# DOE Bioenergy Technologies Office (BETO) 2021 Project Peer Review

# Determination of the Feasibility of Biofuels in Marine Applications 3.1.4.010-013

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Systems Development and Integration Session


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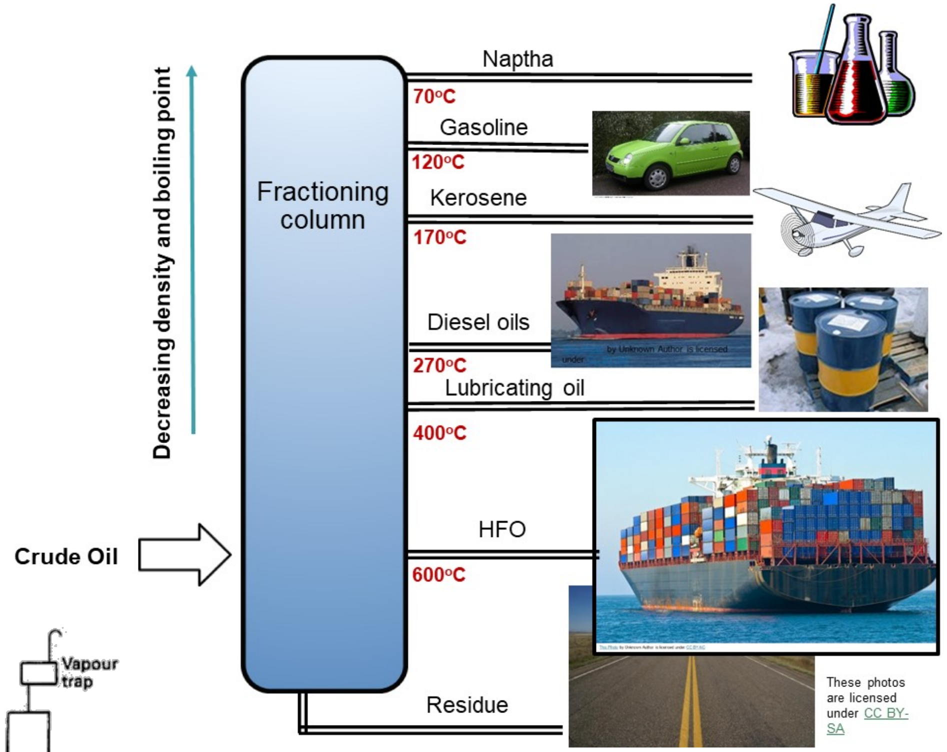
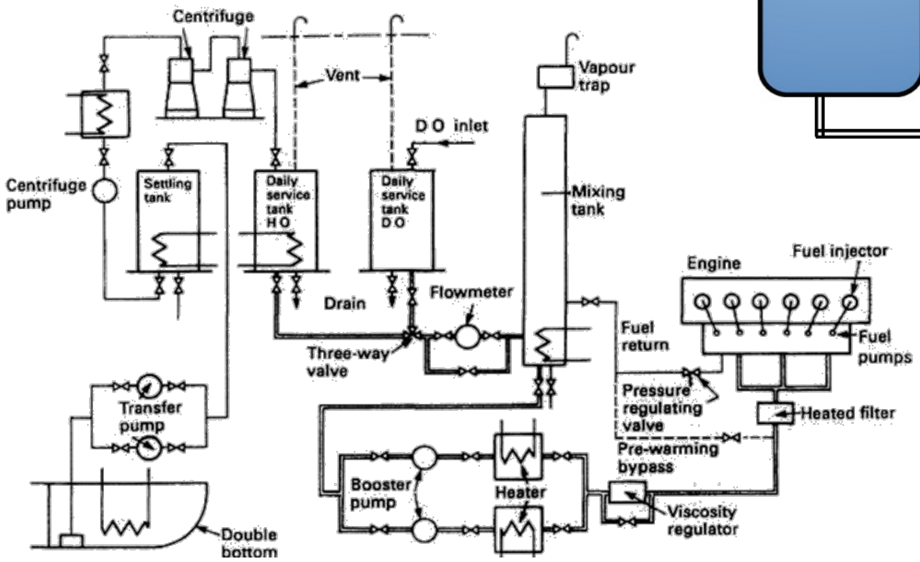
# Goals, Expected Outcomes, and Relevance

- Goal: to provide information to determine if biofuels have potential for the maritime sector. This information is used in technoeconomic analyses (TEA), life-cycle analyses (LCA) and technical feasibility analyses.
- The outcome is to determine whether BETO can, and should, implement a program to develop biofuels to be used in large ocean-going vessels to meet the International Maritime Organization's (IMO's) carbon reduction goals (a 40% reduction relative to 2008 levels by 2030, and between 50% and 100% reduction by 2050).
- Relevance: Biofuels offer a potentially viable fuel for marine engines powered using low-quality heavy fuel oil (HFO)
  - Pathway towards reduction of sulfur and particulate emissions
  - Potential path towards improved efficiency (reduced $CO_2$ emissions)
  - Identifying New Market Opportunities for Bioenergy and Bioproducts
- Key challenges are cost, compatibility, scalability, logistics & lack of reliable information

# Background: Marine Shipping Market

- Over 90% of all goods are shipped via marine vessels fueled with heavy residual fuel oil (HFO) or very low sulfur fuel oil (VLSFO)
  - 40,000 ships worldwide burn ~5.2 million barrels of fuel/day [1] (higher than US aviation and on-road diesel combined)
  - Largest source of global anthropogenic sulfur emissions worldwide, and of black carbon in the Arctic
  - Important contributor to worldwide $CO_2$ emissions (~2%)
- HFO is highly viscous and must be heated to temperatures exceeding 90°C to achieve proper flow
- On-board processing requires:
  - Heaters: maintain flow
  - Separator: remove water & sludge
  - Holding tanks
  - Filters
- In spite of the added hardware & energy costs, HFO is most economical fuel



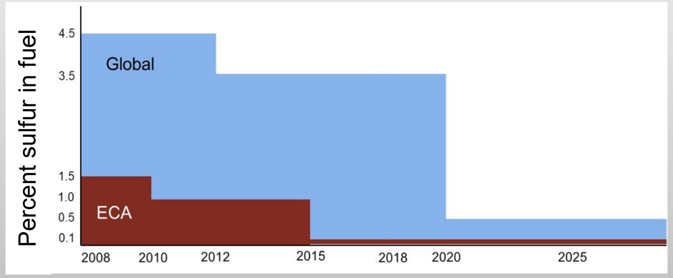



[1] Concawe. "Marine Fuel Facts," [Online].; 2017. Available from: https://www.concawe.eu/wp-content/uploads/2017/01/marine_factsheet_web.pdf.

