E-fuels: the big picture, focusing on the role of electro-methanol

10 insights from our research on under what circumstances electrofuels could become an interesting option in the fuel mix of the transportation sector

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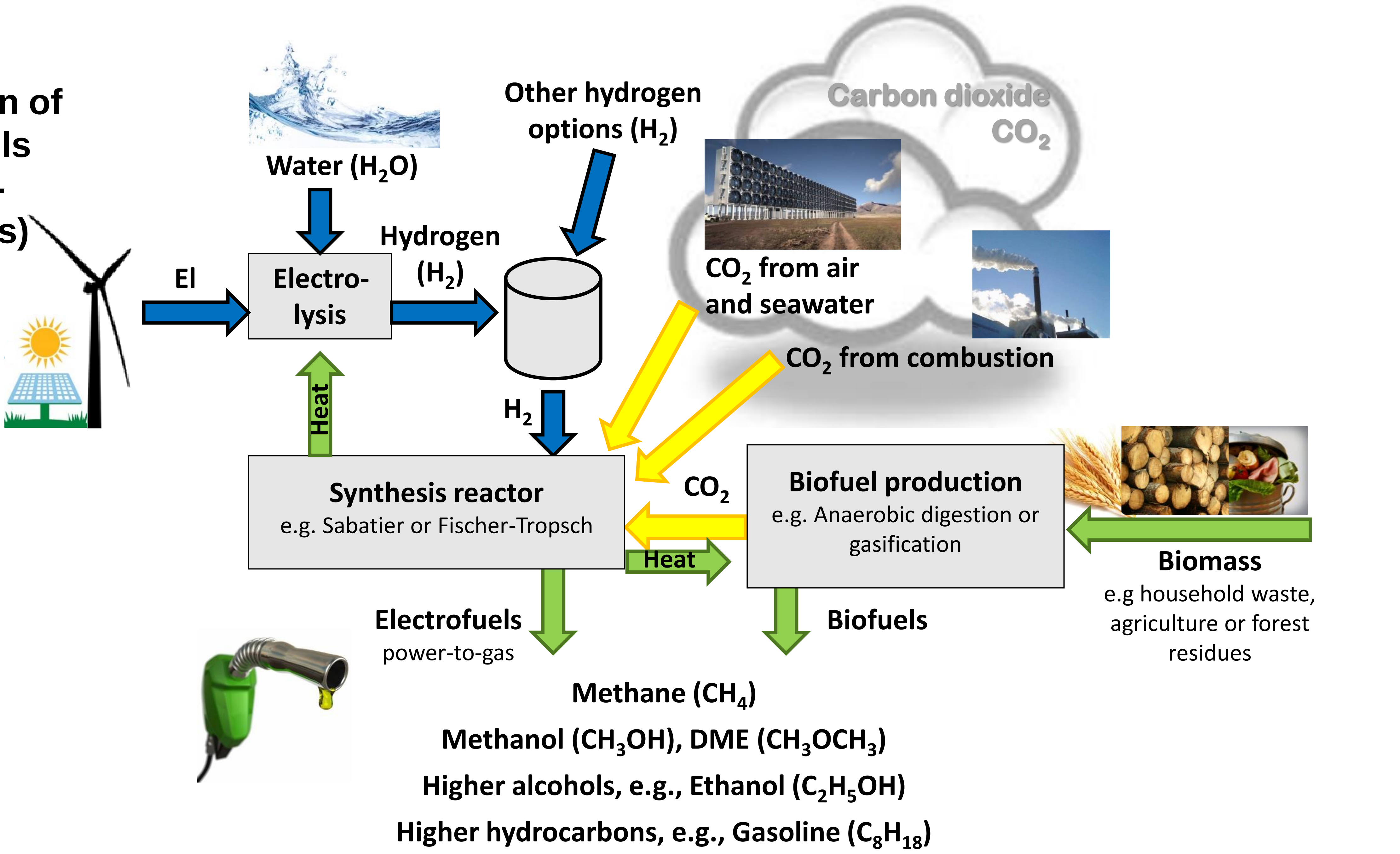
Production of electrofuels (power-to-gas/liquids)



The big picture: under what circumstances could electrofuels become cost-competitive?

