# Bio-oils as marine fuel

## Prospects for the shipping industry

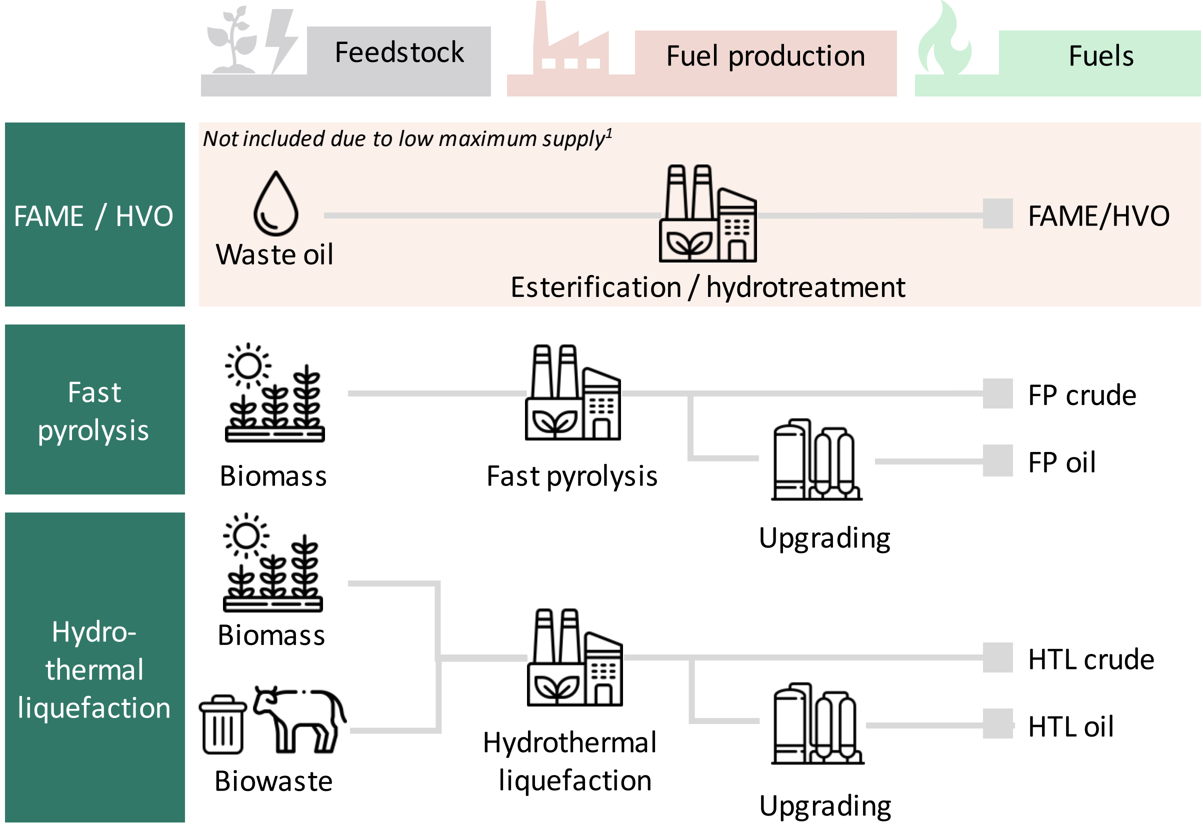
## Documentation of assumptions for NavigaTE 1.0 (2021)

February 2022

**Mærsk Mc-Kinney Møller Center**
for Zero Carbon Shipping

# Agenda

# Bio-oils can be produced by several existing and maturing pathways



- Bio-oils encompass a range of technologies that convert biological material into an oil-like substance
- Bio-oils on the market include FAME and HVO, producible from waste oils or food feedstocks. These have been excluded in the first version of the position paper due to low supply of waste feedstocks[1] and the debatable sustainability of food-based bio-fuels
- New technologies are emerging for producing bio-oils from plentiful feedstocks, such as biomass and biowaste[2] at low carbon intensities: Fast pyrolysis (FP) and Hydrothermal liquefaction (HTL)
- FP and HTL oil are producible in a range of qualities, depending on the amount of upgrading applied: Here we assess a low cost un-upgraded "crude" which requires blending with other fuels to reach specifications, and an upgraded "oil" achieved using hydrotreatment with catalysts which is usable in oil engines without blending
- The maximum blending grade of crude oils is being investigated, and current results indicate 30% for FP crude and 40% for HTL crude
- Lignin Diesel Oil has also been excluded from this first molecule paper due to insufficient information
- Pyrolysis Crude / Oil has also been excluded

