Future visions on maritime energy solutions

and some recent research results

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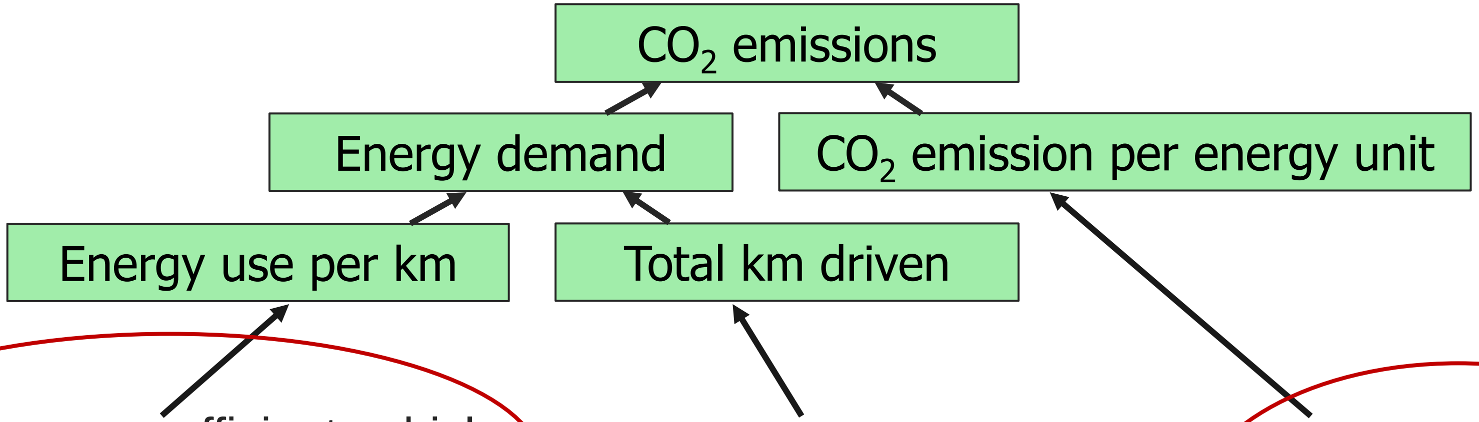
2022-09-01

Main strategies to reduce CO_2 emissions from the transportation sector



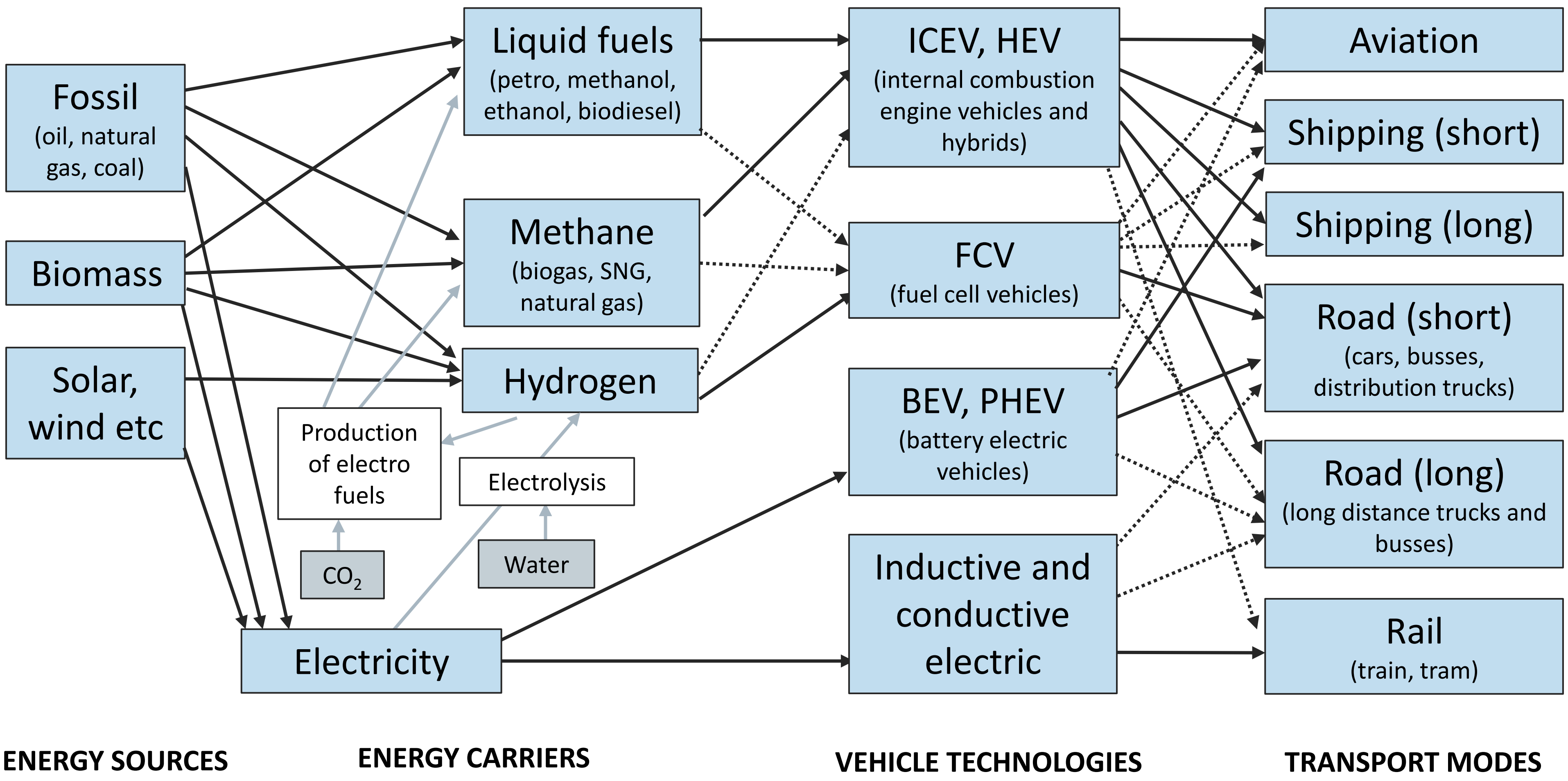
1. More energy-efficient vehicles (incl. hybridization, electrification)
2. Change into more energy-efficient transport modes (e.g. train vs plane, bikes or public transport vs cars)
3. Fuel-efficient driving (Eco-driving, platooning)

4. Increase number of passengers and goods per vehicle or ship
5. City planning for reduced transport demand
6. Locally produced goods
7. Travel free days
8. Longer trucks, larger ships (if filled)
9. De-couple the connection between transport need and economic growth

10. Introduce fuels with lower CO_2 emissions than current fuels

FOCUS IN MY RESEARCH

Different fuels and vehicle technology options are differently well suited for different transport modes



