Methanol as a marine fuel

Prospects for the shipping industry

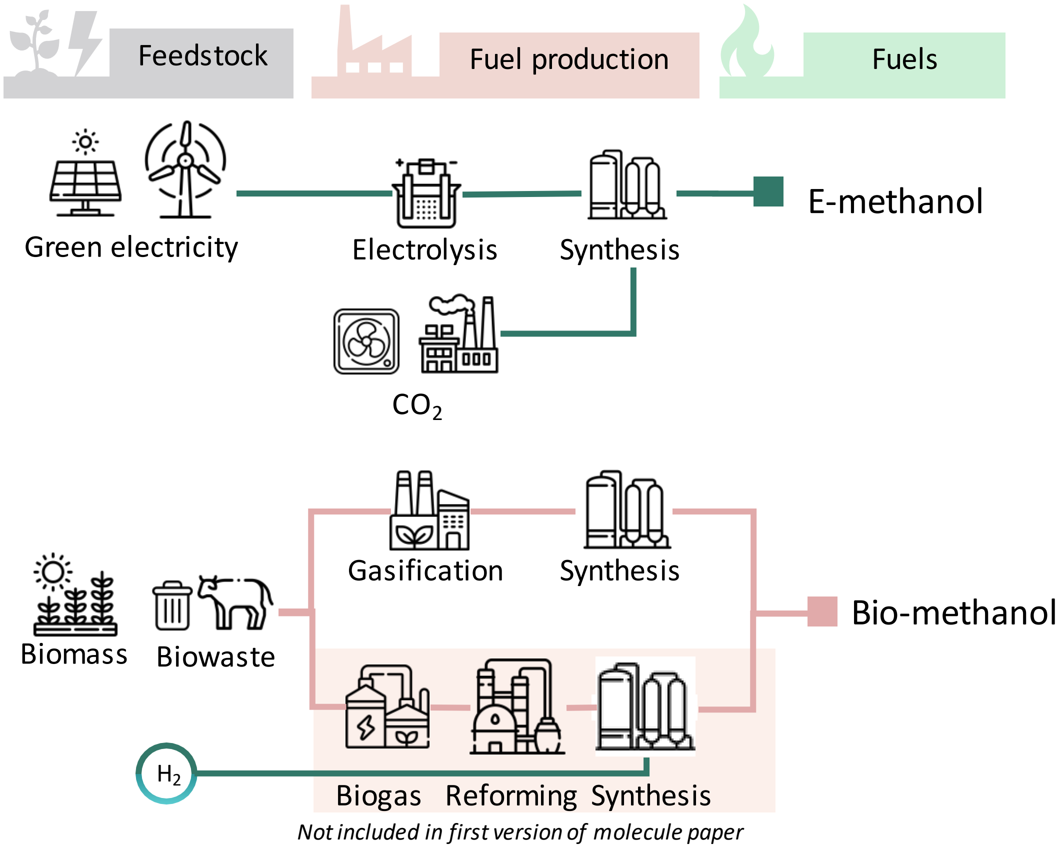
Documentation of assumptions for NavigaTE 1.0 (2021)

February 2022

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

Agenda

Several pathways can produce renewable methanol today



Feedstock

Fuel production

Fuels

Green electricity

Electrolysis

Synthesis

E-methanol

CO_2

Gasification

Synthesis

Biomass

Biowaste

Bio-methanol

H_2

Biogas

Reforming

Synthesis

Not included in first version of molecule paper

- Renewable methanol can be produced from 3 high TRL pathways today:
  - E-methanol, from electricity and CO_2
  - Bio-methanol, from gasification of biomass or biowaste – potentially boosted by additional hydrogen[2]
  - Bio-methanol from reforming biogas made from biomass or biowaste – potentially boosted by additional hydrogen[2]
- CO_2 for E-methanol can be obtained either by capturing CO_2 from a point where it is being emitted (point source - PS) or directly from the air (Direct air capture – DAC)
- Three methanol pathways have been left out of scope from the position paper:
  - The biogas-to-methanol route will be included in the next version of the paper
  - Methanol from the paper Kraft process was excluded due to too low potential to consider for a fleet perspective
  - Grey methanol[1] was excluded due to higher price and emissions than LSFO