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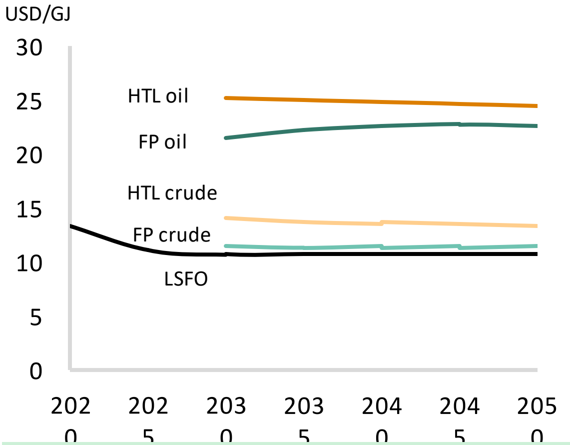
1) See appendix for documentation
2) Biomasses such as residual wood and agricultural wastes. Biowaste such as organic MSW and sewage sludge.
Icons from: Bqlnq, freepik

# Bio-oils could cover 30% of fleet energy in 2050, but uncertainties are high due to immature pathways

## Key conclusions

- Bio-oils could start impacting the fleet fuel mix from 2040, where volumes available for shipping could cover >2% of the energy demand, scaling to 30% in 2050
- Regulatory measures are needed to make bio-oils cost competitive with fossil alternatives, as production costs are 30-150% higher than LSFO prices
- Bio-oils can reduce well-to-wake emissions by >80% from LSFO when produced at highest sustainability standards from non-food waste biomass
- Bio-oils could require fuel system changes, additional NOx reduction system and operational guidelines – depending on the upgrade levels
- Bio-oils supply for shipping will likely be limited by technological risks in conversion steps, maximum roll-out speed of plants and fuel competition with other industries

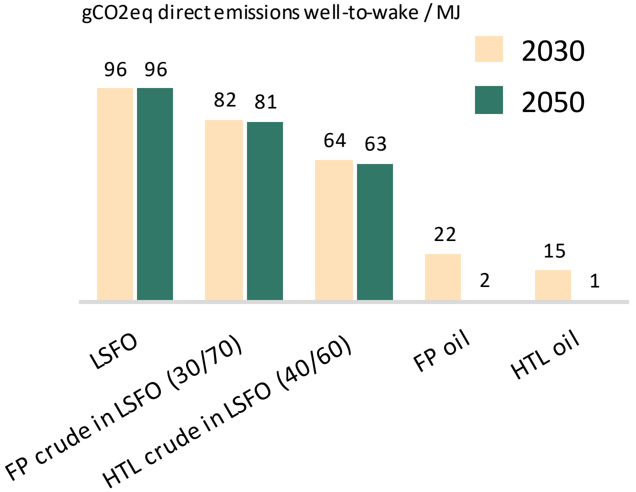
## Cost projections



**Bio-oils will require regulatory measures to compete will fossil alternatives**

- Bio-oils are projected to be 30-150% more expensive to produce than the price of fossil alternatives
- The crude oils are projected to be most cost competitive
- Fast pyrolysis oils are projected to have lower production costs than hydrothermal liquefaction oils

## Well-to-wake Emissions[1]



**Bio-oils are green alternatives to fossil fuels, when sustainable biomass is used**

- Crude bio-oils reduce emissions by >99%, but must be blended to reach specifications
- Blending FP oil (30%) or HTL oil (40%) with LSFO reduces emissions by 16% and 36% on an energy basis
- FP and HTL oil reduce emissions by 80% in 2030 and >99% in 2050 - main contribution is from origin of hydrogen

## Implementation risk

**Pathways are immature, leading to high risk in production, logistics, use and certification**

- **[Availability]** Feedstock and fuel competition with other industries may limit supply
- **[Production]** Conversion technologies are expected to mature late 2020ies
- **[Regulatory]** Fuels vary with feedstock and process. Certification may be complex
- **[Onboard]** Bio-oil storage stability, fuel system corrosion and NOx emissions are uncertain

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[1] Direct emissions from each step of the fuel production pathway, well-to-wake

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# FP oil & crude will need regulatory measures to be competitive with fossil alternatives