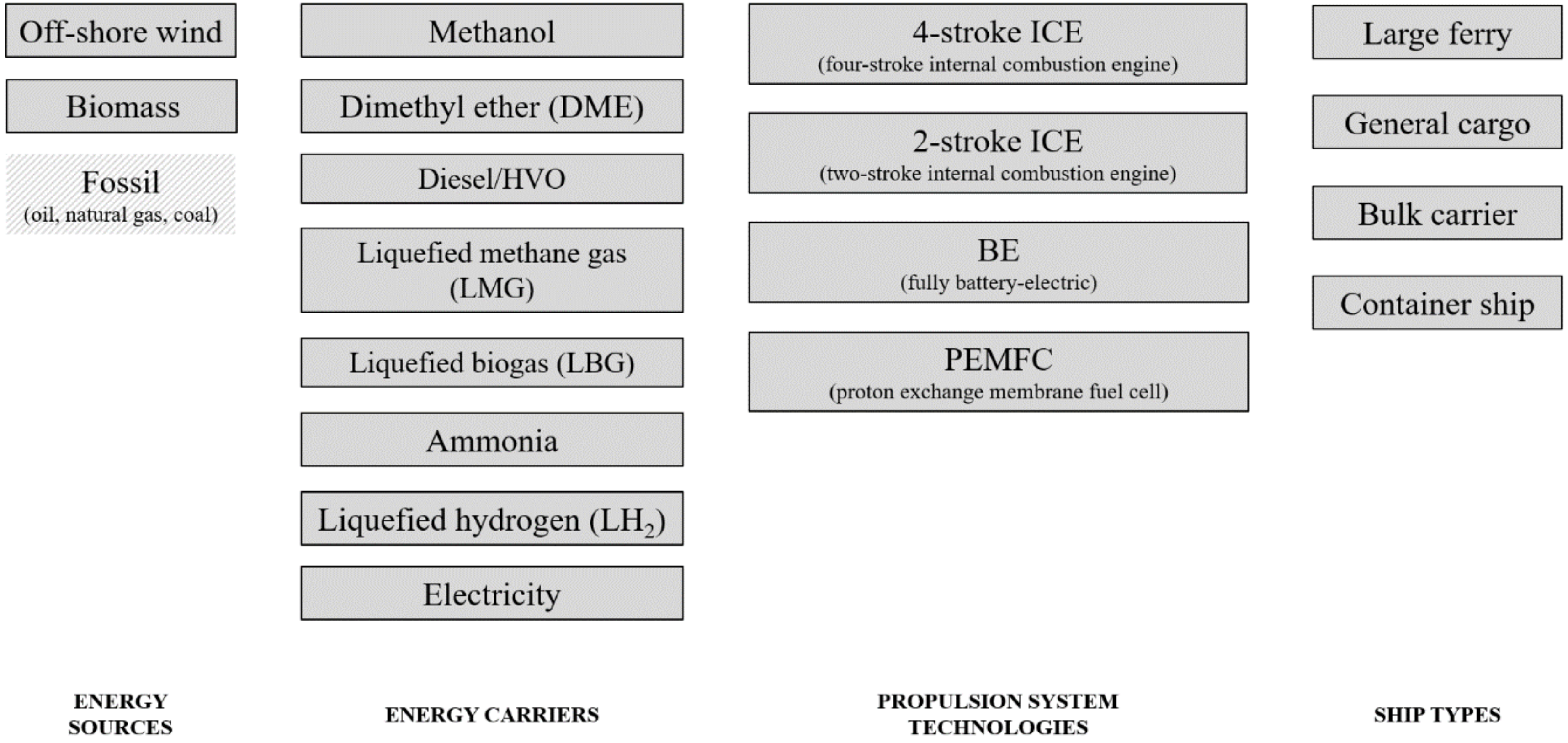
Cost-comparisons
Total cost of ownership
focusing on biofuels, electrolytic hydrogen and electrofuels in the shipping sector

Total cost of ownership (TCO)
- fuel production,
- fuel infrastructure,
- annuitized investments in propulsion technologies,
- energy storage onboard, and
- reduced income due to less cargo space.

Korberg AD, Brynolf S, Grahn M, Skov IR (2021). Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Renewable and Sustainable Energy Reviews 142: 110861

Overview of investigated options

Fossil options are not assessed but included as a comparison



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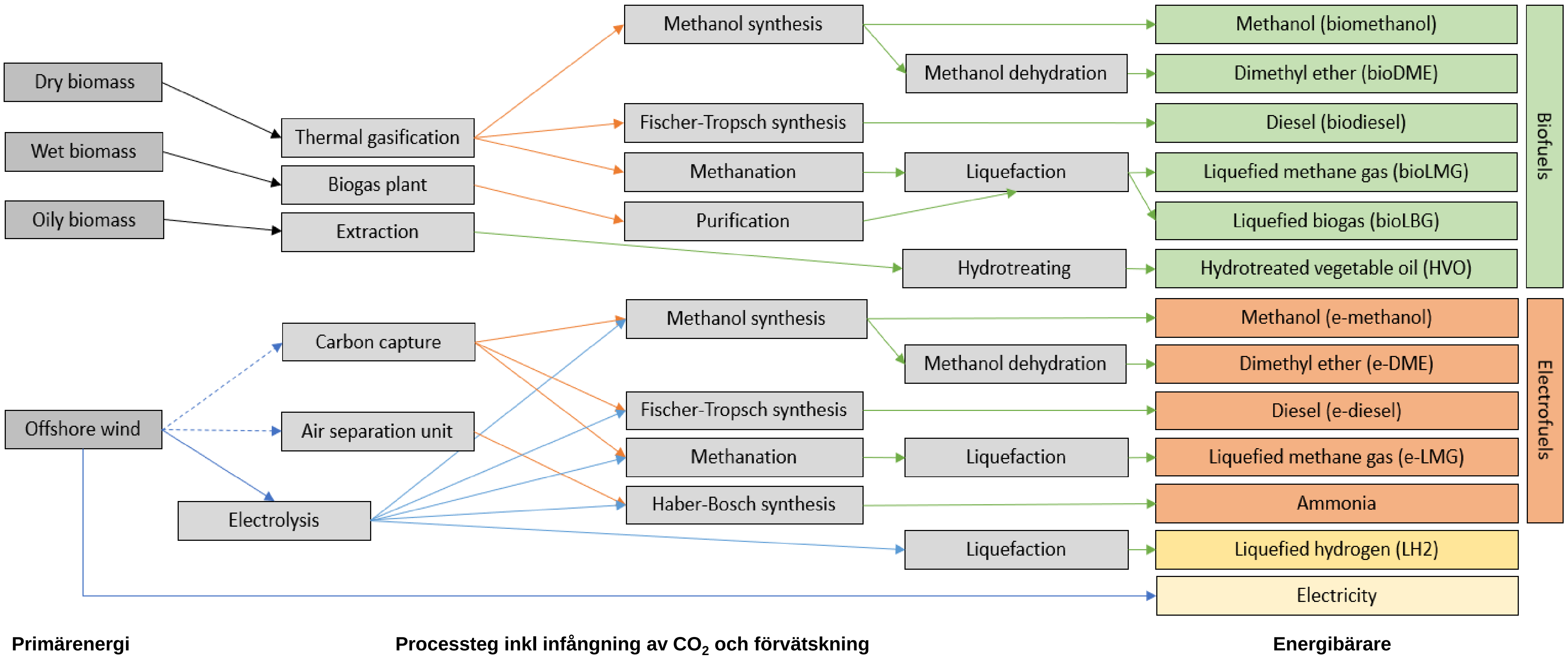
Considered fuels for the shipping sector



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Total cost of ownership (TCO)

For the ship category ”Large ferries”

Color coding: within each fuel category (biofuels, electrofuels) and utilisation rate to highlight the cheapest option (4 blocks).