Icons from: freepik

1) Grey methanol is defined as methanol derived from natural gas

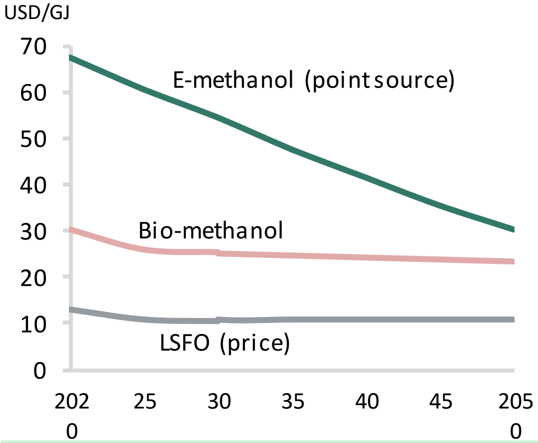
2) Hydrogen can be either green, blue or grey, which will vary the price and emissions

Renewable methanol could play a role in the fleet's decarbonisation from 2035

Key conclusions

- Renewable methanol could begin impacting the fleet fuel mix from 2035, where bio-methanol available for shipping could cover >2% of the energy demand, scaling to 50% in 2050
- Methanol production costs remain >2 times higher than LSFO price, meaning that regulatory measures are needed to make methanol cost competitive
- Methanol for shipping will likely be limited by methanol supply chain scaling and industry competition for feedstocks and methanol
- Onboard integration involves use of known and existing technologies with both reduced tank-to-wake GHG and air pollutant emissions
- Methanol combustion requires pilot fuels (~5%), which may impact emissions

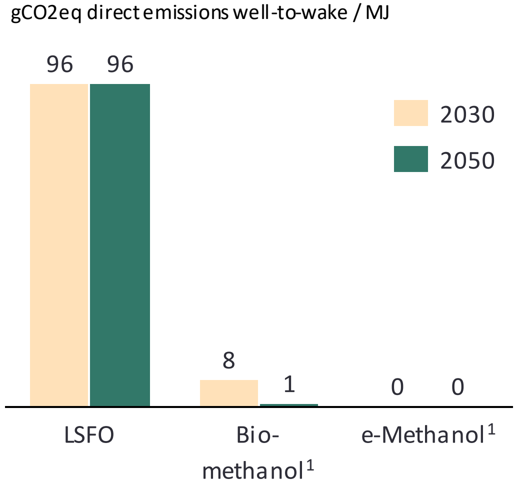
Cost projections



Methanol will require regulatory measures to compete with fossil alternatives

- Renewable methanol expected to be more than 2 times as expensive as fossil oil at least until 2050
- Bio-methanol remains the cheaper renewable methanol option until 2050
- E-methanol cost down driven by cost of renewable energy and improved economies of scale

Well-to-wake emissions



Renewable methanol has low emissions, depending on pilot fuel used

- Bio and e-methanol contain biogenic carbon - doesn't add to global warming
- Bio-methanol could reduce emissions by 70-100% compared to LSFO when waste-based biomasses are utilized
- E-methanol expected to be near carbon neutral, depending on CO_2 source
- Pilot fuel type will impact emissions[1]

Implementation risks

Scaling of supply chain is a key risk

- **[Production]** Renewable Methanol is in low supply and will take time to scale - could reach 2% of fleet needs in 2035
- **[Feedstock]** CO_2 and Biomass competition could limit supply for shipping
- **[Onboard]** Storage volumes and safety barriers to be addressed in onboard systems
- **[Production]** Gasification of biomass is not yet deployed widely yet – some biomass feedstocks might be difficult to process

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[1] Pilot fuel (5%) is needed. Using LSFO, this equals an additional 5 gCO_2eq/MJ. Using e.g. a bio-oil will reduce the impact on emissions.