Review of electrofuels production cost

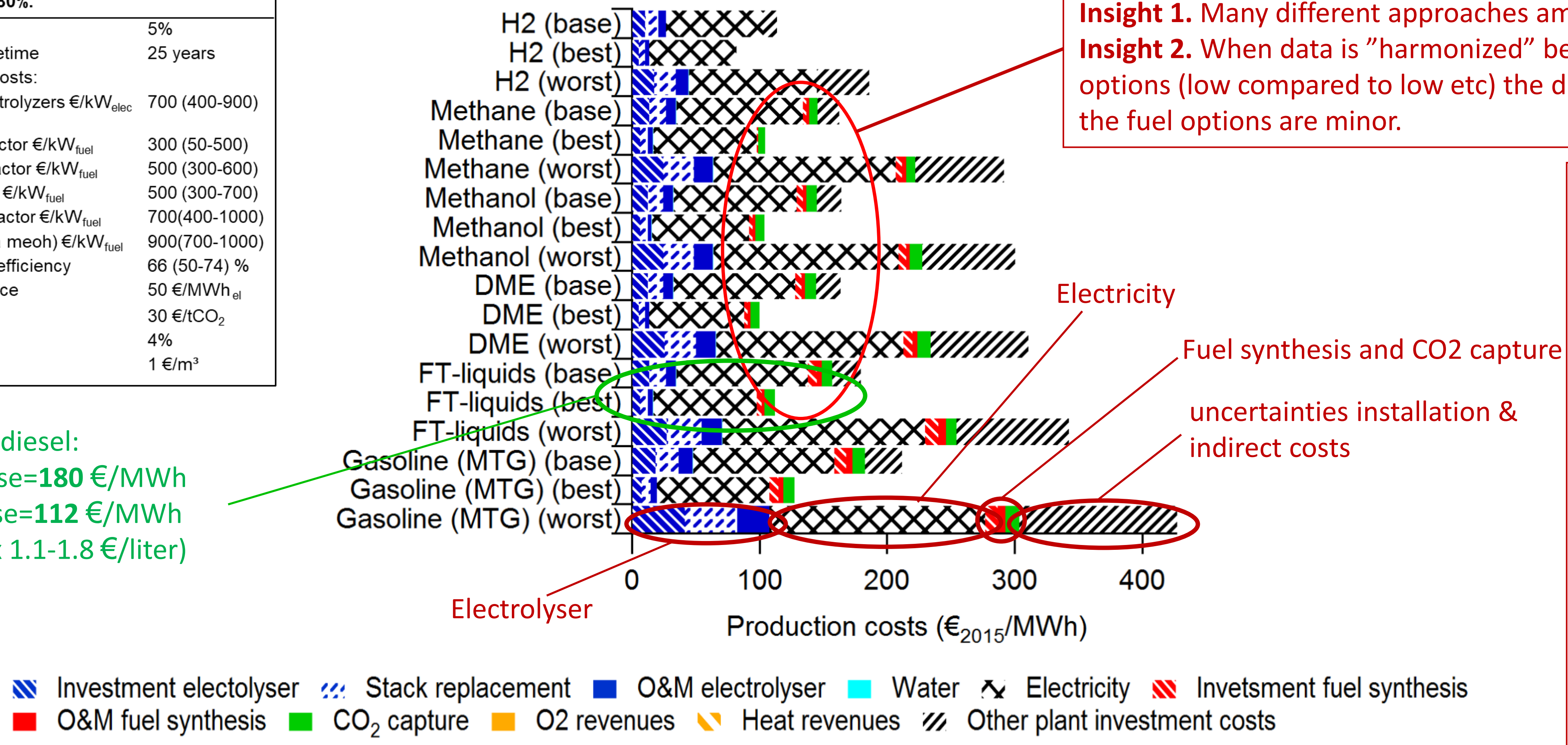
Ref: Brynolf S, Taljegård M, Grahn M, Hansson J. (2018). Electrofuels for the transport sector: a review of production costs. *Renewable & Sustainable Energy Reviews* 81 (2) 1887-1905.

Literature review, data differs. Production cost 2030 (mature costs) different electrofuel options

assuming most optimistic (low/best), least optimistic (high/worst) and median values (base)

Parameters assumed for 2030, 50 MW reactor, CF 80%.	
Interest rate	5%
Economic lifetime	25 years
Investment costs:	
Alkaline electrolyzers €/kW_{elec}	700 (400-900)
Methane reactor €/kW_{fuel}	300 (50-500)
Methanol reactor €/kW_{fuel}	500 (300-600)
DME reactor €/kW_{fuel}	500 (300-700)
FT liquids reactor €/kW_{fuel}	700(400-1000)
Gasoline (via meoh) €/kW_{fuel}	900(700-1000)
Electrolyzer efficiency	66 (50-74) %
Electricity price	50 €/MWh_{el}
CO_2 capture	30 €/tCO_2
O&M	4%
Water	1 €/m³

Electro-diesel:
base case=**180** €/MWh
best case=**112** €/MWh
(Approx 1.1-1.8 €/liter)