## Highlights from cost analysis of FP crude and FP oil

- In all years, the cost of FP crude is 30% higher than the price forecast for LSFO, and the cost of FP oil is 100-150% times higher than LSFO price
- Thus, FP oil and FP crude will need regulatory measures to be cost competitive with fossil alternatives
- The main cost driver for both FP crude and oil is the cost of raw materials:

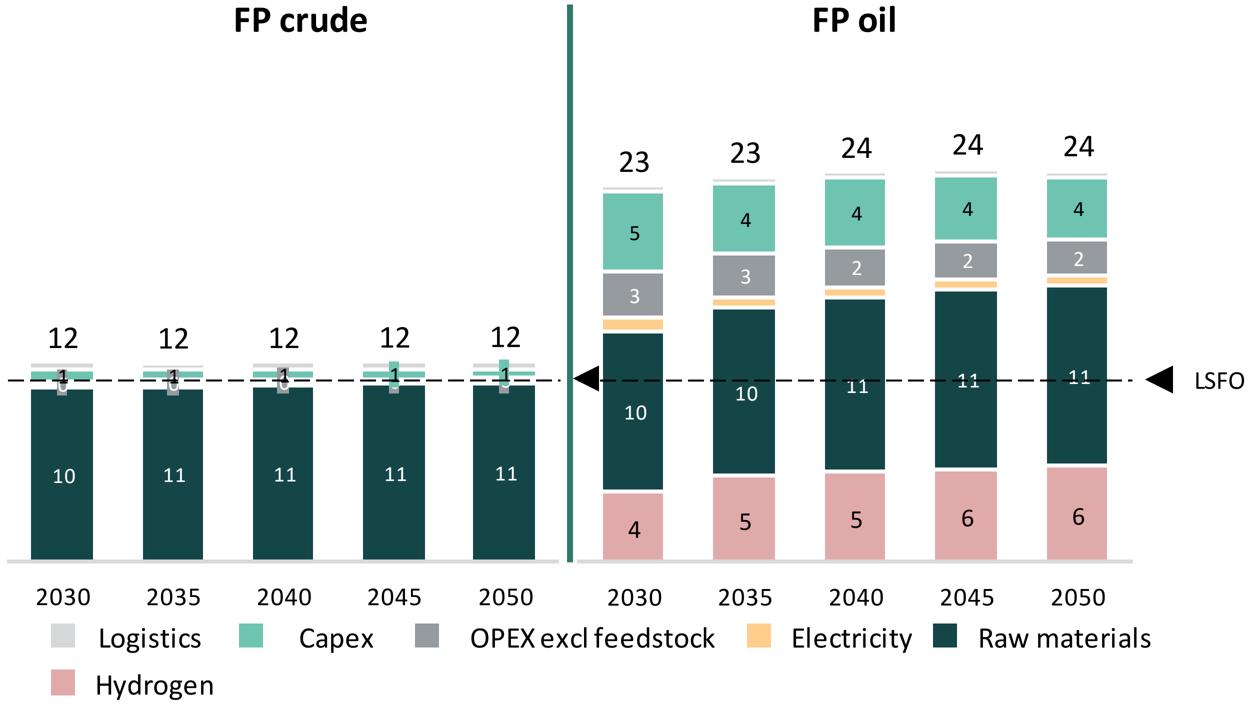
1. Biomass is expected to increase in price towards 2050 as the demand for biomass increases driving the industry to utilize higher cost biomasses
2. Hydrogen for upgrading to FP oil represents 30-35% of the raw materials cost. The composition of hydrogen is expected to change from grey to blue and to green as the cost of these reach competitive levels

- The processing price are expected to increase over time, as the increase in biomass and hydrogen costs will outweigh the learning curve improvement to processing costs

**Pyrolysis oil pathway costs, at port**

Weighted global average[1]

USD/GJ



[1] Assuming 60 % from lowest cost region, 40 % from 2nd lowest, and 0% from 3-5th.