# New emissions targets from International Maritime Organization (IMO) create significant challenges

Fuel sulfur cap: Reduced from 3.5% to 0.5% globally in 2020

"Very low sulfur fuel oil" (VLSFO)




Greenhouse Gas (GHG) emissions:

- Energy Efficient Design Index (EEDI) - present
- IMO mandate of 50% GHG reduction by 2050 (will require new low-carbon fuels)

Current lower-C fuels:

- LNG
- Biodiesel trials

Future net-zero C fuels:

- e-fuels
- Biofuels

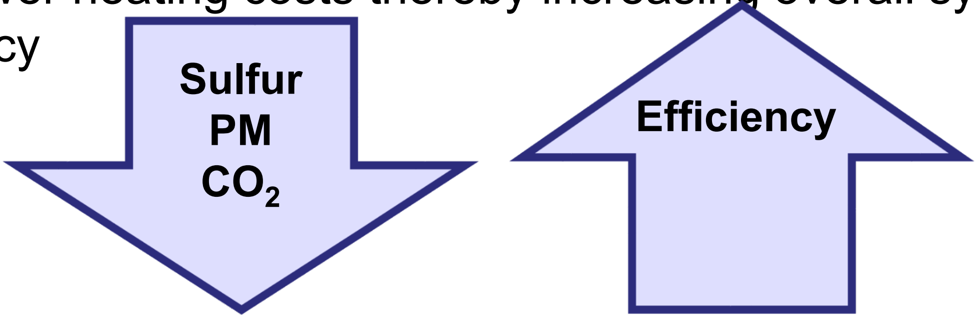


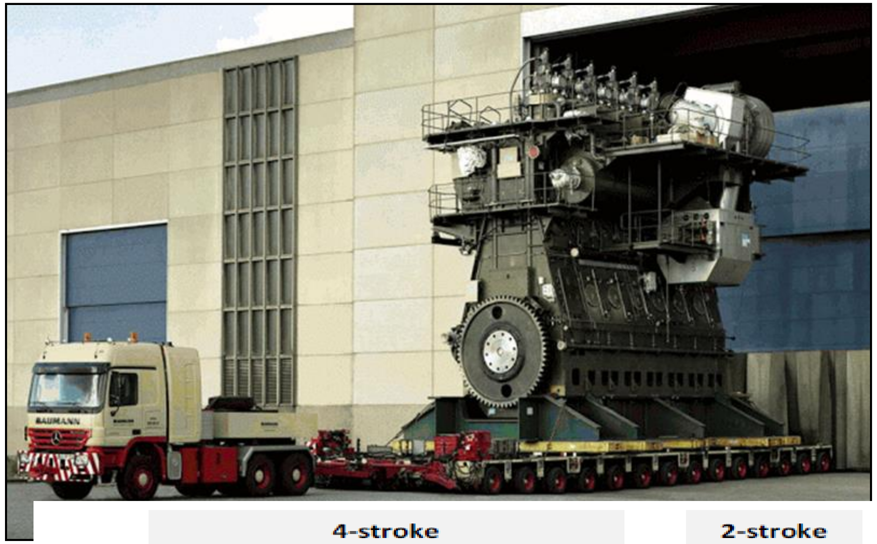
Liquified natural gas (LNG) requires cryogenic storage and dramatically lowers cargo carrying capacity. Methane slip increases GHG emissions.

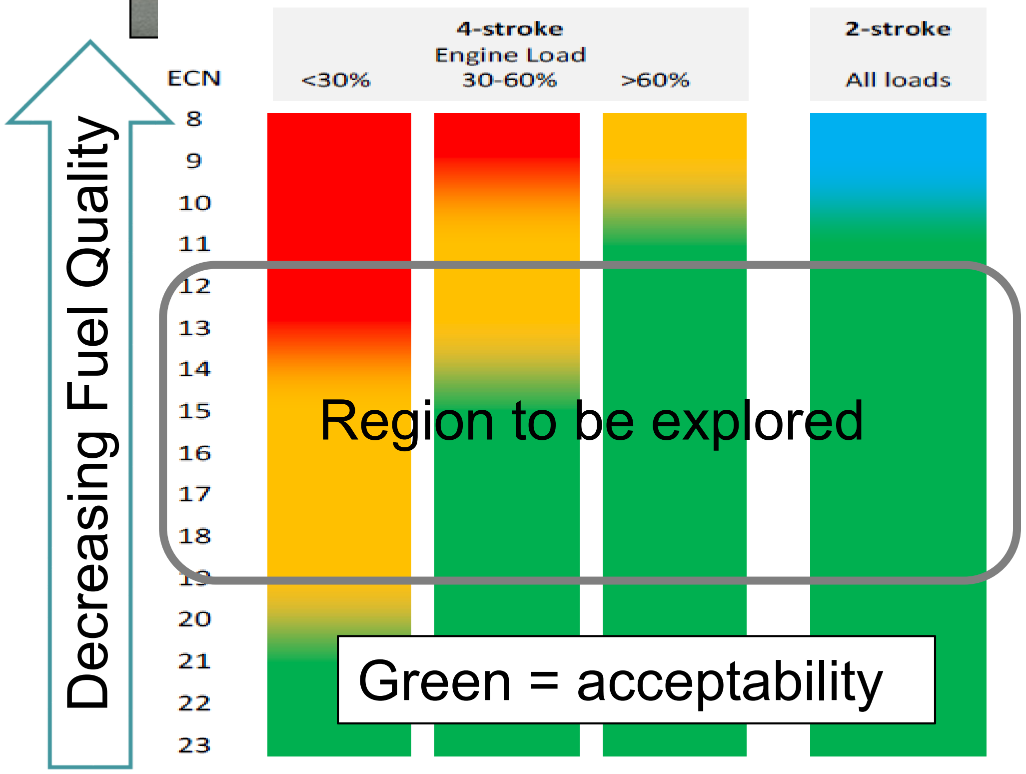
# Biofuels: Creative Advantage

Biofuels are an attractive option due to their capacity to leverage existing fuel and bunkering infrastructure, high energy density, and potential climate benefits.