Results

- Methanol shows lowest cost within both biofuels and electrofuels (but DME, HVO, and ammonia very close).
- Combustion engines (ICE) always lower TCO than fuel cells (FC), but similar for long distance.
- BE lower TCO than all electrofuel options and almost all FC options (only for this ship category, not for larger ship categories).

Acronyms used:
MGO= Marine gas oil (low sulpur bunker oil)
DME= Dimethyleter (from gasification of wood)
LMG= Liquefied methane gas (from gasification of wood)
LBG= Liquefied biogas (from digestion of household waste)
HVO= Hydrotreated vegetable oil
LH2= liquefied hydrogen
ICE= Internal combustion engine propulsion
FC= fuel cell propulsion
BE= battery electric propulsion

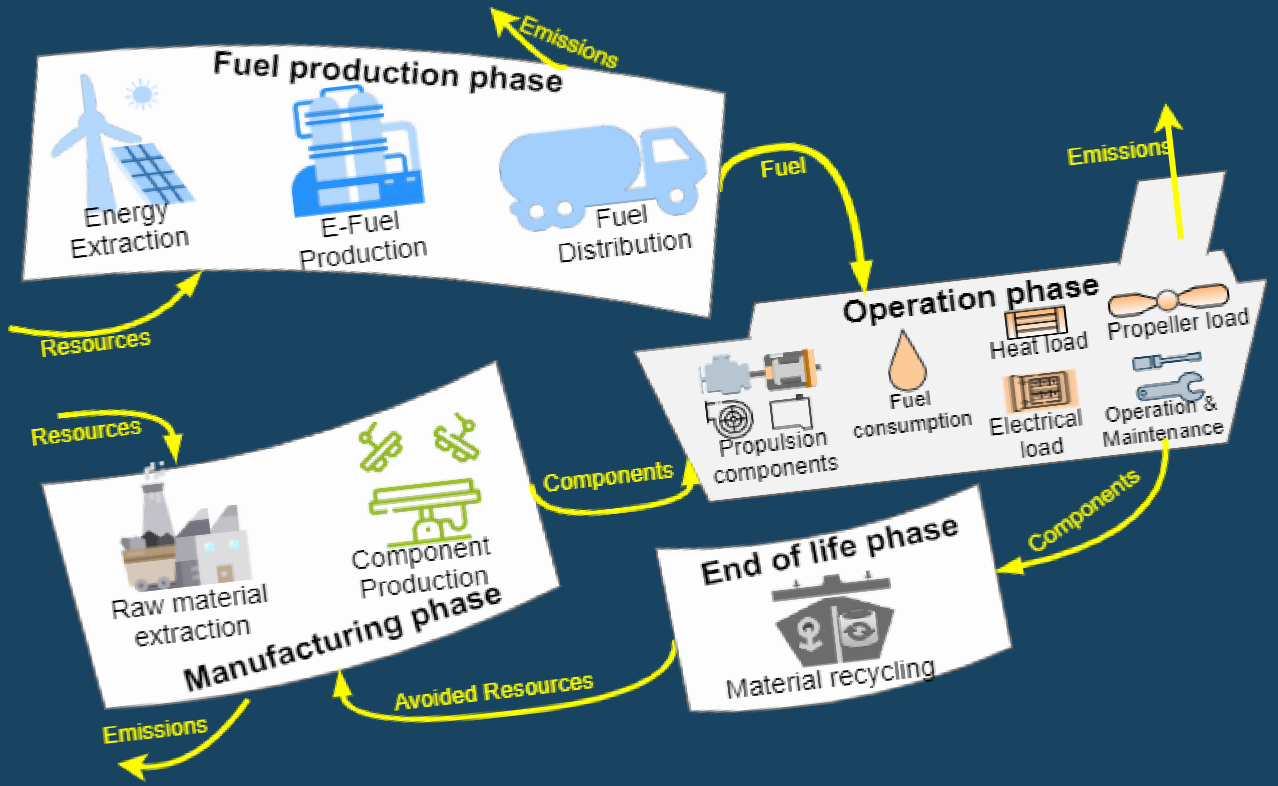
Costs include: fuel production, fuel infrastructure, annuitized investments in propulsion technologies, energy storage and reduced income due to less cargo space.

M€/yr

	Utilisation/trip	Short			Long		
	Propulsion	ICE	FC	BE	ICE	FC	BE
	MGO	0.9			2.4		
Biofuels	Biomethanol	2.0	4.2		5.7	7.2	
Biofuels	BioDME	2.3			6.2		
Biofuels	Biodiesel	2.7			7.6		
Biofuels	BioLMG	3.0	4.9		7.8	8.7	
Biofuels	BioLBG	2.8	4.8		7.4	8.4	
Biofuels	HVO	2.4			6.8		
Electrofuels	E-methanol	3.3	5.3		9.7	10.3	
Electrofuels	E-DME	3.7			10.3		
Electrofuels	E-diesel	4.3			12.5		
Electrofuels	E-LMG	4.3	5.9		11.8	11.9	
Electrofuels	Ammonia	3.7	5.5		10.2	10.6	
	LH_2	4.7	5.3		13.0	11.9	
	Electricity			2.8			8.3

Low TCO M€/year
High TCO M€/year

Source: Korberg AD, Brynolf S, Grahn M, Skov IR (2021). Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Renewable and Sustainable Energy Reviews 142 (2021) 110861



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Life Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping

Kanchiralla, FM, Brynolf S, Malmgren E, Hansson J, Grahn M (2022) Life Cycle Assessment and Costing of Fuels and Propulsion Systems in Future Fossil-Free Shipping. Environmental Science and Technology https://doi.org/10.1021/acs.est.2c03016

Scope covered in the article

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Compared electrofuels from life cycle perspective in terms of:

1. Energy utilization rate
2. Climate change (GWP20 and GWP100).
3. Other Environmental impacts
4. Life cycle cost
5. Carbon abatement cost

Other environmental impacts

- *Acidification (mol H+ eq)*
- *Ecotoxicity, freshwater (CTUe)*
- *Eutrophication, marine (kg Neq)*
- *Eutrophication, terrestrial (mol Neq)*
- *Ozone depletion (kg CFC-11)*
- *Human toxicity, cancer effects (CTUh)*
- *Human toxicity, non-cancer effects (CTUh)*
- *Particulate matter (disease inc.)*
- *Photochemical ozone formation (kgNMVOCeq)*