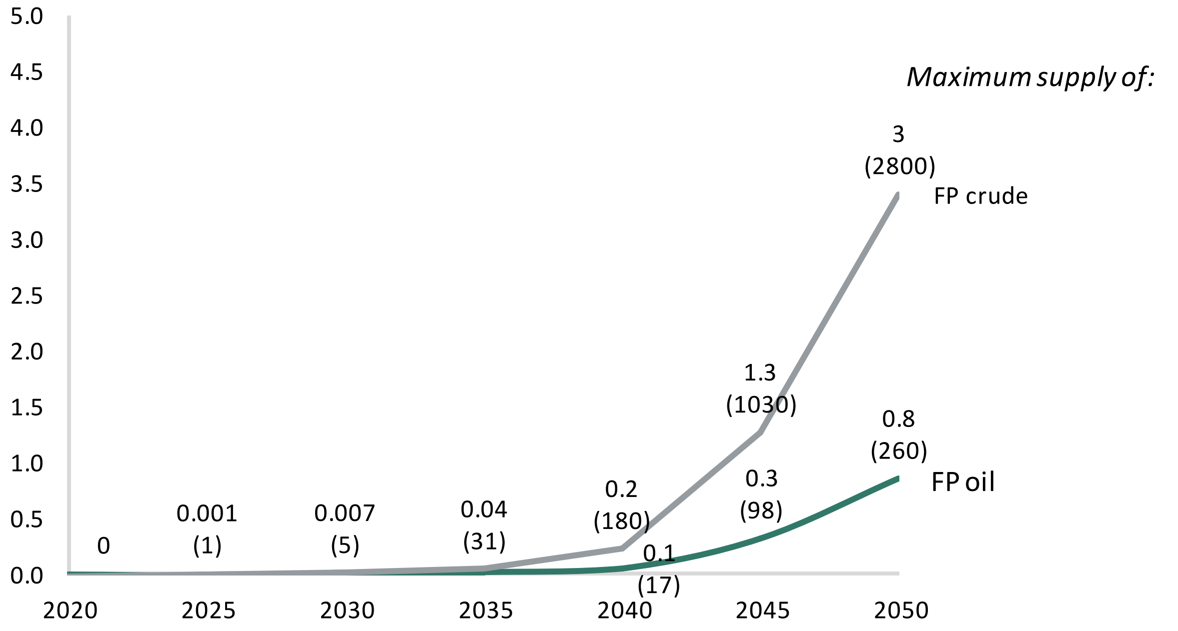
# FP crude and oil could cover 2% of fleet energy in 2040 and 30% in 2050 at maximum growth

## Highlights from supply analysis of FP crude and FP oil

- FP crude is produced today, but is solely used for district heating, industry energy and for bio-based products. FP oil upgrading is still in development (TRL 7)
- The current production for FP crude is 1,3 PJ for all sectors. FP oil is expected to reach TRL 9 in the late 2020s, where three 80 kton plants are projected to be in operation
- To simulate competition with other industries, we set a maximum volume of FP crude & oil obtainable for the maritime industry. Maritime's current fraction of global non-electrifiable energy demand is 8%.[2] For the analysis, we used 16% which can be perceived from the industry taking a first-mover role into bio-fuels, being. able to economize from customers' higher willingness to pay or being imposed stricter regulatory incentives than the other industries Thus, 0.2 PJ of FP crude is available to shipping today
- Considering the maximum roll-out speed, modelled by assessing maximum historical biofuel roll-out speeds of technical and commercial mature technologies with government support,[1] FP crude could grow to impact the global shipping fleet from 2040 with a maximum supply of 0.2 EJ for FP crude (1.7% of shipping's need) and FP oil in 2045 with a maximum supply of 0.3 EJ for shipping (2.5 % of shipping's need)

**Fastest possible roll-out of pyrolysis oil supply available for maritime, with unconstrained demand**

EJ/year
(Standard plants supplying shipping[3])



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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 of 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 plant size: FP crude: 200 kton/year, FP oil: 75 kton/year

# FP oil & crude supply for shipping is mainly limited by technical risks in development and competition for biomass and biofuel

| Subject | Risks | Potential risk mitigations |
|---|---|---|
| Feedstock | ▪ Biomass competition with other industries and fuels is unclear, and could drive up feedstock costs | ▪ Refine assessment of biomass availability and sector competition on a regular basis |
| Production | ▪ 4 small FP crude plants in operation today (TRL 8)<br>▪ FP oil upgrading is still in pilot scale (TRL 6)<br>▪ Competition from other industries could drive up fuel costs | ▪ Investments in research and innovation may accelerate commercialization |
| Logistics | ▪ Logistic & bunkering must be established for FP oil & FP crude – could benefit from existing infrastructure if fully upgraded or blended into established fuels | ▪ Map ports and needed supply<br>▪ Investments in supply infrastructure |
| Regulatory | ▪ Certification of fuels<br>▪ Standards needed to validate the sustainability of biofuel production pathways<br>▪ Regulatory measures will be needed to drive demand for FP oil | ▪ Map the characteristics of bio-oils vs. engine performances to support certification process<br>▪ LCA of WtW supply chain is needed inform decisions about bio-oils sustainability<br>▪ Information campaigns on results in support of decision making (ship owners, regulatory) |