- Marine engines are designed to burn low-grade residuum and can operate effectively on **low-combustion quality fuels**
- Bio-oils from pyrolysis processes and bio-crudes from hydrothermal liquefaction (HTL) processes are expensive to upgrade to be miscible with distillates (diesel, etc.), but have drop-in potential with HFO
- Compliance will raise operating costs such that biofuels may offer an economic alternative
- Biofuels have much lower viscosity, which, if blended with HFO, may lower heating costs thereby increasing overall system efficiency





# Project Overview

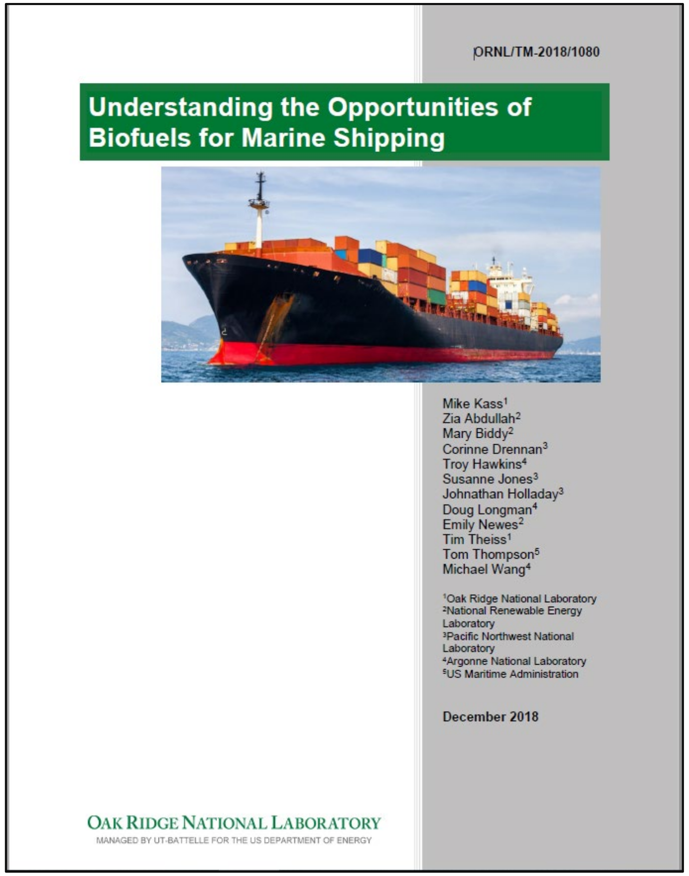
- Multi-lab team formed in 2018 to examine marine biofuel potential opportunities
- Initial motivation driven by potential of bio-intermediates to reduce sulfur emission from 2-stroke crosshead marine engines
- Outcome: Publication describing the opportunities for biofuels for Marine Shipping was distributed to DOT Maritime Administration (MARAD) and industry
- DOE has a strong working relationship with MARAD
  - MARAD funding labs to examine low sulfur ruling impacts, economics, life-cycle analyses, alternative fuel spill impacts, etc.
- Based on the whitepaper study (2018), a research project was initiated to determine the merits of a BETO program devoted to the marine sector
- High level vision is to focus on cost in the near-term and reducing carbon intensity in the long term

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Argonne NATIONAL LABORATORY

OAK RIDGE National Laboratory

Pacific Northwest NATIONAL LABORATORY


ORNL/TM-2018/1080

Understanding the Opportunities of Biofuels for Marine Shipping

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December 2018

OAK RIDGE NATIONAL LABORATORY
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Management

# The effort was divided into seven tasks based on answering seven critical questions.

**Questions for Go/No-GO Determination**

1. What is the range of market prices that must be met?
2. What are the target sustainability parameters?
3. Can compatibility requirements be met?
4. Can scalability needs be met for fuel demand?
5. What system modifications may be needed?
6. What the medium & long term options from the BETO portfolio?
7. What are the fuel supply logistics?

**Tasks**

1. Supply/demand curve and TEA (NREL)
2. Sustainability analyses (ANL)
3. Pathway assessments and analysis (PNNL & NREL)
4. Compatibility analysis (ORNL & ANL)
5. Fuel sample production & testing (PNNL & NREL)
6. Logistics (NREL)
7. Project management (ORNL)