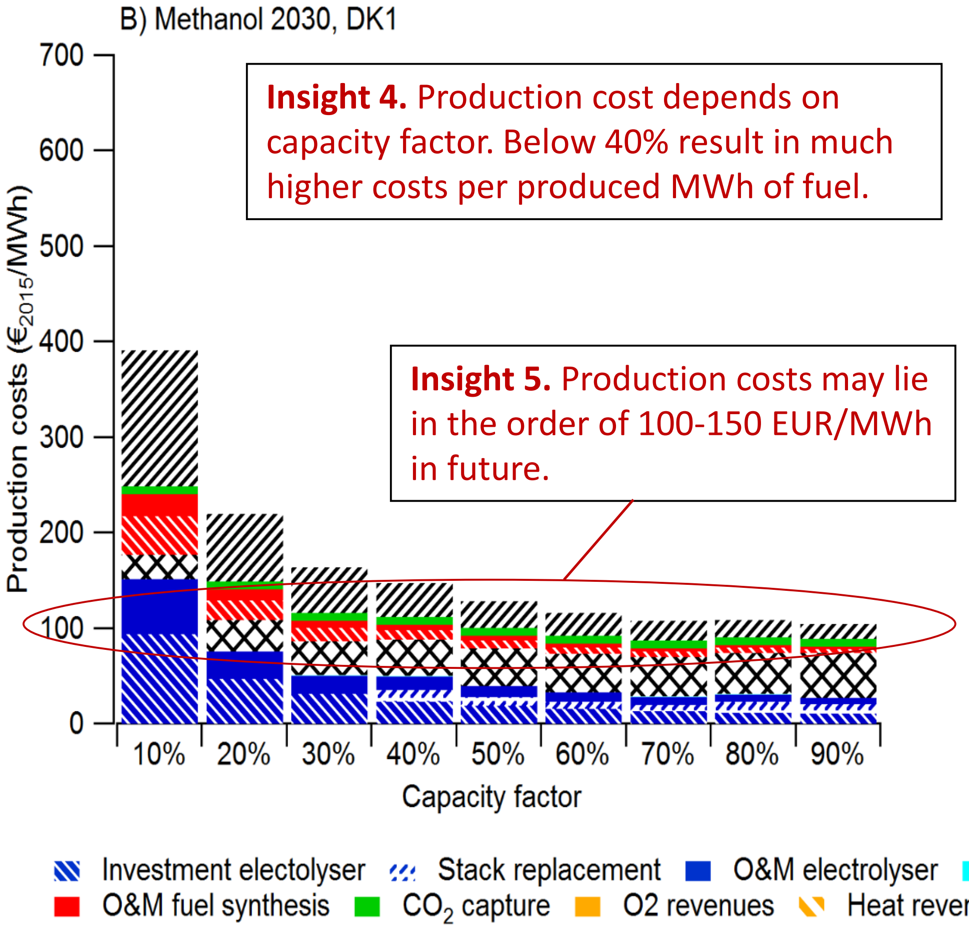


Insight 1. Many different approaches among authors.
Insight 2. When data is "harmonized" between the fuel options (low compared to low etc) the differences between the fuel options are minor.

Insight 3: Costs for electrolyser and electricity dominates
Note. Currently we see a trend towards lower investment cost of electrolyzers (comes with an increased market). Some scenarios also point out a trend towards lower electricity prices in future (if increased variable electricity production).

Source: Brynolf S, Taljegård M, Grahn M, Hansson J. (2018). Electrofuels for the transport sector: a review of production costs. *Renewable & Sustainable Energy Reviews* 81 (2) 1887-1905.

Production cost depend on capacity factor



Insight 4. Production cost depends on capacity factor. Below 40% result in much higher costs per produced MWh of fuel.

Insight 5. Production costs may lie in the order of 100-150 EUR/MWh in future.

Production costs found in literature	
Fossil fuels	40-140
Methane from anaerobic digestion	40-180
Methanol from gasification of lignocellulose	80-120
Ethanol from maize, sugarcane, wheat and waste	70-345
FAME from rapeseed, palm, waste oil	50-210
HVO from palm oil	134-185

Insight 6. Future production of electrofuels have the potential to be cost-competitive to advanced biofuels.
A decrease in investment costs of electrolyzers as well as a reduction of electricity prices would benefit the production cost the most.
Not assess in this study, but a potential revenue from selling excess heat and oxygen would facilitate the cost-competitiveness of electrofuels.

Ref: Brynolf S, Taljegård M, Grahn M, Hansson J. (2018). Electrofuels for the transport sector: a review of production costs. *Renewable & Sustainable Energy Reviews* 81 (2) 1887-1905.

The big picture: under what circumstances could electrofuels become cost-competitive in the shipping sector?

Cost-comparison electrofuels, biofuels, hydrogen and battery electric propulsion

including assessment of total cost of ownership (TCO) for different vessel propulsion technologies for different ship categories

David-Korberg, Brynolf, Grahn, Ridjan-Skov (2020). Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Submitted to Renewable and Sustainable Energy Reviews.

Overview of the investigated options

Fossil options are not assessed but included as a comparison.

ENERGY SOURCES	ENERGY CARRIERS	PROPULSION SYSTEM TECHNOLOGIES	SHIP TYPES
Off-shore wind	Methanol	4-stroke ICE (four-stroke internal combustion engine)	Large ferry
Biomass	Dimethyl ether (DME)	2-stroke ICE (two-stroke internal combustion engine)	General cargo
Fossil (oil, natural gas, coal)	Diesel/HVO	BE (fully battery-electric)	Bulk carrier
	Liquefied methane gas (LMG)	PEMFC (proton exchange membrane fuel cell)	Container ship
	Liquefied biogas (LBG)		
	Ammonia		
	Liquefied hydrogen (LH_2)		
	Electricity		