Case study:
Stena Germanica

Functional unit:
Round trip
Gothenburg – Kiel - Gothenburg

Time horizon:
2030

Cost flow:
Euros with base year 2021

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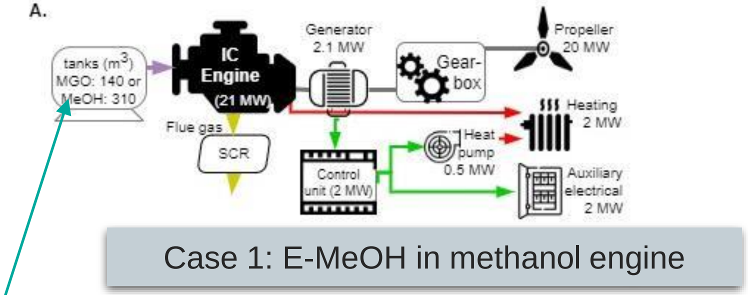
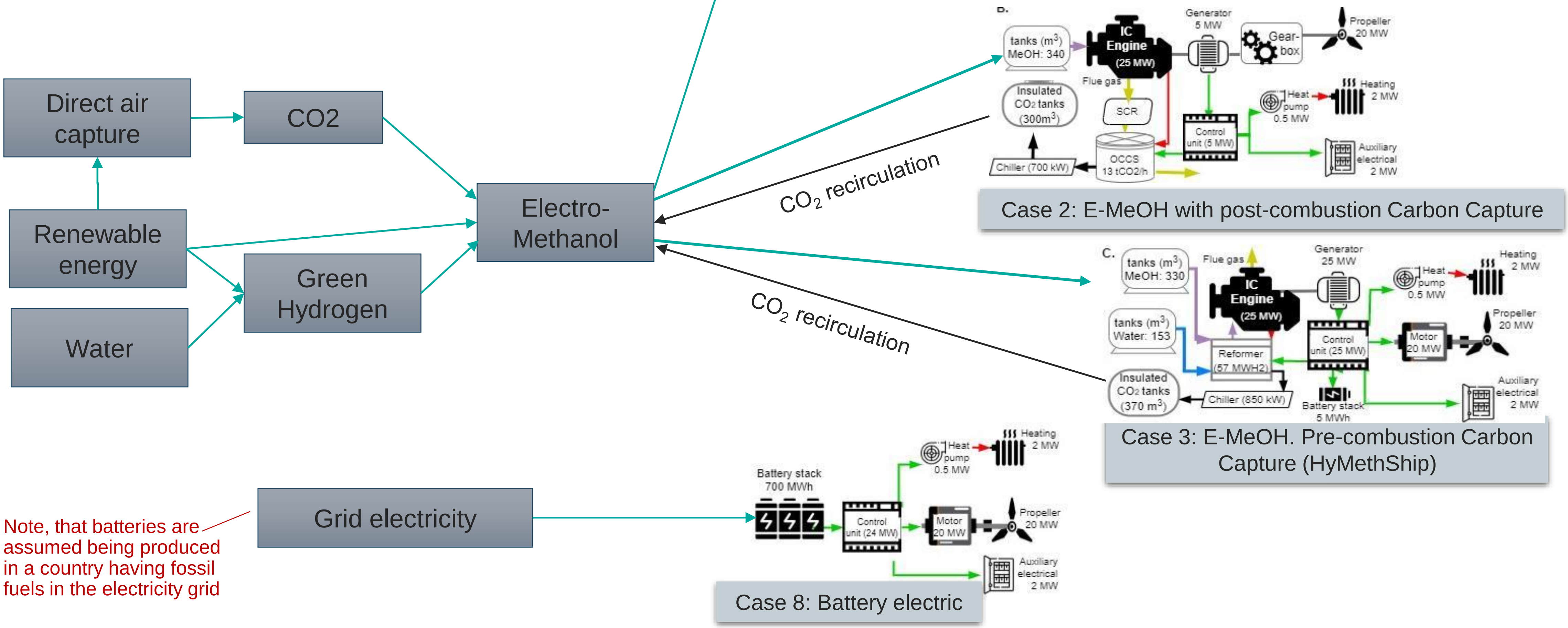
Decarbonization solutions (Case 1 to 3, and 8)