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# HTL oil & crude will need regulatory measures to be cost competitive with fossil alternatives

## Highlights from cost analysis of HTL crude and HTL oil

- In all years, the <u>cost</u> of HTL crude is 50-80% higher than the <u>price</u> forecast for LSFO, and the cost of HTL oil is 110-150% times higher than LSFO price
- Thus, HTL oil and HTL crude will need regulatory measures to be cost competitive with fossil alternatives
- The main cost driver for both HTL crude and oil is the processing plant costs (CAPEX & OPEX), with biomass and hydrogen costs driving most of the remainder:

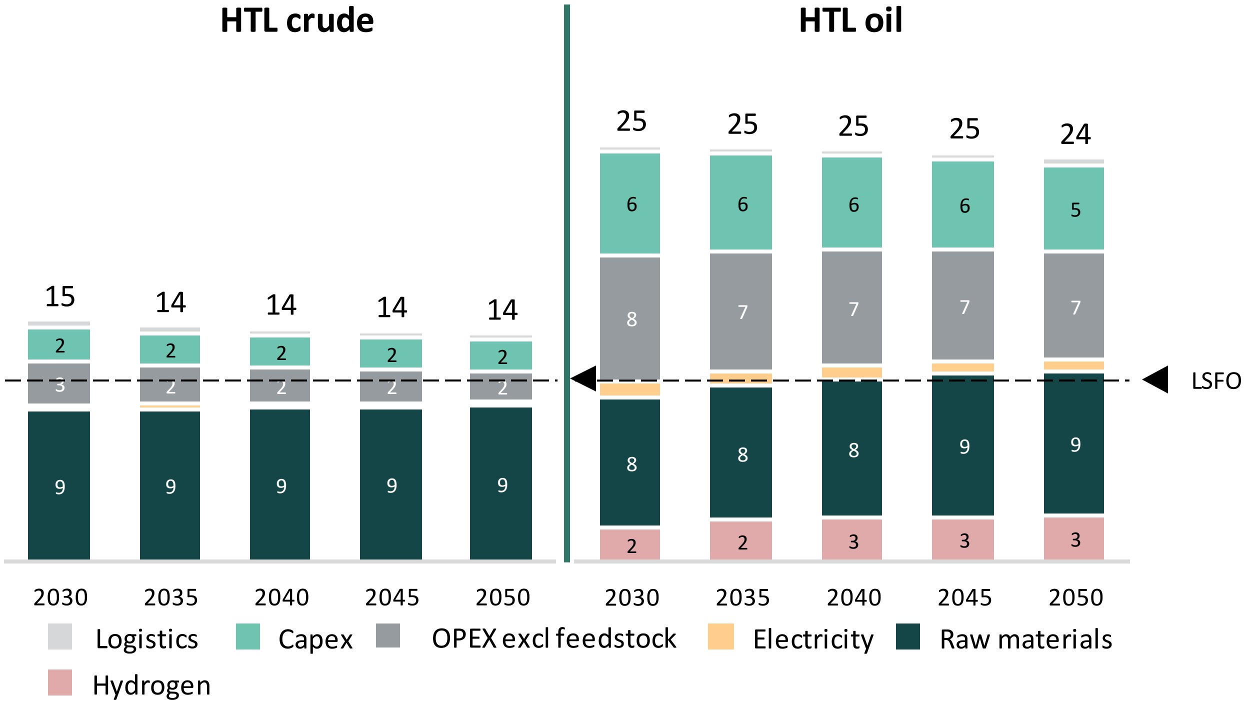
1. CAPEX and OPEX costs are expected to decrease following an industry learning curve. Little improvement from economies of scale is expected due to the associated rise in biomass transportation costs
2. Biomass costs are lower for HTL than FP oil due to the access to sludge and wet waste biomasses. They are expected to increase towards 2050 as the increasing demand for biomass drives the industry to utilize higher cost biomasses
3. The source of hydrogen for upgrading to HTL oil is expected to change from grey to blue and to green as the cost of these reach competitive levels, driving the price up towards 2050

- The processing price are expected to decrease slightly over time driven by learning curves but counteracted by increases in biomass and hydrogen costs

**Hydrothermal liquefaction oil pathway costs, at port**

Weighted global average[1]

USD/GJ



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[1] Assuming 60 % from lowest cost region, 40 % from 2nd lowest, and 0% from 3-5th.