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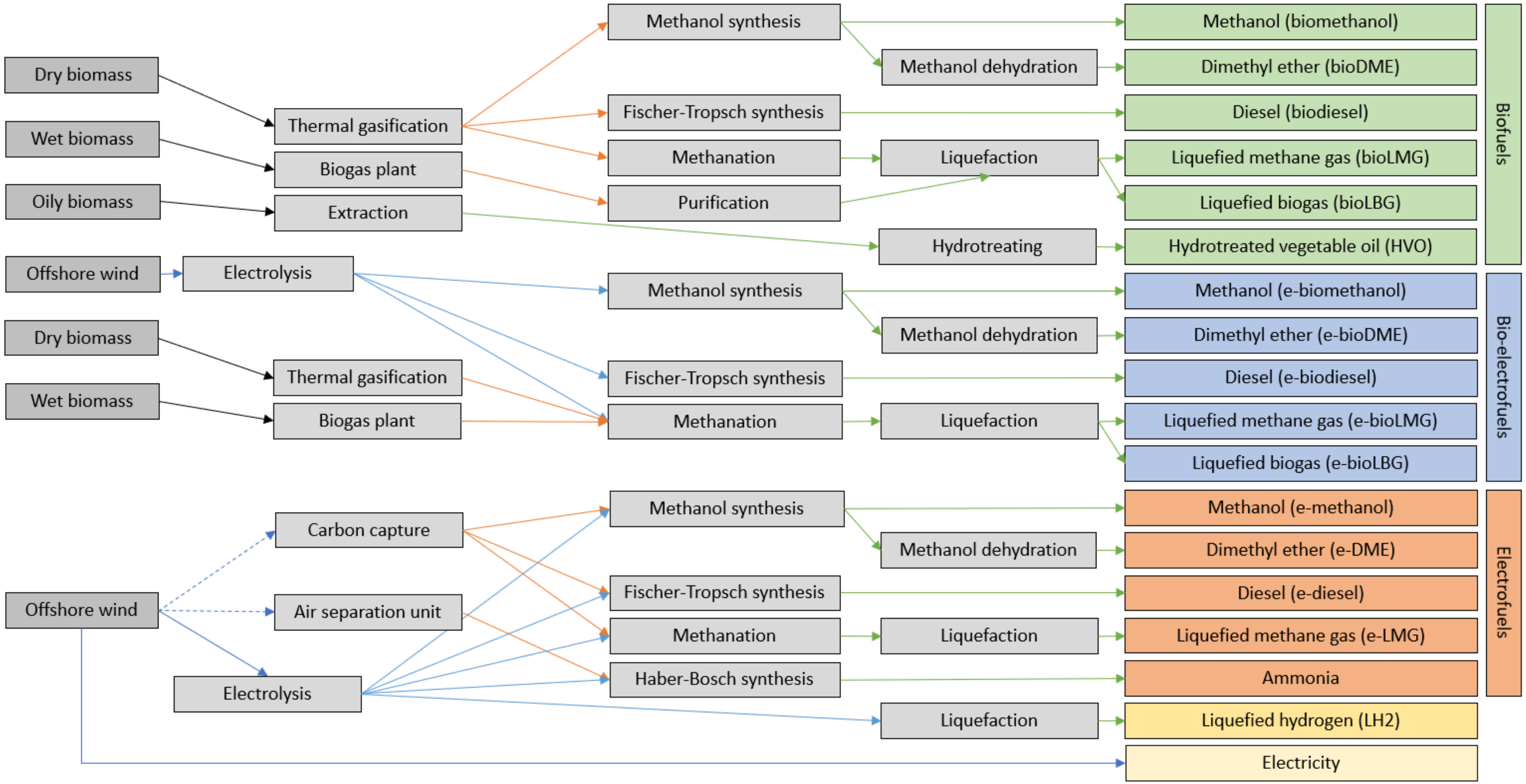
Overview of the fuel production pathways investigated



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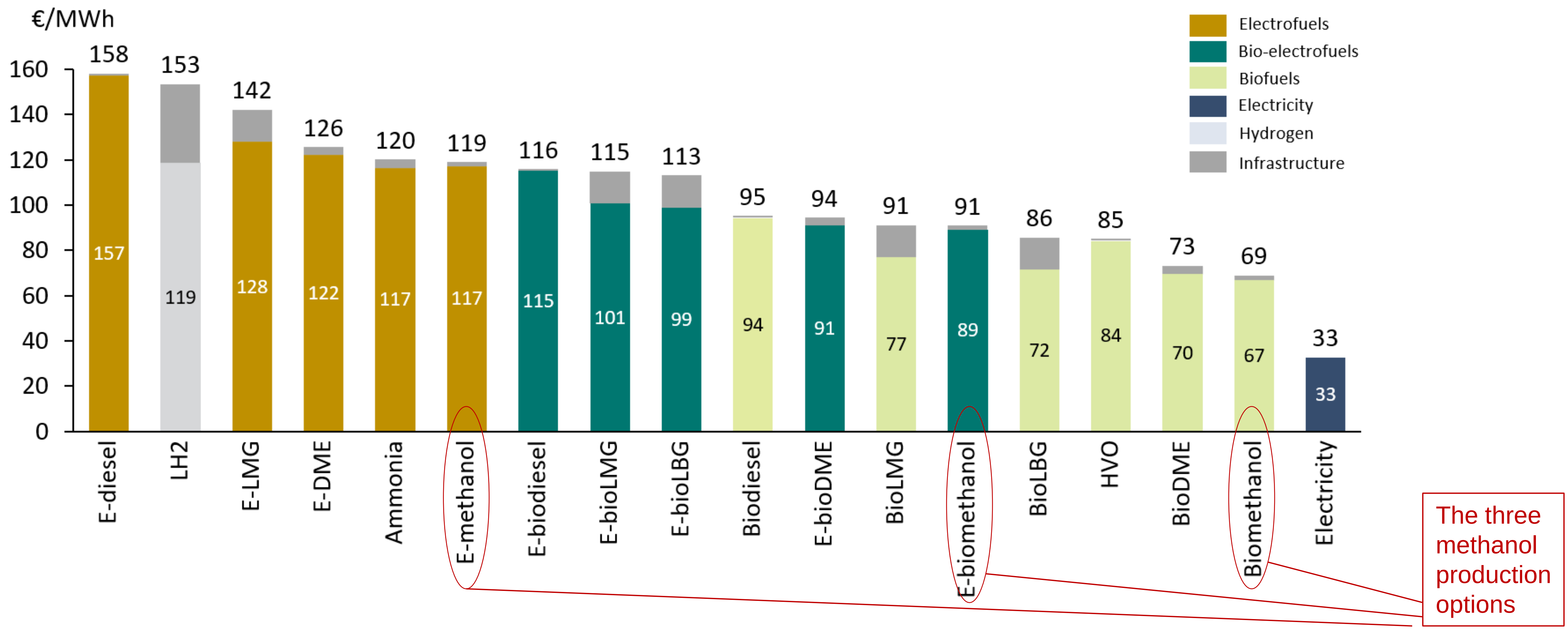
Fuel production costs incl infrastructure, base case