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Bio-methanol production costs are projected at 2-3 times the price of fossil fuel alternatives

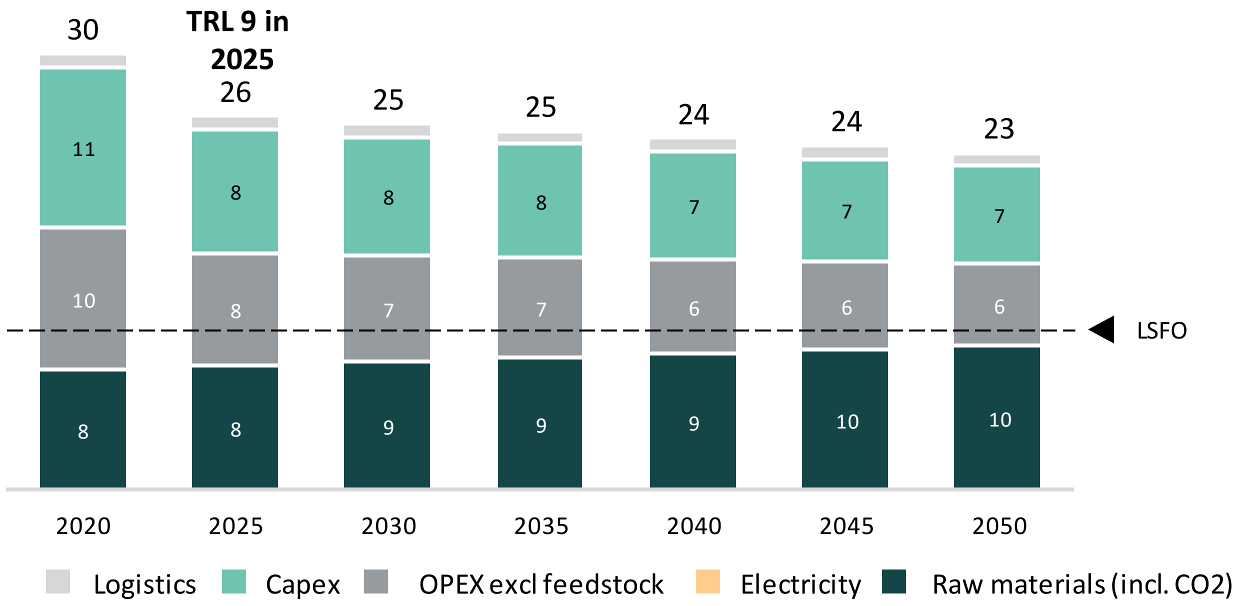
Highlights from cost analysis of bio-methanol pathways

- In all years, the <u>cost</u> of bio-methanol is 2-3 times higher than the <u>price</u> forecast for LSFO at 11 USD/GJ - Bio-methanol will need regulatory measures to be cost competitive with fossil alternatives
- The main cost drivers for bio-methanol is the plant costs (CAPEX and OPEX), representing >60% of the fuel cost in all years, with biomass responsible for remaining costs
- The cost of bio-methanol is projected to decrease by 0,4% per year as a combination of two factors:

1. CAPEX and OPEX are expected to decrease following an industry learning curve. Little improvement from economies of scale is expected due to the associated rise in biomass transportation costs
2. Biomass prices are expected to increase until 2050 as the demand for biomass increases driving the industry to utilize higher cost biomasses

Bio-methanol pathway costs, at port

Weighted global average[1]
USD/GJ



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[1] Assuming 40 % from lowest cost region, 30 % from 2^{nd} lowest, and 10% from $3\text{-}5^{th}$.

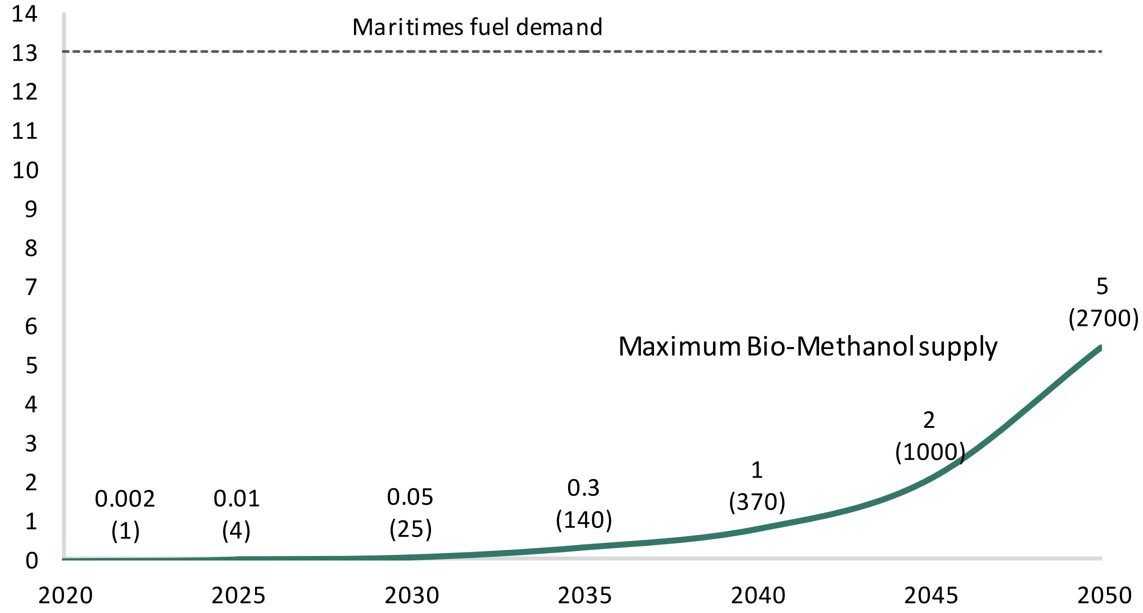
Bio-methanol supply is limited today, but could reach supply volumes necessary to impact global shipping from 2035