# HTL crude and oil could cover 1% of fleet energy in 2040 and 10% in 2050 at maximum growth

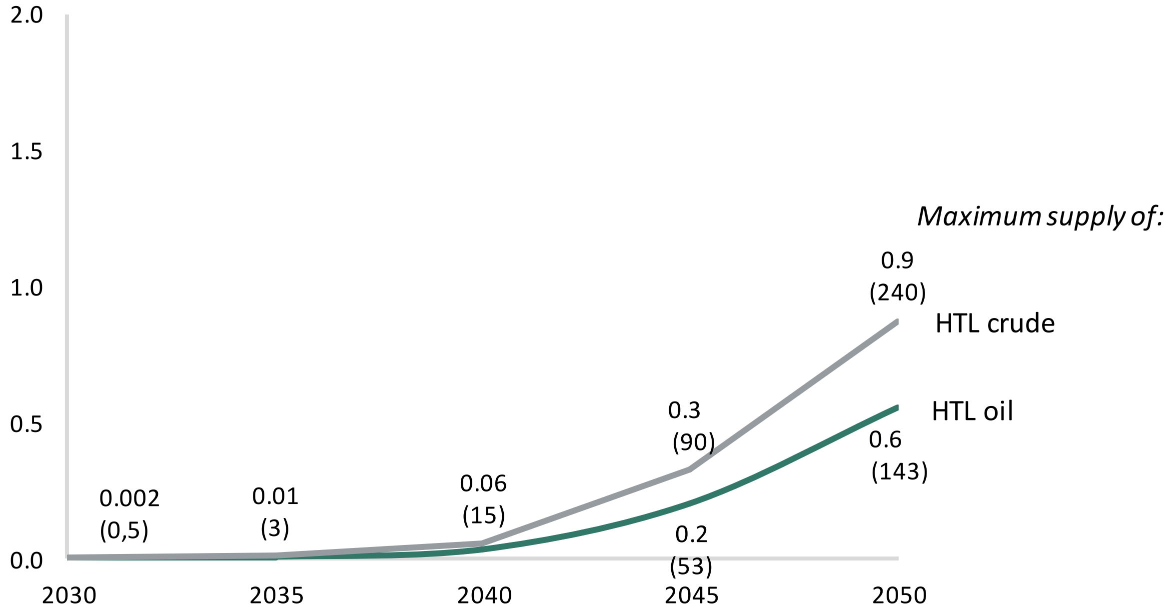
## Highlights from supply analysis of HTL crude and HTL oil

- HTL crude & oil production is still in development (TRL 7 & 6 respectively), and is expected to reach TRL 9 in late 2020s
- We project 3 HTL crude plants (100 kton product/year) and 2 HTL oil plants (80 kton product per year) in operation in 2030
- To simulate competition with other industries, we set a maximum volume of HTL crude & oil obtainable for the maritime industry. Maritime's current fraction of global non-electrifiable energy demand is 8%.[2] For the analysis, we used 16% which can be perceived from the industry taking a first-mover role into bio-fuels, being able to economize from customers' higher willingness to pay or being imposed stricter regulatory incentives than the other industries
- Considering the maximum roll-out speed, modelled by assessing historical biofuel roll-out speeds of technical and commercial mature technologies with government support,[1] HTL crude & oil could grow to impact the global shipping fleet from 2045 with a maximum supply of 0.3 EJ for HTL crude (2.5% of shipping's need) and 0.2 EJ for HTL oil (1.6% of shipping's need)

**Fastest possible roll-out of Hydrothermal liquefaction oil supply available for maritime, with unconstrained demand**

EJ/year

(Standard plants supplying shipping[3])



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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 plant size: HTL crude: 115 kton/year, HTL oil: 92 kton/year

# Adoption of HTL oil & crude in shipping is mainly limited by technical risks in development and competition for biomass and biofuel

Considering current activities:

| Subject | Risks | Expected mitigation timing |
|---|---|---|
| Feedstock | ▪ Biomass competition with other industries and other fuels is unclear, and could drive up feedstock costs | ▪ Refine assessment of biomass availability and sector competition on a regular basis |
| Production | ▪ No HTL full-scale plants in operation today (TRL 7)<br>▪ HTL oil upgrade technology in pilot scale (TRL 6)<br>▪ Competition from other industries could drive up fuel costs | ▪ Investments in research and innovation may accelerate commercialization |
| Logistics | ▪ Logistic & bunkering must be established for HTL oil & HTL crude – could benefit from existing infrastructure if fully upgraded or blended into established fuels | ▪ Map ports and needed supply<br>▪ Investments in supply infrastructure |
| Regulatory | ▪ Certification of fuels<br>▪ Standards needed to validate the sustainability of biofuel production pathways<br>▪ Regulatory measures will be needed to drive demand for FP oil | ▪ Map the characteristics of bio-oils vs. engine performances to support certification process<br>▪ LCA of WtW supply chain is needed inform decisions about bio-oils sustainability<br>▪ Information campaigns on results in support of decision making (ship owners, regulatory) |