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Total cost of ownership (M€/yr). Base case.

Ship category: large ferries.
Three different utilization rates: short, medium, long distance.

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

The colour coding is within each fuel category and utilisation rate to highlight the cheapest option.

MGO and BE are coloured differently but are comparable in terms of costs to all other cases in the ship travel category.

Methanol shows lowest cost within all fuel categories.

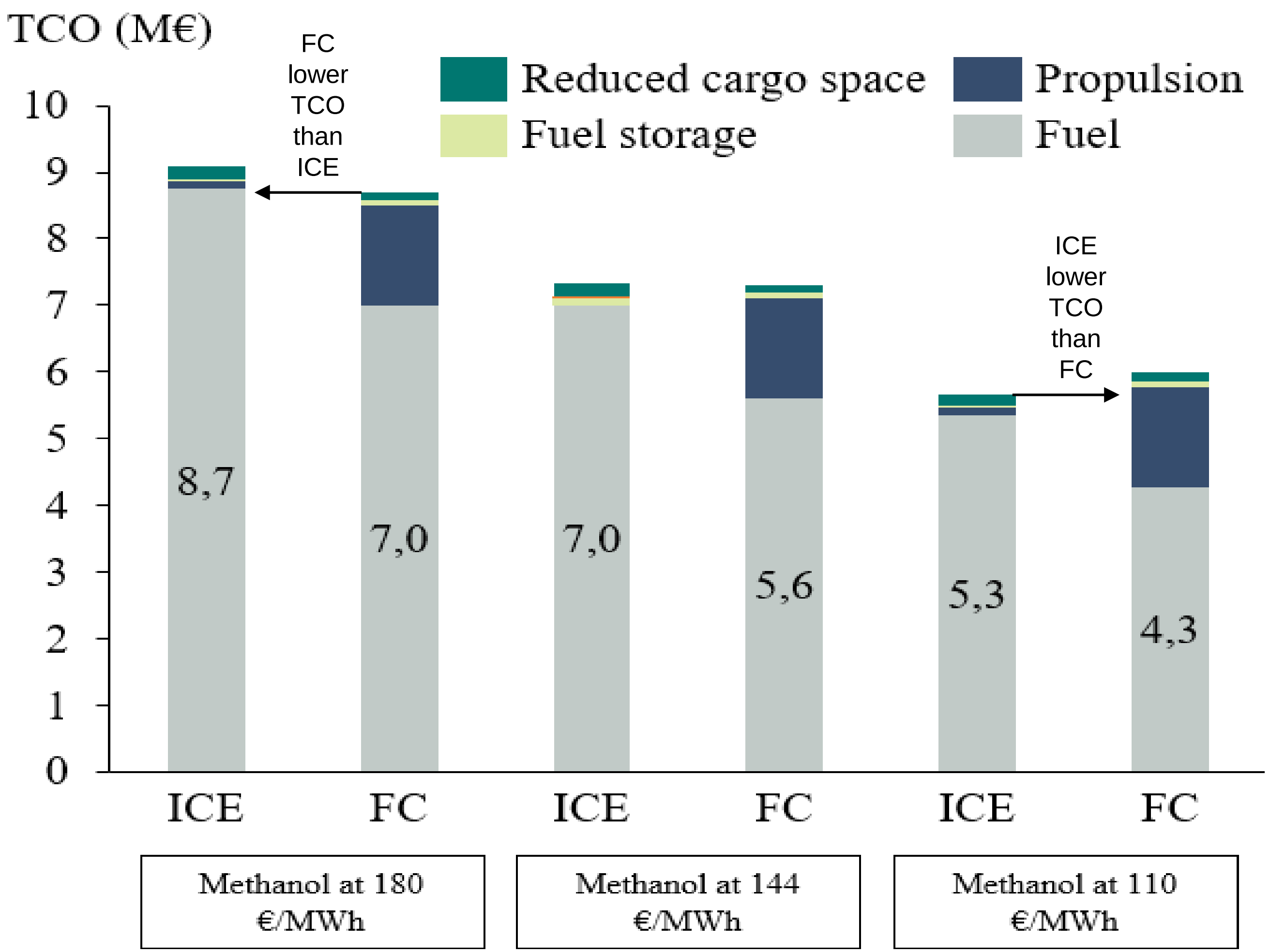
The three methanol production options

Insight 7. Methanol and E-methanol may be the lowest cost option from a TCO perspective in the shipping sector.