Highlights from supply analysis of bio-methanol

- Bio-methanol is in limited supply today at around 5 petajoule per year from a handful of commercial plants. Capacity at individual production plants tend to be small (1-20% of fossil units)
- Considering the maximum roll-out speed, modelled by assessing historical biofuel roll-out speeds of technical and commercial mature technologies with government support[1], bio-methanol could reach ~2 EJ in 2035 for all industries (data not shown)
- To simulate competition for biomass and methanol with other industries, we set a maximum volume of bio-methanol obtainable for the maritime industry. Maritime's current fraction of non-electrifiable energy demand from all sectors globally is 8%.[2] For the analysis, we used 16% to which can be perceived from the industry taking a first-mover role into biofuels, being able to economize from customers' higher willingness to pay or being imposed stricter regulatory incentives than the other industries
- Based on this analysis, Bio-Methanol could begin impacting the global shipping fleet from 2035 with 0.3 EJ available to shipping (2.5% of shipping's energy need)
- Availability could increase ~25% if it becomes an industry standard to add hydrogen to the syngas to increase yields

Fastest possible roll-out of bio-methanol supply available for maritime, with unconstrained demand

EJ/year
(plants supplying shipping)



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1) The fastest growth rate observed, that of US Biodiesel from 2003-2016², was used for the early roll-out from 0-1,5 EJ for maritime of each biofuel. To represent a slower global roll-out after 1,5 EJ for maritime, the growth rate of global ethanol from 2003-2016 was used above 1,5 EJ. US Biodiesel followed logarithmic growth by formula 10^(log(x)+0,152). This is the highest growth observed, between global ethanol (0,086), Global biodiesel (0,110), Latin America ethanol (0,027) and EU Biodiesel (0,130)
2) Based on internal study identifying the amount biomass needed to cover the non-electrifiable energy need of global sectors. Sectors (EJ): Shipping (30), Aviation (30), Road transport (30), Electricity balancing (30), Peak load heating (50), Industry (50), Plastic (90), Cement (30), Steel (20)
3) Standard plants size: 150 kton methanol /year

Adoption in shipping is mainly limited by the roll-out rate of production plants and competition with other industries

Subject	Risks	Potential risk mitigations
Feedstock	▪ Biomass competition with other industries and other fuels is intense, and could drive up feedstock costs for methanol production	▪ Refine assessment of biomass availability and sector competition on a regular basis
Production	▪ Production not fully mature with few operational assets (TRL 8) ▪ Fuel-grade methanol plant configuration unclear ▪ Competition from other industries could drive up fuel costs	▪ Commercial maturity of gasification plant must be achieved before the end of the decade ▪ Upon achieved TRL 9, rapid roll out of plants must happen by 2030 ▪ Shipping fuel grade methanol standard must be established by 2025
Logistics	▪ Decentralized production requires new logistic pathways ▪ Standardization of bunkering and safety	▪ Bunkering facilities must be established in major port
Regulatory	▪ Risk of using non-sustainable bio-methanol due to non-transparency of feedstock sourcing	▪ Feedstock sustainability criteria established

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Electro-methanol production costs are projected at 3 - 8 times the price of fossil fuel alternatives

Highlights from cost analysis of e-methanol pathways

- In all years, the <u>cost</u> of e-methanol is ca. 3 - 8 times higher than the <u>price</u> forecast for LSFO at 10 USD/GJ.
- Production cost is projected to decrease by 13% p.a. and reach 28 USD/GJ by 2050.