**Communication and Information Dissemination**

1. Biweekly telecons with group and task teams
2. Stakeholder input achieved by web meeting and workshop

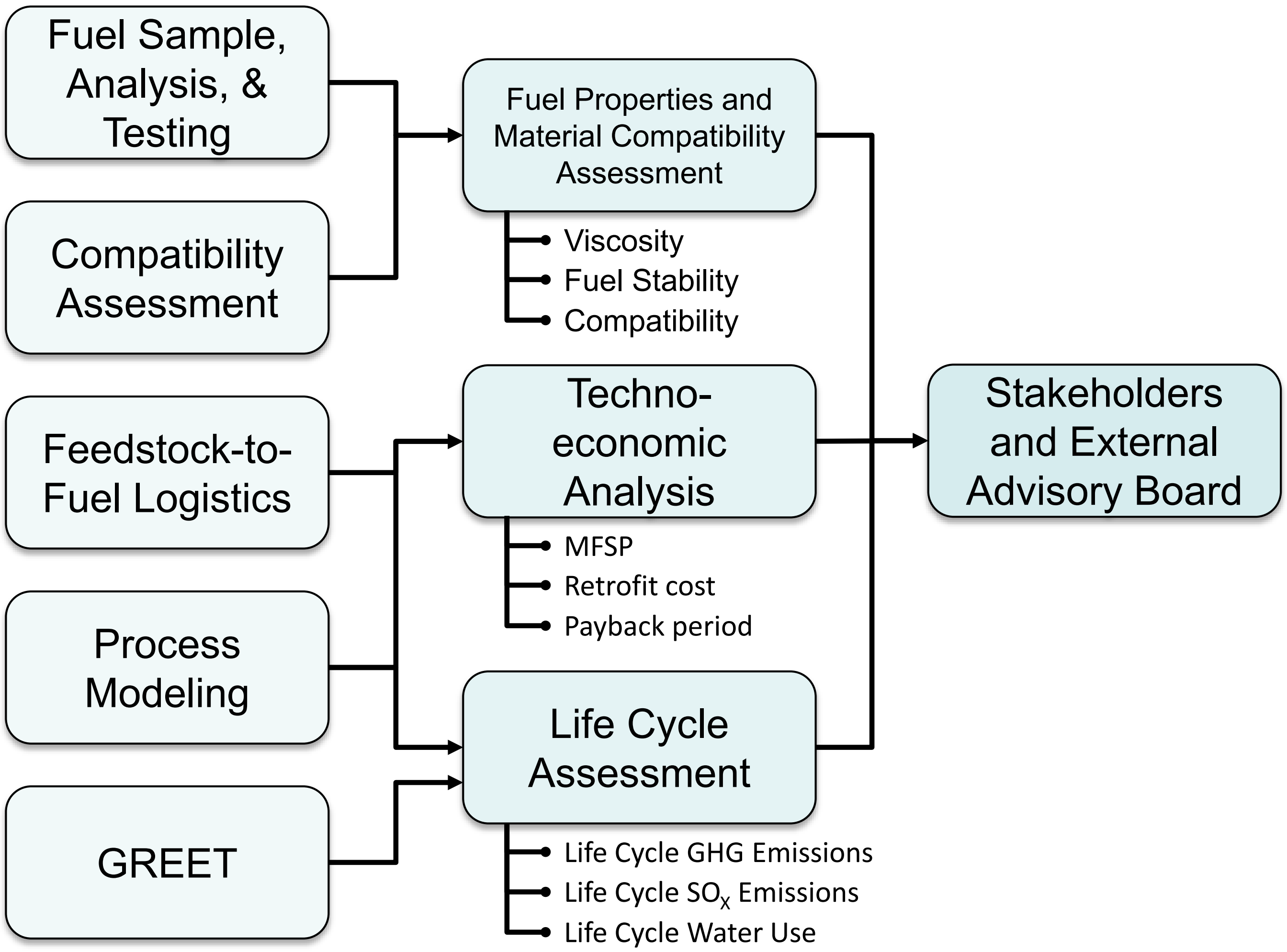
| Risks | Mitigation approach |
|---|---|
| Harmonization of efforts | Group meeting held to coordinate fuels, properties, terminology |
| Lack of data | Bi-weekly telecoms at group/task level<br>Leverage with relevant BETO and MARAD projects |

Approach

# Integrated Framework for Evaluating Marine Biofuels

**Integrated Modeling Framework**

- Interdisciplinary analysis that considers economic, environmental, and technical metrics
- Estimate key performance criteria using a combination of fuel property and material compatibility evaluation, feedstock-to-fuel logistics and technology scale up, techno-economic analysis, and life cycle assessment
- Down-select promising marine biofuel pathways, and engage with Maritime Stakeholders and External Advisory Board



Approach

# Research team identified the following fuels & properties

## Biofuels

Bio-oil
Bio-crude
Lignin ethanol oil
Fischer-Tropsch (F-T) diesel
Renewable diesel

## Baseline Fuels

HFO/VLSFO
Marine gas oil (MGO)
LNG
Fischer-Tropsch diesel
Biodiesel, methanol & ethanol

Note that there are multiple feedstock and production pathways

| Categories | Properties | Baseline Fuel Types | | | | | | Biofuels | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | HFO | MGO | LNG | Biodiesel | Methanol | Ethanol | CFP Bio-oil | HTL Bio-crude | Lignin ethanol oil | F-T diesel | Renewable diesel |
| Engine/Fuel System/Bunkering Infrastructure | Material compatibility (corrosivity and wear) | | | | | | | | | | | |
| | Fuel-fuel compatibility & stability (ASTM D4740 | | | | | | | | | | | |
| | Component compatibility (viscosity at 50 & 100C) | | | | | | | | | | | |
| | Blend limits | | | | | | | | | | | |
| | Waste generation/disposal | | | | | | | | | | | |
| Fuel Characteristics | Production maturity | | | | | | | | | | | |
| | Scalability | | | | | | | | | | | |
| | Transport | | | | | | | | | | | |
| | Engine use maturity | | | | | | | | | | | |
| Fuel Properties | Composition/impurities | | | | | | | | | | | |
| | Stability | | | | | | | | | | | |
| | Density | | | | | | | | | | | |
| | Volumetric energy density | | | | | | | | | | | |
| | Combustion quality | | | | | | | | | | | |
| | Cold filter plugging point | | | | | | | | | | | |
| | Viscosity | | | | | | | | | | | |
| | Lubricity | | | | | | | | | | | |
| Economic | MFSP ($/gge) | | | | | | | | | | | |
| | Price uncertainty | | | | | | | | | | | |
| | Current fuel cost | | | | | | | | | | | |
| | Current fuel reliability | | | | | | | | | | | |
| | Retrofit cost | | | | | | | | | | | |
| | Retrofit schedule | | | | | | | | | | | |
| | Fuel Standards | | | | | | | | | | | |
| Safety | Human health (toxity, carcinogenic, etc.) | | | | | | | | | | | |
| | Flammability limit | | | | | | | | | | | |
| | Suffocation potential | | | | | | | | | | | |
| | Explosion risk | | | | | | | | | | | |
| Environmental | Life Cycle GHG Emissions | | | | | | | | | | | |
| | Life Cycle Sulfur Emissions | | | | | | | | | | | |
| | Life Cycle NOx Emissions | | | | | | | | | | | |
| | Life Cycle SOx Emissions | | | | | | | | | | | |
| | Life Cycle PM Emissions | | | | | | | | | | | |
| | Life Cycle Water Use | | | | | | | | | | | |
| | Large spill/release impact | | | | | | | | | | | |