	TCO [M€]	Short			Medium			Long		
		ICE	FC	BE	ICE	FC	BE	ICE	FC	BE
	MGO	0.9			1.7			2.4		
Biofuels	Biomethanol	2.0	4.2		3.9	5.7		5.7	7.2	
Biofuels	BioDME	2.3			4.2			6.2		
Biofuels	Biodiesel	2.7			5.2			7.6		
Biofuels	BioLMG	3.0	4.9		5.4	6.8		7.8	8.7	
Biofuels	BioLBG	2.8	4.8		5.1	6.6		7.4	8.4	
Biofuels	HVO	2.4			4.6			6.8		
Bio-electrofuels	E-biomethanol	2.6	4.7		4.9	6.6		7.3	8.5	
Bio-electrofuels	E-bioDME	2.9			5.4			7.9		
Bio-electrofuels	E-biodiesel	3.2			6.2			9.2		
Bio-electrofuels	E-bioLMG	3.6	5.4		6.6	7.8		9.6	10.2	
Bio-electrofuels	E-bioLBG	3.6	5.3		6.5	7.7		9.5	10.1	
Electrofuels	E-methanol	3.3	5.3		6.5	7.8		9.7	10.3	
Electrofuels	E-DME	3.7			7.0			10.3		
Electrofuels	E-diesel	4.3			8.4			12.5		
Electrofuels	E-LMG	4.3	5.9		8.0	8.9		11.8	11.9	
Electrofuels	Ammonia	3.7	5.5		6.9	8.0		10.2	10.6	
	LH_2	4.7	5.3		8.8	8.6		13.0	11.9	
	Electricity			2.8			5.5			8.3

Low
High

Total cost of ownership methanol used in ICE vs FC for three different methanol production cost levels



Ship category: general cargo ships
Medium utilisation.

Balance between cost and efficiency
Lower cost fuels (bio-methanol) show lower TCO in ICE (compared to FC).

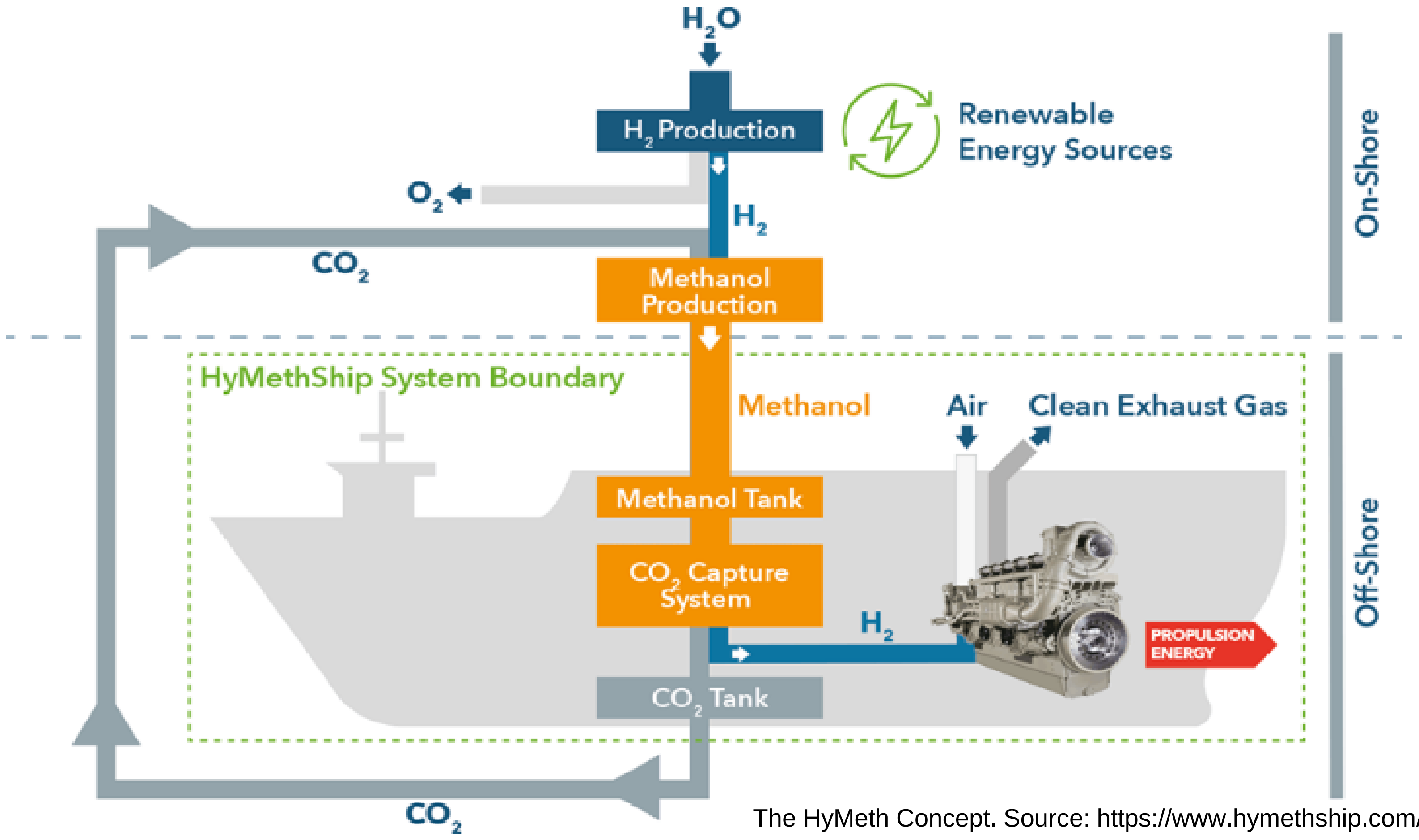
More costly fuels (electro-methanol) show lower TCO when used in the FC systems (compared to ICE).