- The cost of e-methanol is sensitive to 3 primary factors:

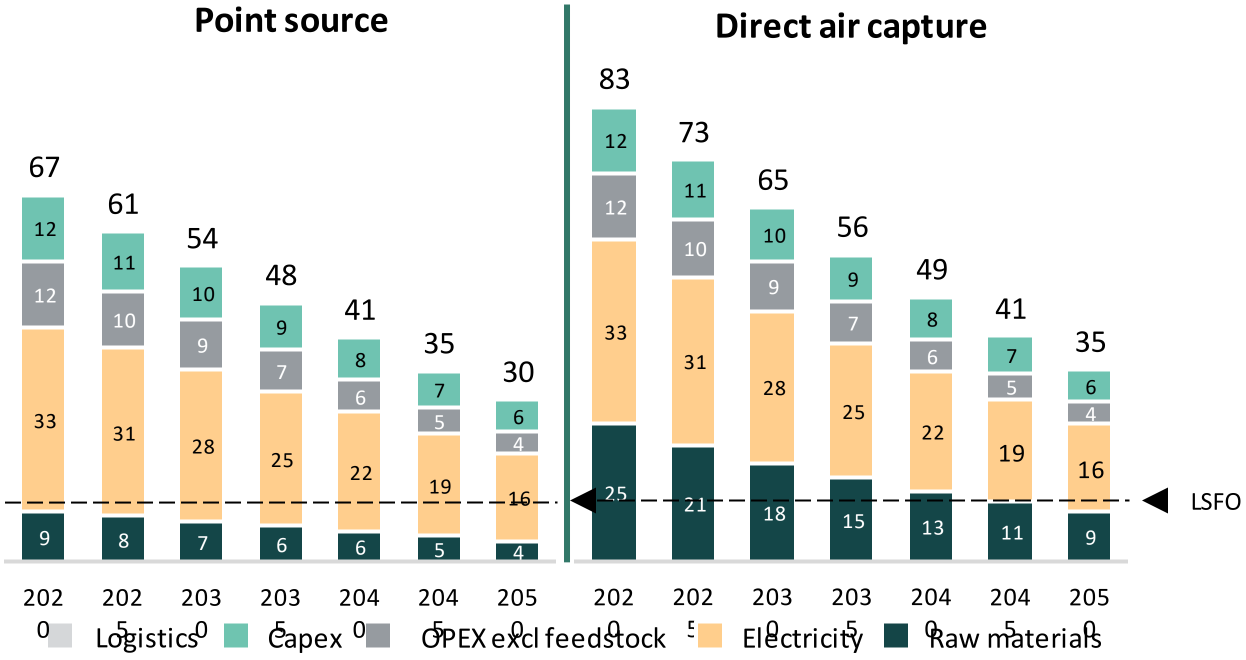
1. Renewable electricity cost comprises the largest portion of production cost. The intermittent unavailability of RES creates requirements for power buffering or equipment turndown. Since the RES cost differs between regions, it is a determining factor for the location of e-methanol plants.
2. When point sources become scarce, to cost of e-methanol will also depend significantly on the cost of CO_2 from direct air capture (due to limited availability of renewable CO_2 point sources).
3. The cost effectiveness of methanol production depends critically on economies of scale, whereby larger plants are far more economical. Since the local availability of CO_2 (certified as renewable) is expected in short supply, near-term e-methanol plants will be smaller, without achieving the economies of scale familiar to modern, conventional methanol plants.

E-methanol will need financial measures in order to be cost competitive with fossil alternatives

E-methanol pathway costs, at port

Weighted global average[1]

USD/GJ



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1) Assuming 40 % from lowest cost region, 30 % from 2nd lowest, and 10% from 3-5th.