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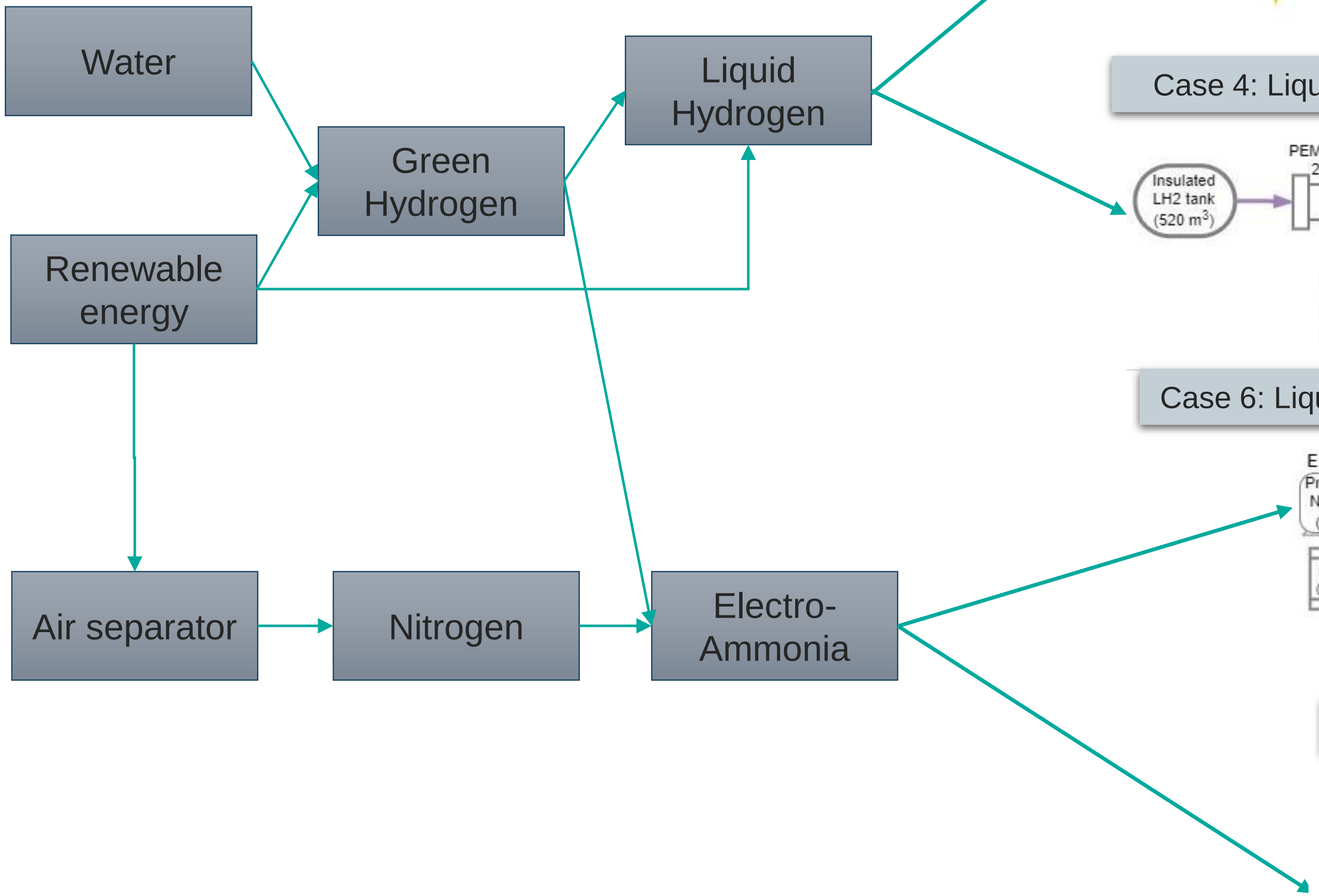
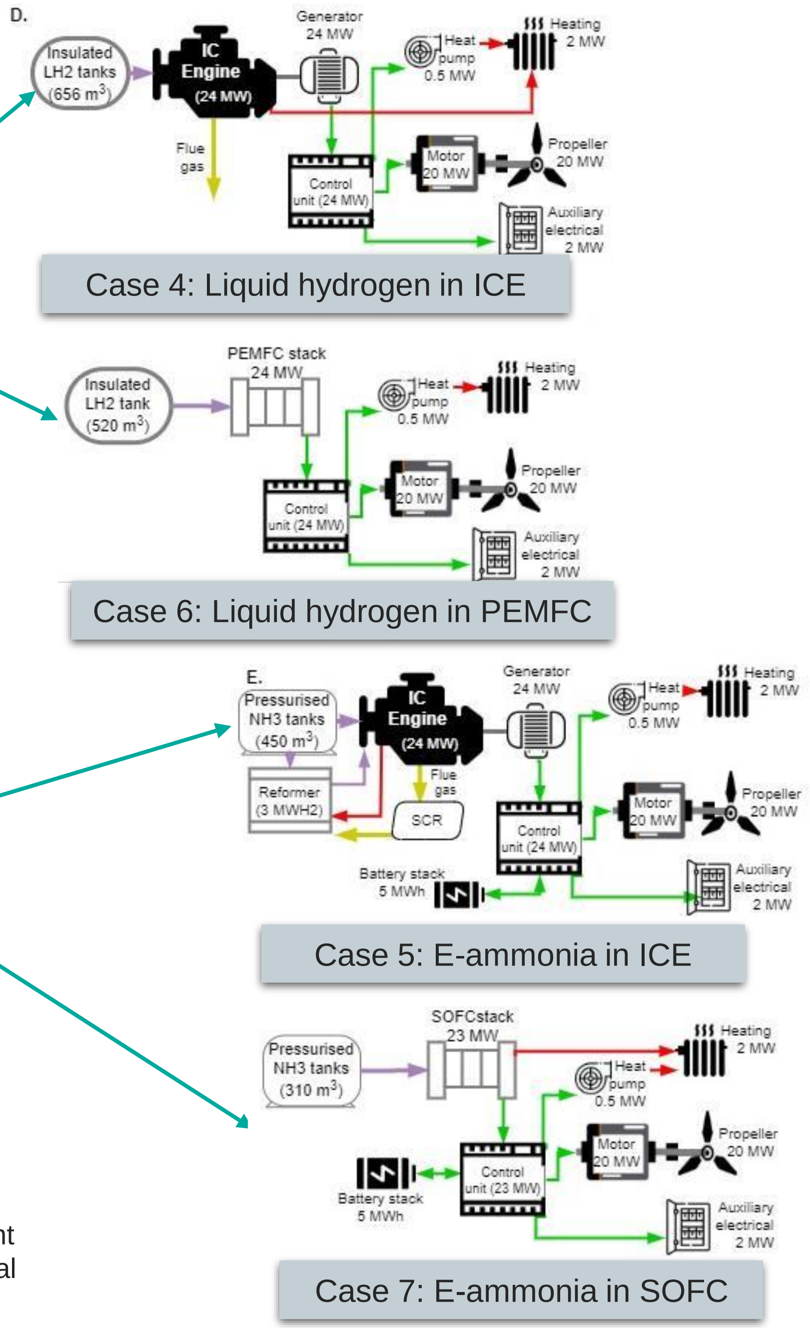
Decarbonization solutions (Case 4 to 7)





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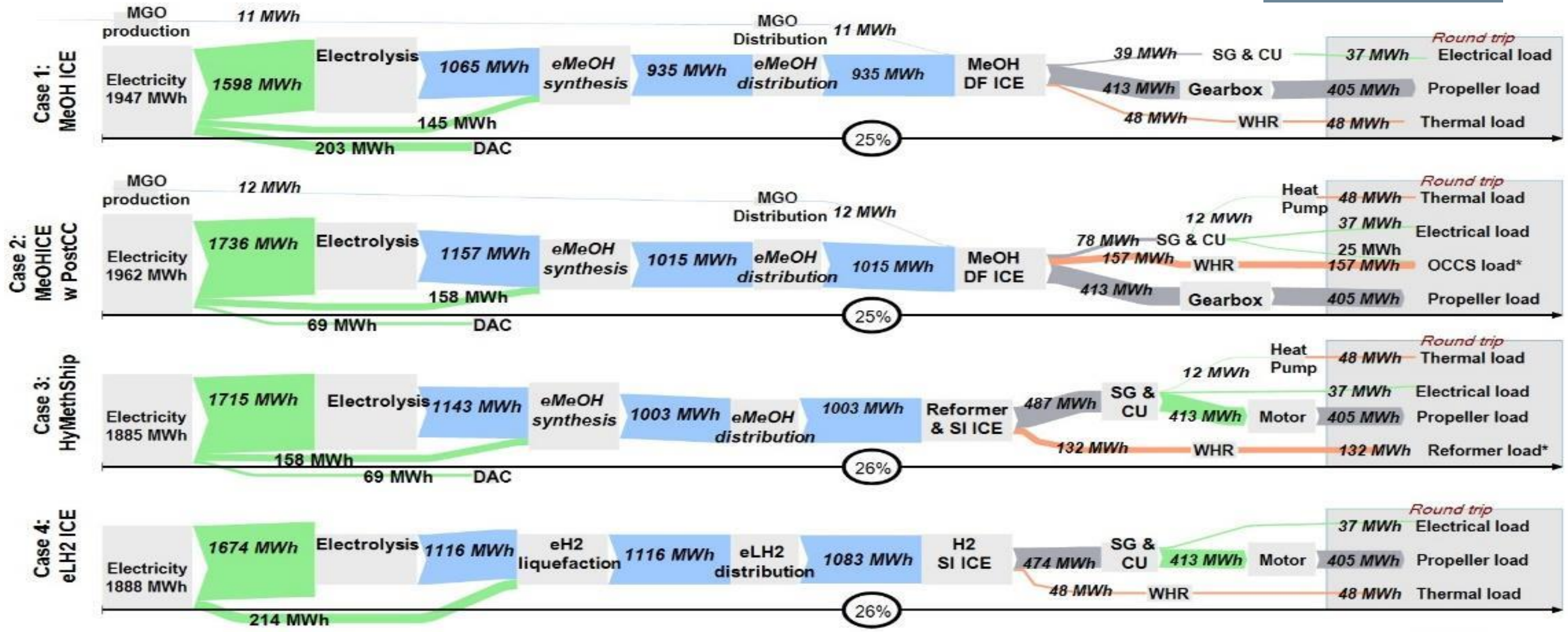
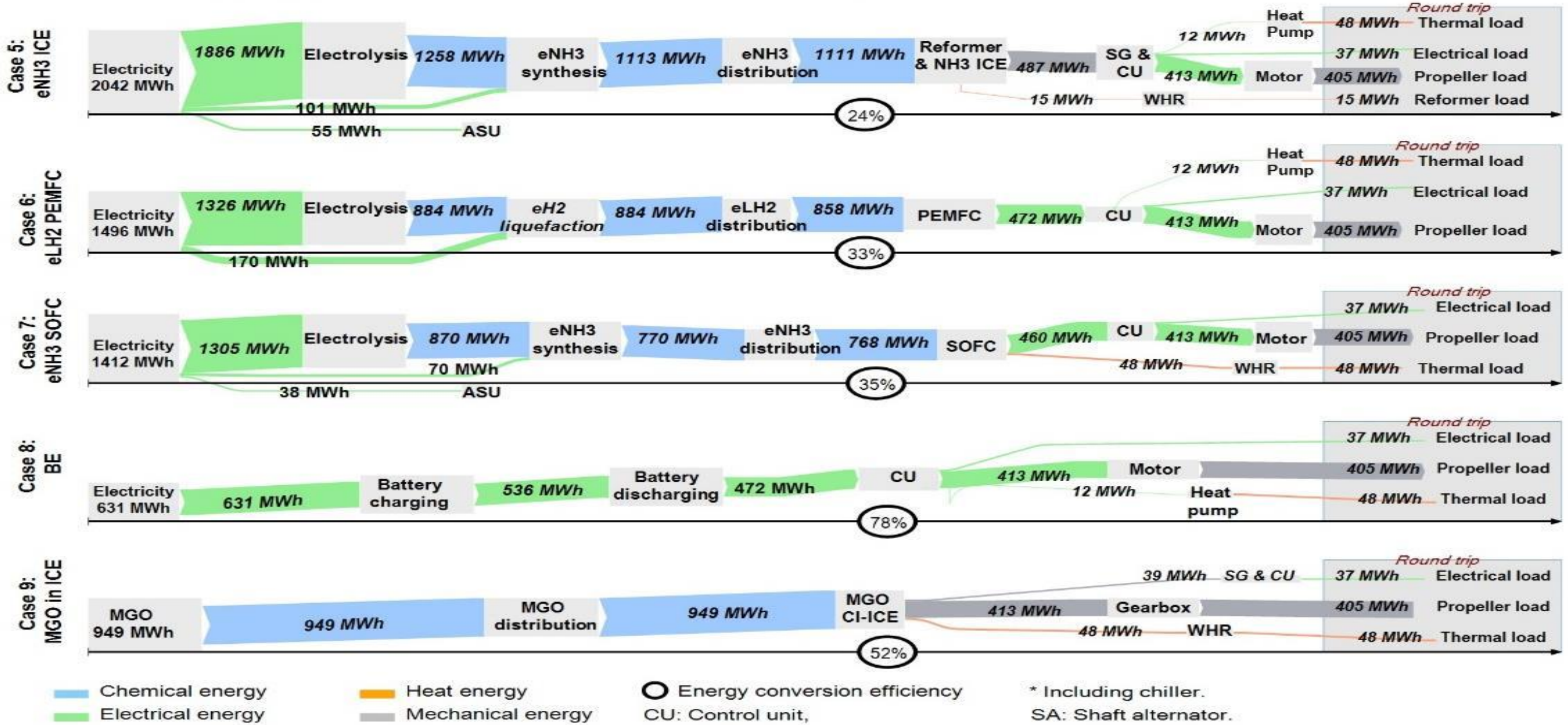
Energy conversion efficiency