Insight 8. E-methanol may have a lower total cost of ownership if used in fuel cells instead of internal combustion engines.

David-Korberg, Brynolf, Grahn, Ridjan-Skov (2020). Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Submitted to Renewable and Sustainable Energy Reviews.

On-going project HyMeth. Electro-methanol in hydrogen ICE ship

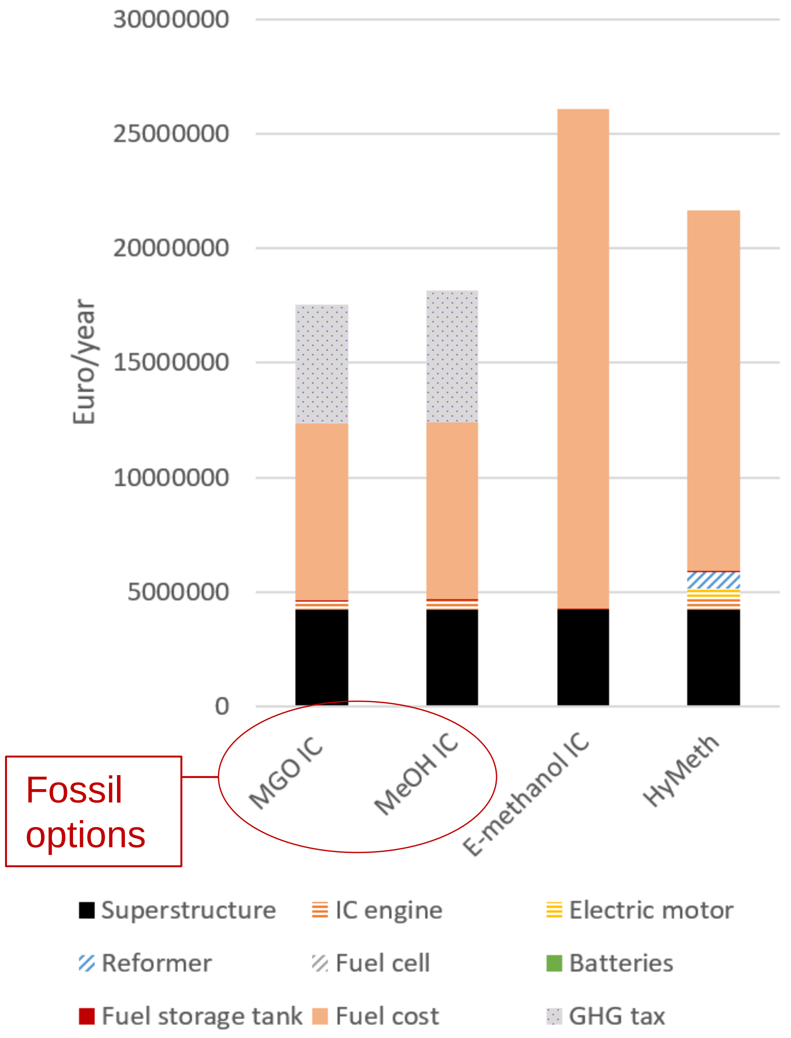
- The HyMeth Ship system combines a membrane reactor, a CO_2 capture system, a storage system for CO_2 and e-methanol, as well as a hydrogen-fuelled combustion engine into one system.
- The new concept allows for a closed CO_2 loop ship propulsion system while maintaining the reliability of well-established marine engine technology.



The HyMeth Concept. Source: https://www.hymethship.com/

Malmgren E., Brynolf S., Martin Borgh M., Joanne Ellis J., Grahn M., Wermuth N. (2019). The HyMethShip Concept: An investigation of system design choices and vessel operation characteristics influence on life cycle performance. *Proceedings of 8th Transport Research Arena TRA 2020, April 27-30, 2020, Helsinki, Finland.*

Annual cost of the propulsion system and fuel for a RoPax (vehicles and passengers) vessel using different fuels



Results in EUR/yr show that

- Electro-methanol in ICE has the highest costs (electro-methanol produced using direct air capture of CO_2). (E-methanol used for propulsion).
- Electro-methanol in the HyMethShip concept assume no cost for CO_2 capture since CO_2 is recycled*. (Hydrogen used for propulsion)
- The higher capital cost (from the additional components needed) in HyMeth is outweighed by the lower production cost of electro-methanol.
- The total cost for fossil marine gas oil (MGO) and natural gas based methanol (MeOH) are lower than the renewable options also if assuming a carbon tax of 100 Euro/tonne CO_2 equivalent.

*) in reality losses throughout the system will require additional CO_2 from carbon capture. The system losses are between 1-10% depending on production process efficiencies.

Insight 9. E-methanol converted to hydrogen combined with CO2-recycling has cost-advantages over e-methanol combusted without onboard CO2-capture.