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# Bio-oil emission benefits are similar to other bio-fuels, but could require fuel system changes, additional after-treatment and operational guidelines

**General note:** Bio-oil considerations are mostly based on current experience with FAME-based bio-fuels. Additional considerations have been identified based on known or expected differences, however, further investigation is needed before confirming main considerations and potential risk mitigations.

| Subject | Considerations | Potential risk mitigations |
|---|---|---|
| "Drop-in" distinction & fuel specification | • FAME, HVO and vegetable oil have been used onboard vessels without major modifications, mainly strong fuel management practices and some caution<br>• Bio-oils are less developed for marine use with different fuel characteristics that can impact systems<br>• In addition to fuel oil replacements, bio-oils could be used as a pilot for alternative fuels<br>• Bio-oil energy densities are similar to fossil-based fuel oils and require roughly the same volume<br>• Burning properties can be like fossil-based equivalents, however, the flashpoint must be above 60°C under SOLAS regulations<br>• Current ISO standard is not applicable to bio-oils<br>    • Only considers FAME up to 7% in certain distillate grades<br>    • Insurances, warranties and contracts may include clauses on ISO 8217<br>    • Equations are not valid for calorific values<br>    • No analysis tool for measuring how much biofuel a fuel contains<br>    • Acid number does not differentiate between strong acids in fossil fuels and weak acids in bio-fuels | • Proper bio-oil fuel specifications and standards to be developed<br>• Collaborate with fuel providers to determine optimal fuel standard that balances fuel-based (upgrading) and vessel-based measures |
| Fuel storage & systems | • Acids in crude grades can lead to corrosion in the fuel system<br>• Bacterial growth can occur at the oil/fuel and water interface<br>• Oxidative stability can lead to breakdown of the fuel and formation of harmful components, potentially leading to corrosion and filter blockages | • Fuel system materials to be compatible with acids and fuel characteristics (e.g., elastomers/sealing material)<br>• Tank coatings and cleaning procedures<br>• Ensure excess water can be drained |

Sources: MAN Energy Solutions "Concerning 100% biofuel and blends with ISO 8217 compliant fossil fuels" 22 March 2021*
ABS "Sustainability Whitepaper: Bio-fuels as Marine Fuel" May 2021

* MAN Energy Solutions experience are solely related to FAME and FAME-blends of biofuels. Considerations related to all other types of bio-oils and future blends are not currently known.

# Bio-oil emission benefits are similar to other bio-fuels, but could require fuel system changes, additional after-treatment and operational guidelines

| Subject | Considerations | Potential risk mitigations |
|---|---|---|
| Safety | • Bio-oils can be considered equivalent to residual fuels in terms of heating value, density, etc. but they have own distinct composition. | • For marine applications a careful review of the ship's fire plan documents and system layout in collaboration with Class may be necessary. |
| Energy converters | • Engines can manage bio-oils with proper analysis and optimization<br>• Bunkered (or mixed) fuel could have properties not suitable for use (flashpoint, viscosity, cold flow properties, water content, acid number/value)<br>• Measured calorific value needs to be used to run the engine efficiently | • Analyse bunker fuel to confirm compliance and adjust parameters such as fuel tank and system temperatures, fuel injection temperature and viscosity or cylinder lubrication rates<br>• Optimize engine combustion using actual calorific value<br>• High-quality fuel filter system |
| Emissions | • Tank-to-wake carbon emission intensity are similar to MGO<br>• Local air pollutants including SOx and PM are reduced due to their low sulphur content and high oxygenation<br>• NOx emission characteristics display large variation depending on bio-fuel chosen, engine and engine load, potentially requiring further NOx reduction<br>• Increased NOx emissions can lead to non-compliance with MARPOL Annex VI Regulation 13<br>• Engines are currently certified on fuel derived from petroleum refining | • In case NOx increase is above acceptable level, engine adjustments (with potential efficiency impact), water injection, selective catalytic converter (SCR) or exhaust gas recirculation (EGR) technology can reduce NOx emissions at the engine or as part of after-treatment |