System energy efficiencies:
24-36% for all ICE cases,
33-35% for all both FC cases
78% for BE
52% for fossil MGO

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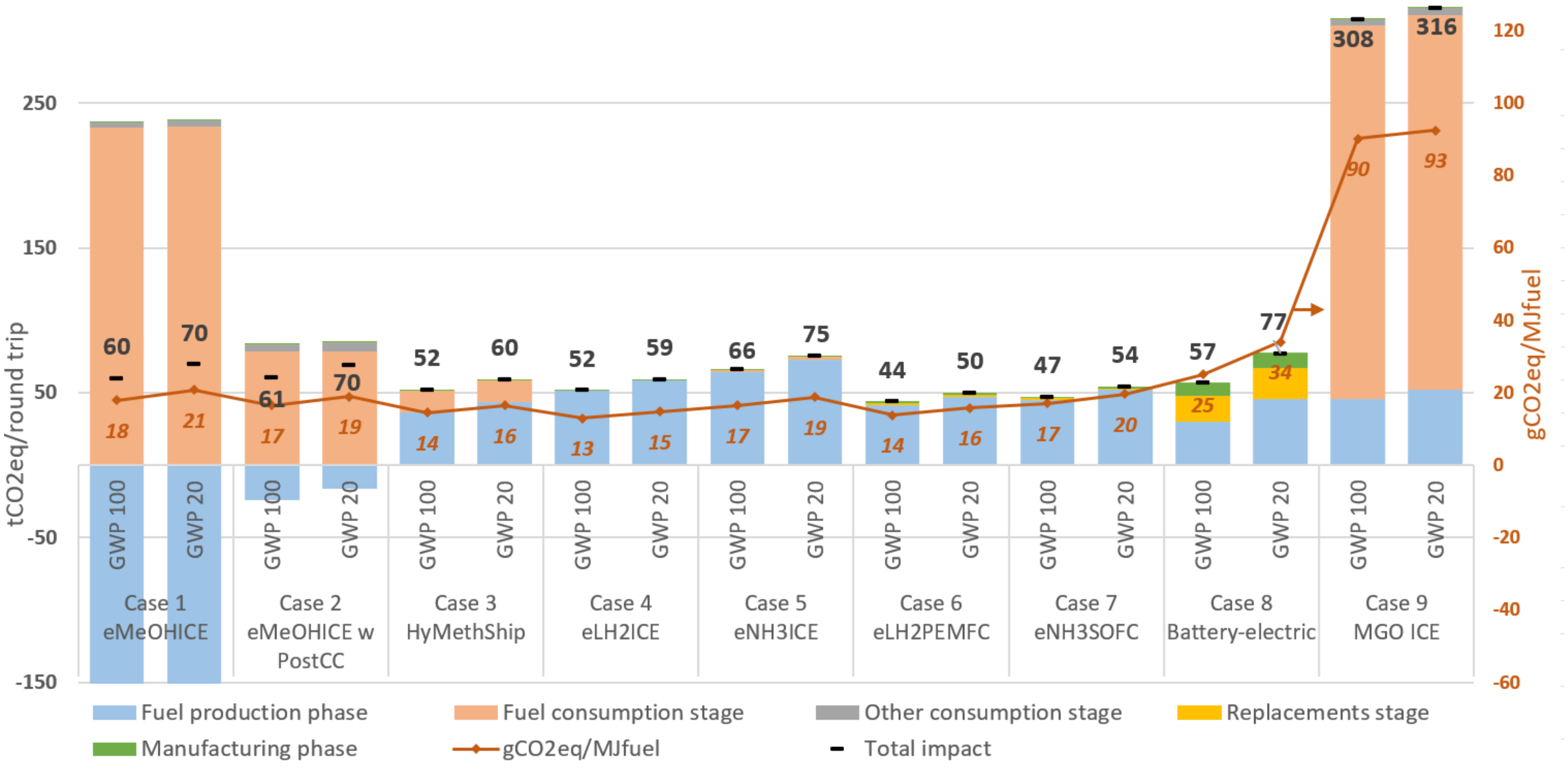
Global warming potential



- GWP20 always slightly higher than GWP100.
- E-methanol assuming DAC balancing CO2 from the combustion.
- MGO the highest GWP.
- Otherwise, relatively similar GWP for all cases.