E-methanol supply is limited by large-scale supply of certified CO_2 and by developments in renewable hydrogen production

Subject	Risks	Milestones to Implementation
Feedstock	▪ Reliable supply of CO_2 certified as renewable, at the scale required to make methanol plants of competitive capacity ▪ Optimizing and scaling of hydrogen production by electrolysis, in turn dependent on availability of RES	▪ Scale-up of renewable CO_2 supply chain, initially with biogenic sources and later direct air capture; this CO_2 feedstock additionally requires the development of logistics infrastructure for distribution. ▪ Scale-up of RES capacity to meet global demand and be available for shipping: address land use policies, labor, and infrastructure; secure growth of battery materials supply chain (or other solutions to address variable electricity supply). High-paced growth of Electrolysis sector: manufacturing and supply chain.
Production	▪ Production site location with proximity to RES & CO_2 feedstocks ▪ Improvements to conventional methanol process: capturing off-gas, catalysts to accommodate reactor water content, etc.	▪ New commercial methanol plants operating on low-cost RES and with adequate proximity both to relevant ports and to centralized CO_2 supply. ▪ Scale-up of electro-methanol infrastructure globally.
Logistics	▪ Potential need for separate distribution, if quality of methanol for fuel is different than current qualities (AA) ▪ Standardization of bunkering and safety	▪ Establish green corridors with sufficient critical mass of supply at ports.
Regulatory (Supply)	▪ Production off-gas would create emissions if used as fuel. ▪ Certification for which CO_2 point sources are considered renewable.	▪ Monitoring of (and regulatory standards for) restricting methane emissions. ▪ Implement regulatory standards to certify the emissions associated with feedstock.

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Widespread implementation requires addressing safety barriers, effects of increased storage volume and expansion of commercially available engine types

Subject	Considerations	Potential risk mitigations
Energy density and volume	• Requires 2.5 times the volume and 2 times the weight compared to VLSFO for the same energy content	• With more flexibility to locate the integrated storage tanks, onboard volume requirements can be considered comparable or even less than LNG vessels (conversion of slop tanks on some tankers not currently allowed) • Depending on vessel type, size and operational profile, optimize speed and range requirements or accept more frequent bunkering
Fuel Supply & Storage	• Can be stored in integrated tanks at ambient temperature and pressure (stainless steel or carbon steel with methanol-resistant coatings like inorganic zinc-silicate) • Cofferdams or adjacency to ballast tank/side shell currently required • Corrosive to certain materials typically used in natural gas and distillate fuel systems including aluminium and titanium alloys • Hard-to-remove deposits on injection systems seen in automotive industry	• Corrosion-inhibiting additives or special coatings • Material selection including for tanks (stainless or carbon steel with coatings)
Safety	• Low flashpoint (11C) fuel and wide explosion range increases fire risk • Burn at low temperatures with a nearly invisible flame and no smoke • Toxic and poisonous with vapor being heavier than air	• Similar risk-based approach as done for LNG can be used (IGF Code) • Tank location, protection, inerting and venting, spill containment, vapor and fire detection, fire fighting, crew training and familiarization • Double-wall ventilated piping in engine room (similar to LNG) • Leverage experience from the chemical industry to adapt safety barriers and procedures

Sources: Methanol Institute "Methanol as a Marine Fuel Report"
ABS "Sustainability Whitepaper: Methanol as Marine Fuel" February 2021
MAN Energy Solutions "The Methanol-fuelled MAN B&W LGIM Engine"

Widespread implementation requires addressing safety barriers, effects of increased storage volume and expansion of commercially available engine types

Subject	Considerations	Potential risk mitigations
Regulation	• Regulations not in place or fully adapted to methanol properties • Current TTW regulation would not accept methanol from renewable sources as carbon-neutral	• IGF Code will accept methanol as a fuel starting November 2022 • Regulatory emission calculation basis to be changed from TTW to WTW
Energy Converters	• Two-stroke diesel cycle methanol engines require pilot fuel (about 5%) • Dual-fuel two-stroke engines are commercially available and used mainly on methanol tankers (limited type and power range options) • Dual-fuel four-stroke engines under development • Fuel cells have been demonstrated onboard vessels, but not yet commercially available (TRL 9 excepted around 2030)	• Engine development programs already ongoing with more options available 2022-2023 • Fuel cell technology development and demonstration projects
Emissions	• Tank-to-wake CO2 reduction of around 10% compared to HFO Tier II • SOx and particulate emissions reduced >90% compared to HFO Tier II • Commercially available NOx reduction system will be needed (EGR, SCR or water injection) to meet Tier III	

Sources: Methanol Institute “Methanol as a Marine Fuel Report”
ABS “Sustainability Whitepaper: Methanol as Marine Fuel” February 2021
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