Approach

# Background

***Tasks 1-3 (Supply/Demand &TEA, Sustainability & Pathway Assessments)***

- Survey known cellulosic biofuels & assess relative merits as marine fuels
- Compile initial list of fuels, production modes & properties
- Incorporate stakeholders' feedback from web meeting and CMA workshop for validation and screening-level economic study
- Feedback used to develop and prioritize final list of fuels, production modes & properties
- Perform TEA and LCA of medium-term and transitional opportunities
- Revise or develop new pathways (e.g., tailoring product slate, minimizing processing) to reduce costs
- Input to LCA study

***Tasks 4-5 (Fuel sample production and compatibility evaluation):***

- Produce representative samples
- Evaluate compatibility & combustion performance
- Identify representative materials and flow specifications

***Task 6 (Logistics)***

***Task 7 (Management):*** Research and stakeholder engagement

***All Tasks*: Assimilate** and **synthesize** findings (i.e., from all tasks)

# Top Technical Challenges

| Technical challenges | The Go/No-Go decision will be made based on economic costs associated with biofuel production relative to potential GHG and efficiency benefits |
|---|---|
| • Fuel blend compatibility (need to avoid precipitation and polymerization)<br>• Fuel system compatibility<br>  • Combustion (Estimated Cetane Number)<br>  • Viscosity control<br>• Fuel flexibility<br><br>**Economic challenges**<br>• Feedstock cost<br>• Pathway costs<br>• Scalability<br>• Logistics | **Criteria is based on:**<br>• Near-term assessments of biofuel costs versus the predicted fuel costs for baseline fuels<br>• Mid-term/transitional efficacy of bio-oil and bio-crude as HFO substitutes. Can serve both aviation and marine markets.<br>• Long-term potential for carbon reduction<br>• Industry willing to pay premium<br>• GHG reduction<br>• Fueling system efficiency improvements |

Future Activities:

- Refinement of TEA & LCA
- Continued stakeholder outreach and engagement
- Engine-based experiments

Impact

# Marine emissions are challenging to eliminate, but biofuels offer potential for significant near-term impact

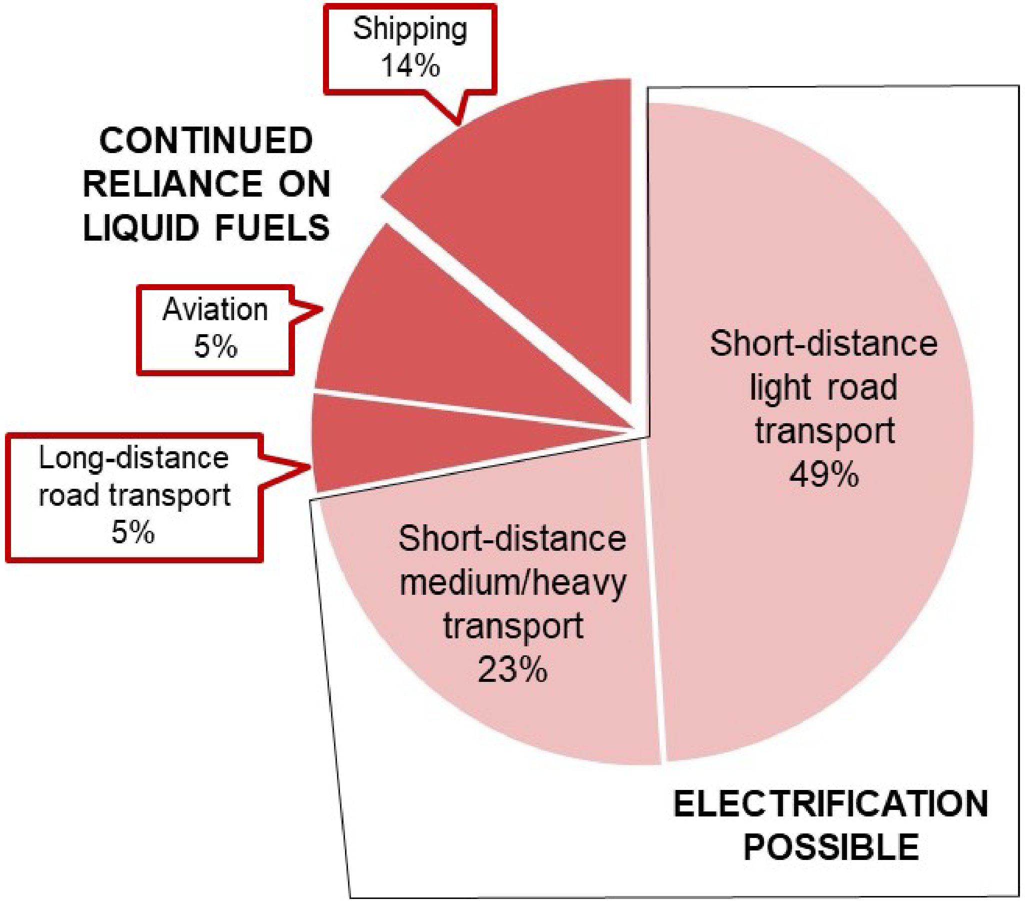
Shipping emissions account for 18% of global transportation-sourced 20-year $CO_2$-equivalent global warming potential (GWP)