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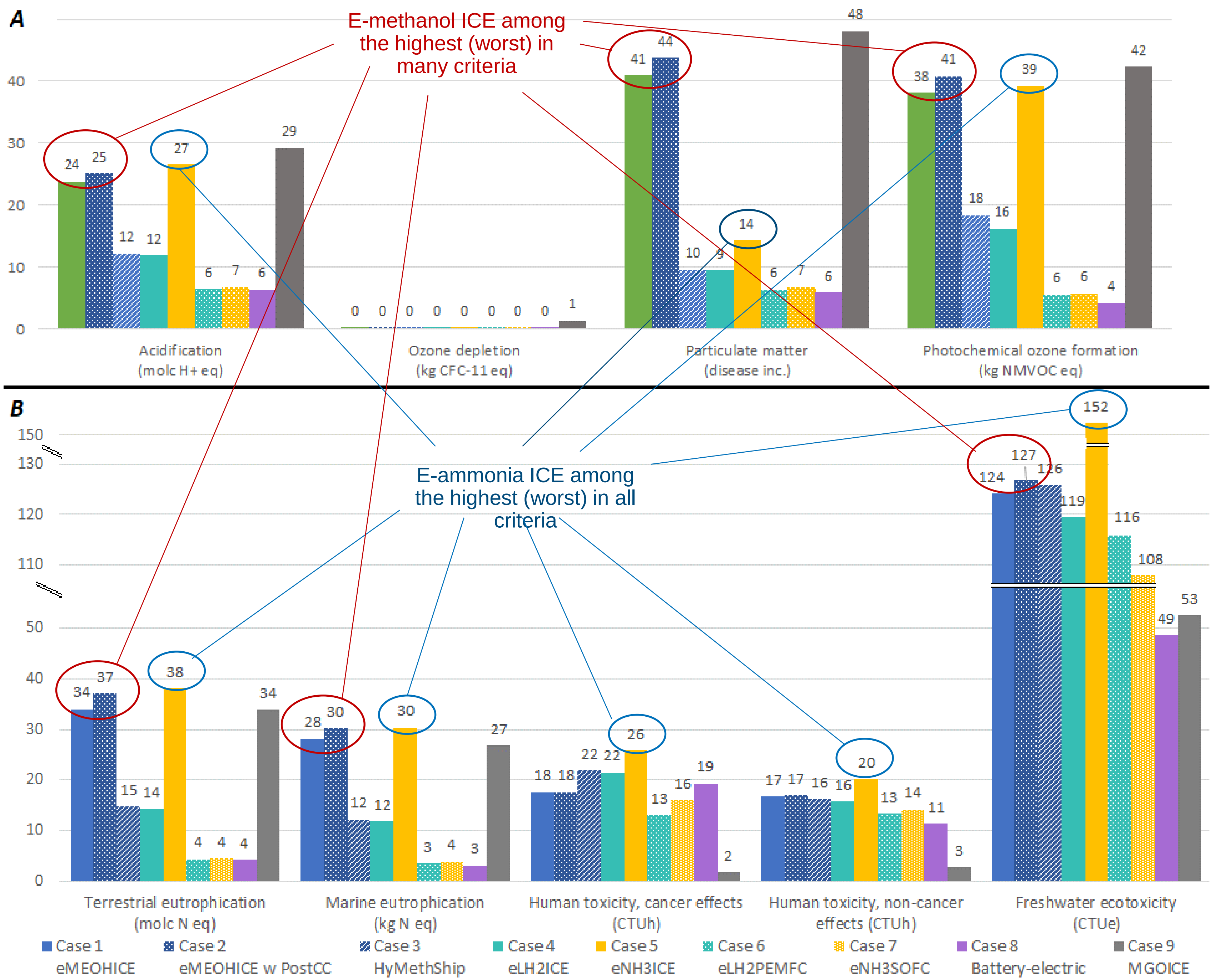

Other environmental impacts

Hydrogen and battery electric (BE) typically perform the best

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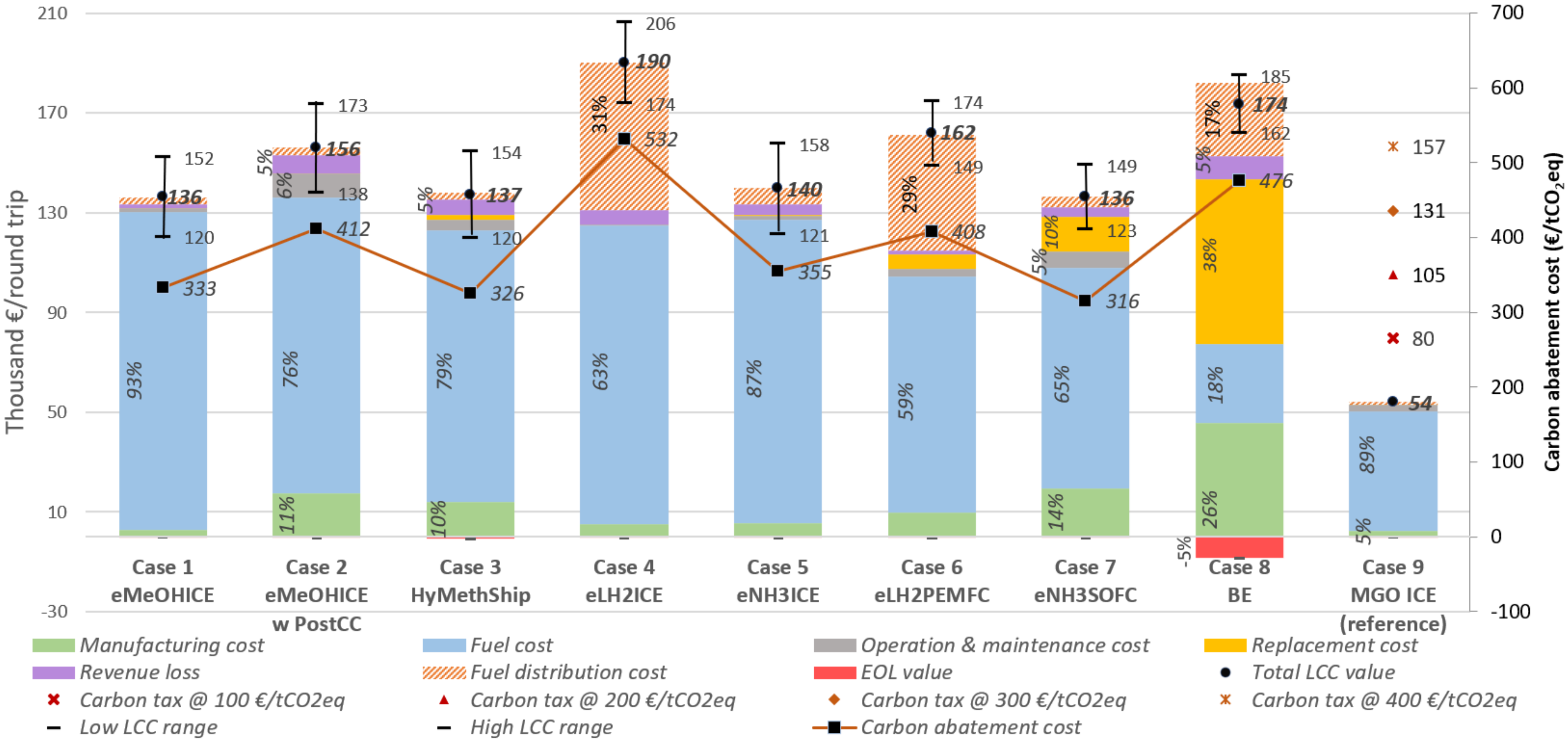
Economic impact assessment