Malmgren E., Brynolf S., Martin Borgh M., Joanne Ellis J., Grahn M., Wermuth N. (2019). The HyMethShip Concept: An investigation of system design choices and vessel operation characteristics influence on life cycle performance. *Proceedings of 8th Transport Research Arena TRA 2020, April 27-30, 2020, Helsinki, Finland.*

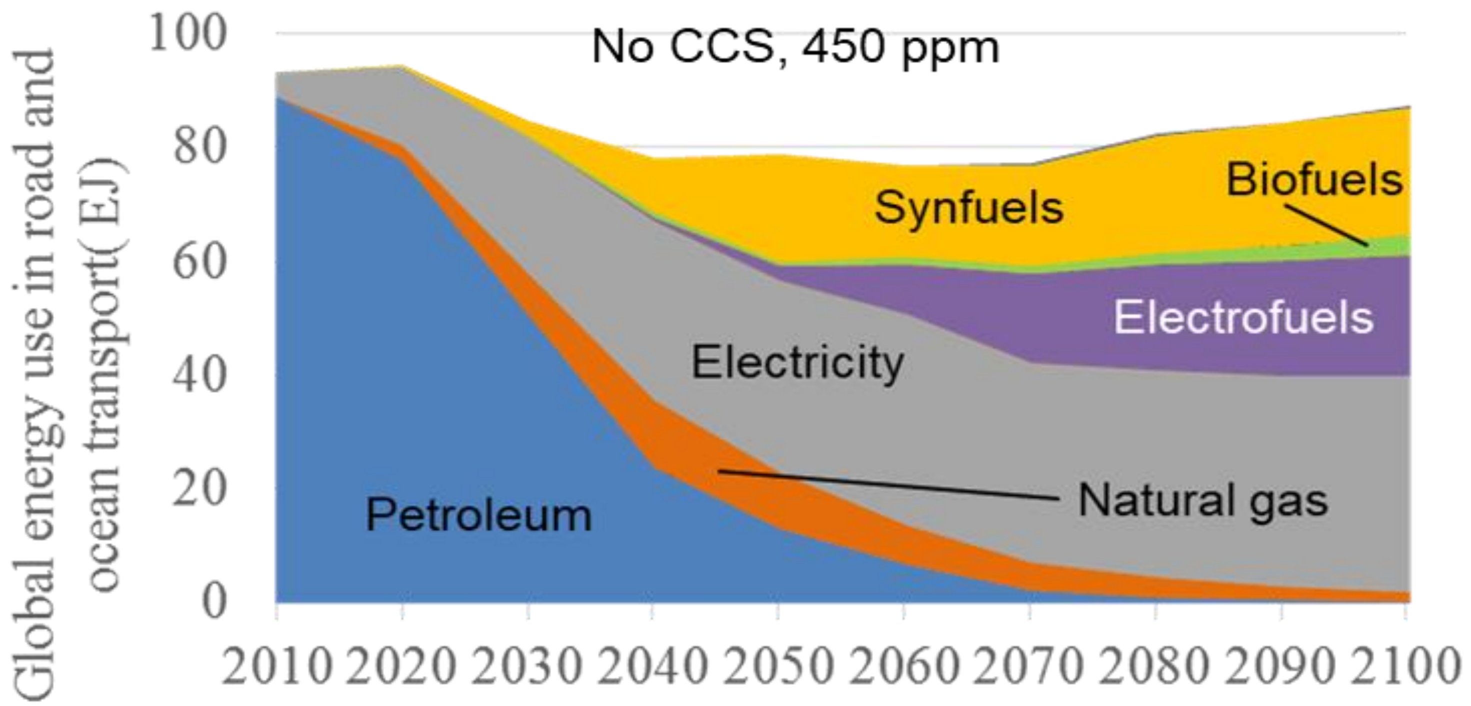
The big picture: the potential future role of electrofuels

Cost-effective scenarios of the global future fuel mix for road and ocean transport sector,

assuming stringent CO2 reduction targets

Ref: Brynolf S, Taljegård M, Grahn M, Hansson J. (2018). Electrofuels for the transport sector: a review of production costs. *Renewable & Sustainable Energy Reviews* 81 (2) 1887-1905.

Cost-competitiveness of electrofuels in a global energy systems context, example of results from the cost minimising energy systems model GET



Synfuels: H2 from thermal split of water + CO2
Electrofuels: H2 from electrolysis of water + CO2

This is a result from assuming that large scale CCS is not an accepted and available technology. (When assuming CCS is available, no electrofuels are shown in the scenarios.)

From a cost-effective perspective, the captured CO2 can contribute to climate mitigation (a stabilization of atmospheric CO2 concentration of 450 ppm) at a lower cost if stored underground, instead of recycled into electrofuels (if large carbon storage is an accepted and available technology).

The amount of electrofuels in the future fuel mix for road and ocean transport sector depend to a large extent on the amount of CO_2 that can be stored away from the atmosphere.

Insight 10. The future role of electrofuels may depend on the acceptance of CCS.

Source: Lehtveer M., Brynolf S., Grahn. M. "What future for electrofuels in transport? – analysis of cost-competitiveness in global climate mitigation". Environmental Science & Technology. Vol. 53 (3), p. 1690-1697.

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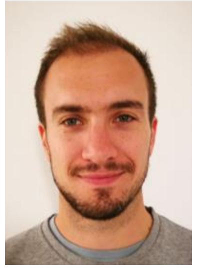
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