methane (25 GWP) slip solution not available	Retrofit/New Build Proven in service	Retrofit/New Build First ship in 2025 Engines and fuel cells under development
Transition Pathway		Carbon capture unlikely	Blue hydrogen	No mid term solution	Carbon capture unlikely	Blue ammonia

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Conclusions on Marine Decarbonisation

- Marine currently uses around 240 million tonnes per year of oil and it needs to reduce the total carbon emissions 50% by 2050, with each ship reducing its Carbon Intensity by 70%
  - Energy source/fuel needs to decarbonise
- Hydrogen and batteries are solutions for short range ships (e.g. ferries, port bound vessels) but not for ocean going vessels which make up the majority of the marine sector energy use
- Ammonia is the likely future majority fuel for the marine sector
  - Grey ammonia is currently produced already shipped around the world at large scale
    - Existing 180 million tonnes per year market, of which 20 million tonnes are shipped globally
    - Additional circa 240Mtoe (Blue or Green) needed by 2050 with significant infrastructure investment by suppliers and ports
  - Engines and fuel cell solutions are under development, expect demo ships in next 4 years

Yara plans CO2-free ammonia plant in farming and shipping shift

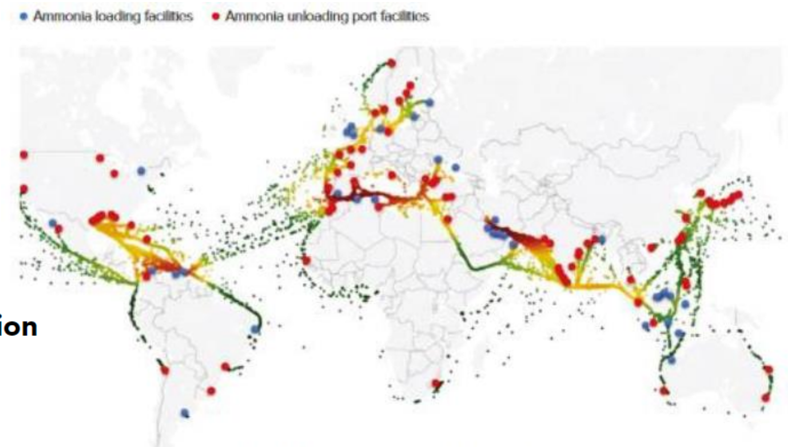
0.5 million tonnes per year

Saudi Arabia to export renewable energy using green ammonia

1.2 million tonnes per year

Asian RE Hub — now 26 GW and $36 billion

9.9 million tonnes per year



https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/

Source: Yara plans CO2-free ammonia plant in farming and shipping shift | Reuters, Shipping players to develop ammonia-powered vessel | The DCN
Saudi Arabia to export renewable energy using green ammonia - Ammonia Energy Association, Green ammonia in Australia, Spain, and the United States - Ammonia Energy Association