$$\text{Carbon abatement cost}(€/tCO_2eq) = \frac{\text{LCC relative to reference } (€/\text{functional unit})}{\text{Life cycle GWP relative to reference } (tCO_2eq/\text{functional unit})}$$



- E-methanol and E-ammonia lowest cost of the studied cases.
- There is a need for a carbon fee of 300-400 €/tCO2 for e-fuels to compete with fossil MGO.

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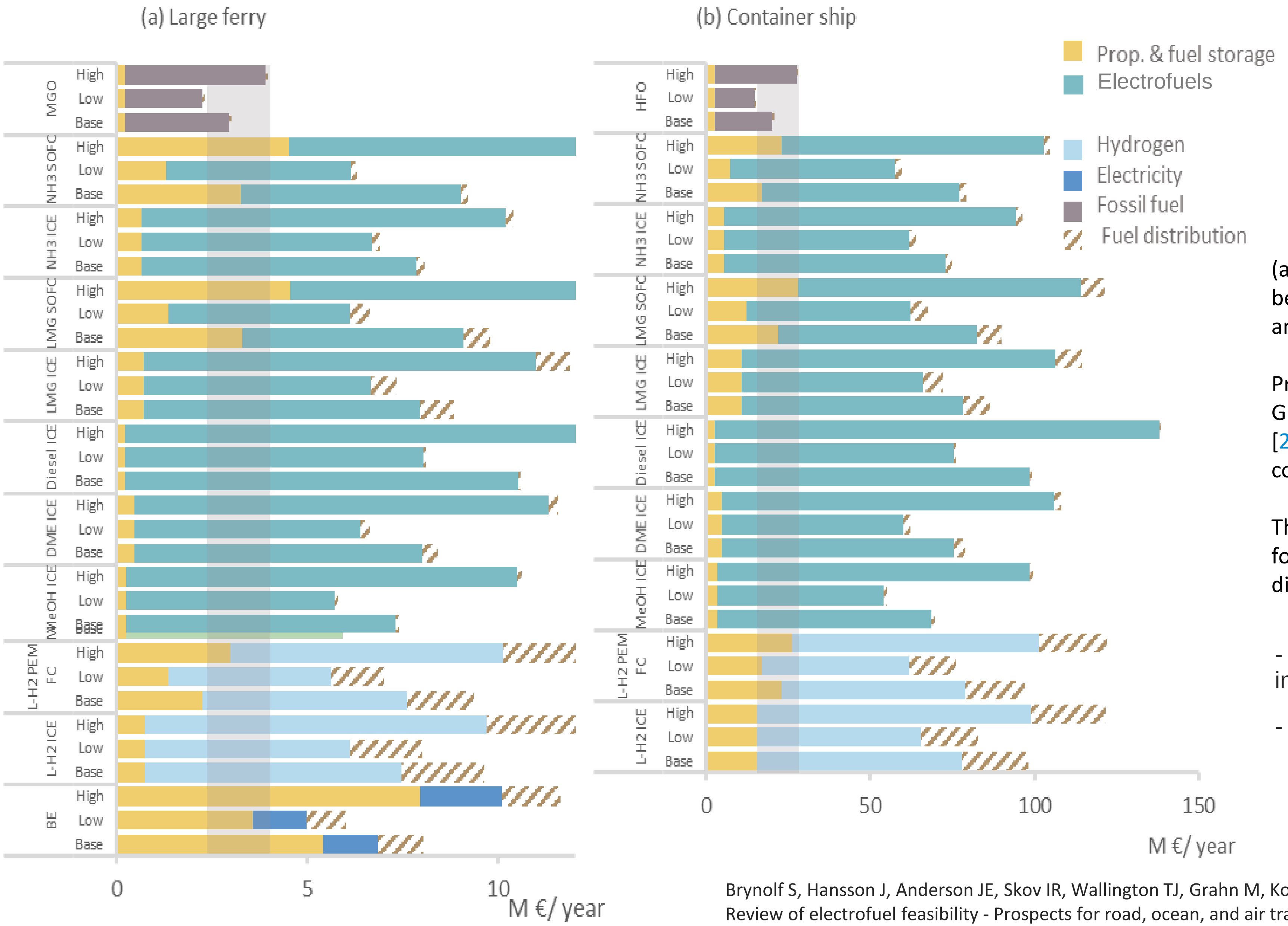
Cost-comparison fuels, vehicles and fuel infrastructure focusing on electrolytic hydrogen and electrofuels

Brynolf S, Hansson J, Anderson JE, Skov IR, Wallington TJ, Grahn M, Korberg AD, Malmgren E, Taljegård M (2022). Review of electrofuel feasibility - Prospects for road, ocean, and air transport. Progress in Energy, 4 (4), 042007.

Mobility costs (approx 2030) for different electrofuels, electrolytic hydrogen and battery electric propulsion (BE) and marine gas oil (MGO)



(a) large ferry with 1260 h of annual operation and 6 h between bunkering and (b) container ship with 5280 h of annual operation and 480 h between bunkering.

Production costs for e-fuel and bio-e-fuel were taken from Grahn *et al* [6] all other data were taken from Korberg *et al* [27] considering a 3% discount and technical lifetimes for the components.

The shaded area represents the cost of the conventional fossil alternative (MGO ICE, HFO ICE), also including a fuel distribution cost.

- LH2 FC in parity with LH2 ICE, (FC higher investment cost but less fuel needed)
- Difficult to compete with conventional fossil fuels.

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General reflections on future maritime energy solutions

- Three types of energy carriers have the potential to substantially reduce the fossil CO_2 emissions from the transportation sector:
  - fuels including carbon atoms as **biofuels/electrofuels**,
  - fuels without carbon **hydrogen/ammonia**, and
  - **electricity**.

- It is most likely that parallel solutions will be developed, e.g.
  - There are many advantages for electric solutions in cities (Battery electric and hydrogen in fuel cells). Aspects like a reduction of NOx, soot, and noise. I forsee it is likely different electric/hydrogen solutions dominating close to cities (also applies to electric buses, cars, delivery trucks, trams, metro etc).
  - There are several challenges for electrifying long-distance transport (especially ships and aircraft). Electrofuels (including e-ammonia) may complement the world’s limited amount of biofuels for these transport modes. (My research points at that LNG produced from fossil natural gas is a short term solution). Hydrogen in combustion engines is a joker difficult to forsee.


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