This includes Black Carbon which also significant GHG impact: ~4% $CO_2$-equivalent 20yr GWP

Large potential market for biomass and biofuels: global shipping consumes 300 Mt/year

Results disseminated by
- Ongoing communications with DOT
- Publications, example includes Ensyn reaching out as a result of the Energy & Fuels article
- Stakeholder engagement through web meeting and conference workshops

Transportation $CO_2$ by source (~7.5 Gt/yr globally)




"Smith et al. (2015) estimate that ship $CO_2$ emissions will **increase** 50%–250% from 2012 to 2050, and CE Delft (2017) projects that emissions will **increase** 20%–120% over the same period for global temperature rise scenarios less than 2°C"

# Marine Biofuels Workshop held in October 2020 was instrumental in getting stakeholder viewpoints and perspectives


**Panelists and speakers included noteworthy experts:**

- ***Bart Hellings***, Chief Operating Officer of GoodFuels
- ***Dirk Kronemeijer***, CEO and Founder of GoodFuels
- ***Lee Kindberg***, Head of Environment and Sustainability of Maersk, North America
- ***Adrian Tolson***, Director of Blue Insight
- ***John Larese***, Technical Advisor for ExxonMobil Marine Fuels
- ***Chrystos Chryssakis***, Business Development Manager for DNV GL Maritime

# Stakeholder Feedback

- Industry not be aware of full range of biofuel types (e.g. bio-oils and bio-crude)
- Industry has not settled on a specific biofuel. Evaluating multiple options. This includes novel fuels such as lignin ethanol oil (LEO).
- The industry does not have a consistent strategy for meeting future decarbonization plans and is considering multiple options.
- Industry strongly supported the notion of a US government research and development program and would be willing to help support the same.
- Global market and global considerations such as feedstock, fuel availability and sustainability are important
- It is doubtful that a single future fuel will serve the entire industry. Multiple new options will need to be considered and implemented.
- Concerns over the deployment of multiple fuel types and future 'stranded assets'
- New fuel standards focusing on biofuels may be needed.
- Cost is not the sole driving concern. Good stewardship is important.
- In 2018, Maersk pledged to achieve net zero carbon emissions by 2050, and is pursuing the deployment of carbon-neutral vessels by 2030.
- Because the average lifetime of a marine vessel is ~20 years, there is an urgent need to rapidly identify alternative fueling options for the Marine sector in order to meet IMO 2050 targets

MÆRSK

ExxonMobil

MAN

WORLD SHIPPING COUNCIL
PARTNERS IN TRADE

# Tasks 1-3

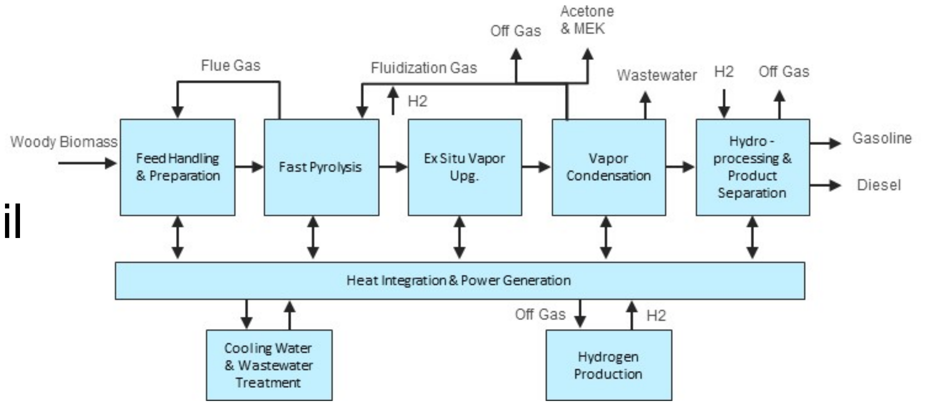
**Reviewed biofuel production pathways & scalability:**

- Screened biofuels (largely based on BETO's conversion pathways) and assessed their relative merits regarding marine applications
- Revised metrics to enable better assessment of biofuel production pathways
- Identified potential biofuel pathways that could serve as the focus for future analysis
- Assimilated & synthesized findings (from all tasks)
- Synergy between marine and aviation needs

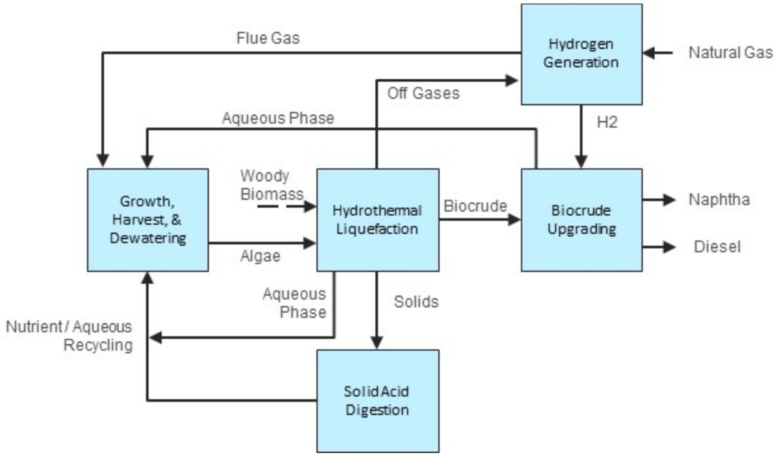
**Performed TEA on identified high-priority marine biofuel pathways, including:**

- Non-catalytic fast pyrolysis (FP) bio-oil
- Catalytic fast pyrolysis (CFP) bio-oil
- Hydrothermal liquefaction (HTL) biocrude
- Lignin-ethanol oil
- Biogas/landfill gas
- F-T diesel
- Renewable diesel
- Heavy cuts from jet fuel pathways