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# FAME has not been included in the position paper due to low potential

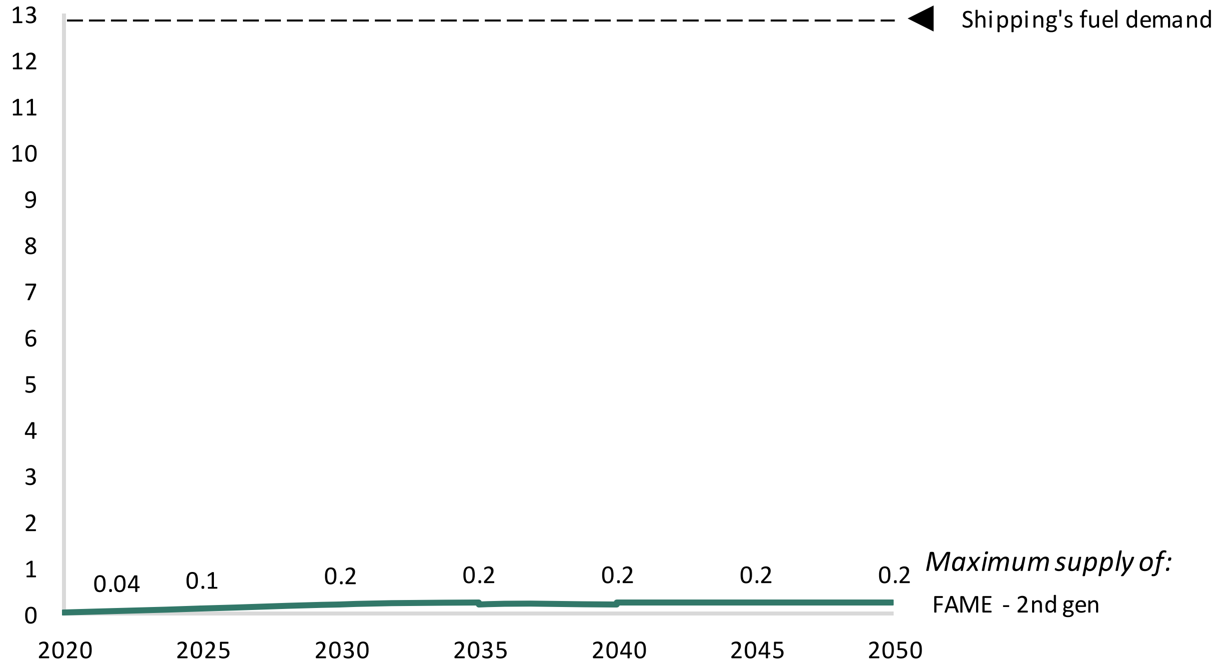
# FAME from waste products (2nd gen) could support up to 2% of shipping's energy need

## Supply analysis conclusions

- FAME is produced from two sources today: Food oils ( palm oil, soybean oil…) and waste oil (used cooking oil, acid oil…). FAME made from food oils, here named 1st gen, is considered to have high emission factors due to using land space, which either directly or indirectly causes deforestation – therefore, we only consider FAME produced from waste (2nd gen)
- Today, the global 2nd gen FAME production is 0,3 EJ for all sectors[3]. To simulate competition with other industries, we set a maximum volume of FAME obtainable for the maritime industry. Maritime's current fraction of global non-electrifiable energy demand is 8%.[2] For the analysis, we used 16% which can be perceived from the industry taking a first-mover role into bio-fuels, being able to economize from customers' higher willingness to pay or being imposed stricter regulatory incentives than the other industries Thus, 0.04 EJ is available to shipping today (0.3% of shipping's energy need)
- The maximum global potential of 2nd generation oils converted to FAME is believed to be 1.5 EJ (~40 mt/year)[4], or 0,24 EJ for shipping assuming a 16% availability (1.8% of shipping's energy need)
- Considering the maximum roll-out speed, modelled by assessing historical biofuel roll-out speeds of technical and commercial mature technologies with government support,[1] FAME could grow to maximum supply of 0.2 EJ in 2030 for shipping (1.8% of shipping's need)

**Fastest possible roll-out of 2nd generation FAME supply available for maritime, with unconstrained demand**

(EJ/year)



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3) UFOP (2020) Report on Global Market Supply 2019/2020

4) Ecofys (2019), ICAO (2018)