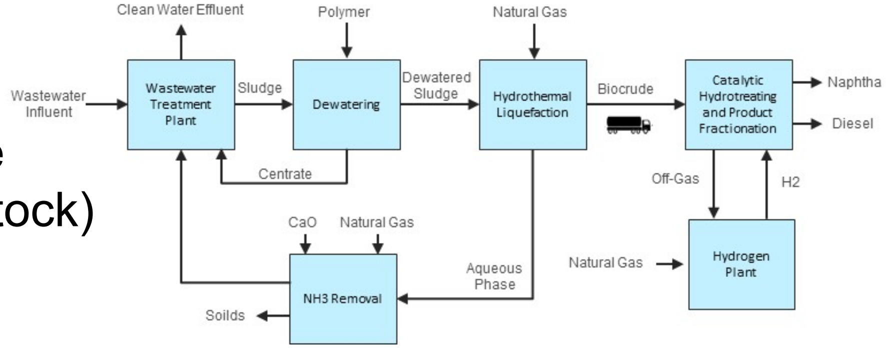
CFP bio-oil



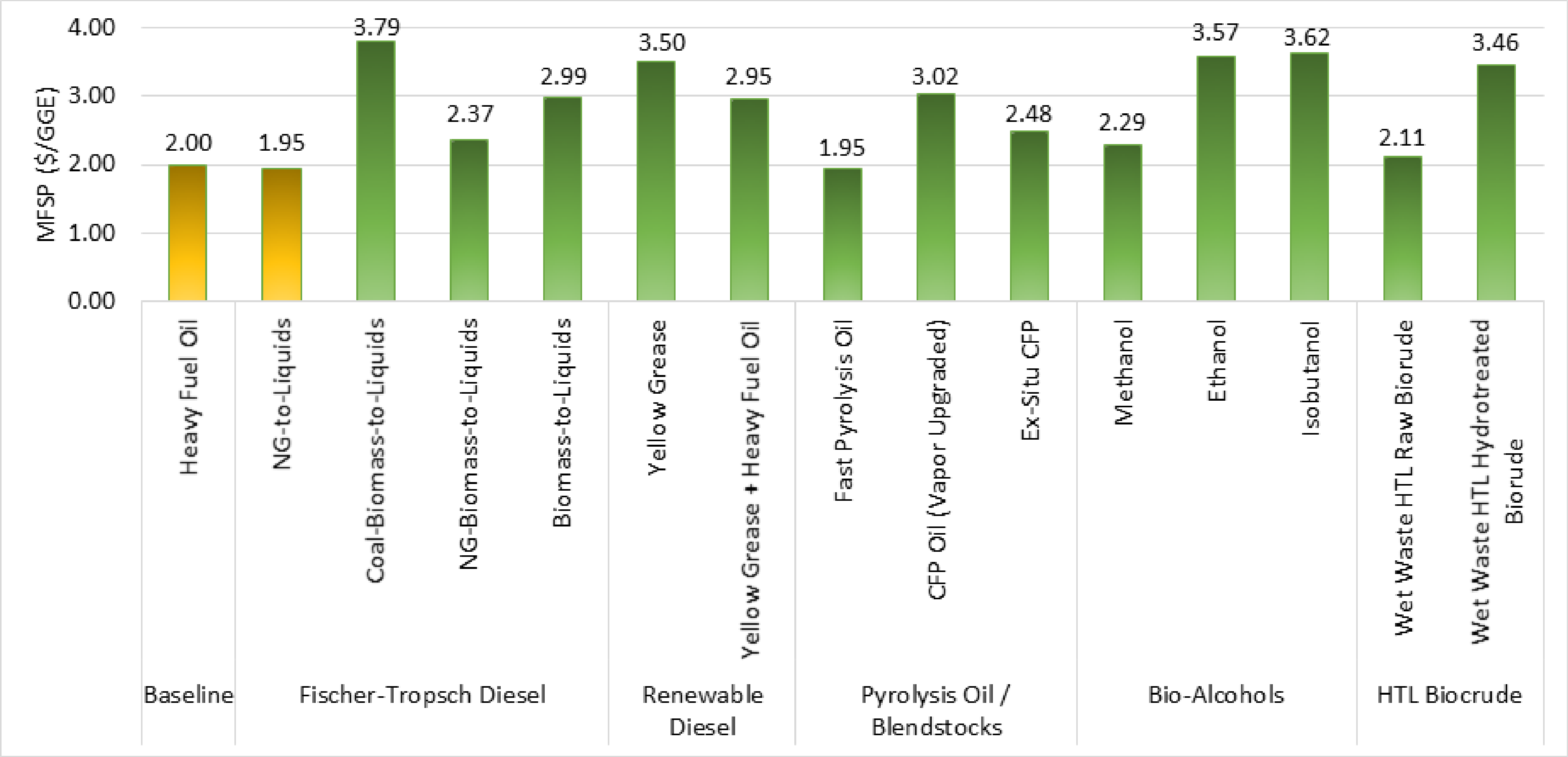

HTL bio-crude (woody feedstock)




HTL bio-crude (sludge feedstock)

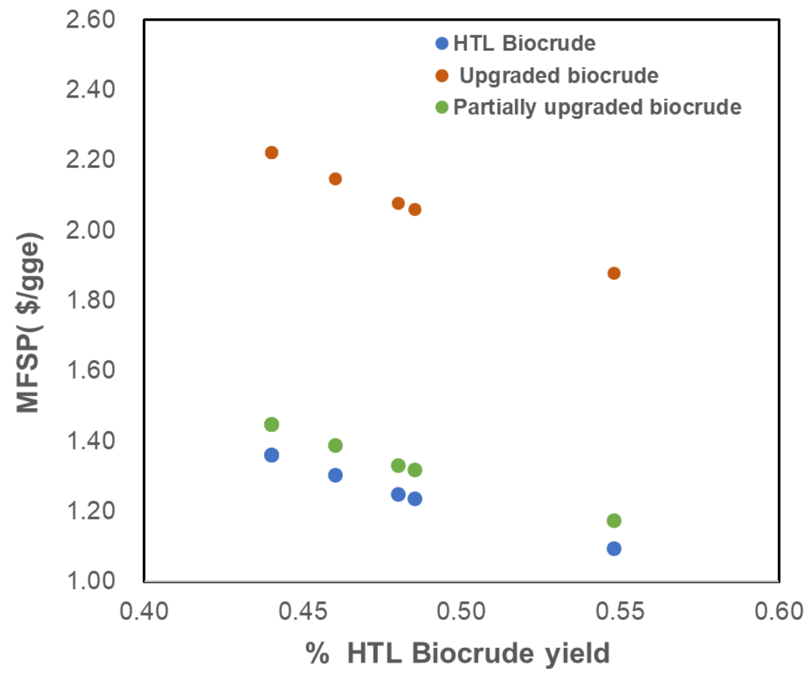


# Tasks 1-3 Preliminary TEA Shows that Bio-oil and Bio-crude fuel costs can approach those of HFO and exceed those of the bio-alcohol baseline options

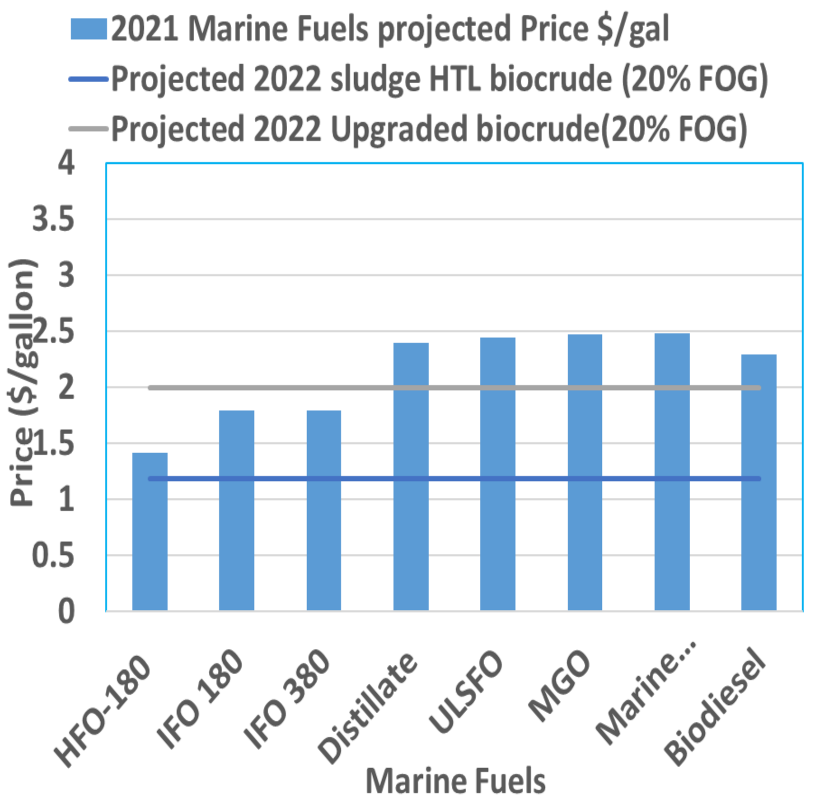


# Tasks 1-3 Preliminary HTL and Upgraded Biocrude TEA

- The yield, processing step counts, and process size play significant roles in lowering the final biocrude price.
- HTL Biocrude yields vary concerning the feedstock composition.
- The TEA analysis was conducted based on the HTL experimental yield results generated from different blends of HTL biocrude feedstocks like sludge, FOG, manure, food waste.
- The 80% wet waste and 20% FOG (fats, oils, and grease) feedstock gives higher biocrude yield. More analysis is underway to determine the impact of feedstock composition on HTL biocrude cost




**This preliminary analysis is based on the 2022 target case at HTL plant size of 1000 TPD.**




**Sludge and 20% FOG HTL and upgraded biocrudes costs compared to some marine fuel prices.**

Marine fuel prices are based on the Defense Logistics Agency's periodic publications. Fuels names are as follows: HFO-180:Fuel Oil, Marine, Residual, Grade RME-180; IFO 180:Fuel Oil, Intermediate Grade RME-180; IFO 380:Fuel Oil, Intermediate Grade RMG-380; Distillate: Fuel Oil, Naval, Distillate; ULSFO: Ultra Low Sulfur fuel oil; MGO: Gas Oil, Marine; Marine Diesel: Commercial Marine Diesel; Biodiesel: Biodiesel ( Transesterification).

Potential Biocrude costs could approach some of marine fuel selling prices

# Tasks 1-3: Environmental Performance Heatmap Shows the GHG Benefits of Biofuels

## Environmental Performance

- Dedicated Biomass pathways demonstrate >50% reduction in GHG emissions relative to HFO
- The environmental performance of marine biofuels is commensurate with IMO's[1] Long-term GHG Emission Reduction Targets

## Marine Biofuel Pathways

- 17 Novel Marine Fuel Pathways Evaluated to-date
- 6 Marine Methanol Pathways Added to Argonne's GREET Model in FY20

| | Marine Fuel Pathways / Environmental Metrics | GHG | CO2 | CH4 | N2O | SOX | NOX | PM2.5 | PM10 | Water Use |
|---|---|---|---|---|---|---|---|---|---|---|
| Dedicated Biomass | Woody Biomass / Fischer-Tropsch / Diesel | -94% | -95% | -92% | -5% | -84% | -5% | -79% | -79% | 191% |
| | Woody Biomass / Pyro / Bio-Oil | -89% | -91% | -85% | 47% | -95% | -9% | -79% | -78% | -58% |
| | Forest Residue & Clean Pine / CFP / RD | -86% | -89% | -85% | 105% | -95% | -8% | -78% | -78% | -10% |
| | Soybean / Oil Extraction / SVO | -85% | -93% | -87% | 519% | -93% | -9% | -79% | -79% | 2882% |
| | Yellow Grease / Hydrotreating / Diesel | -85% | -87% | -74% | -1% | -99% | -9% | -79% | -79% | -79% |
| | Forest Residue / IDL / Methanol | -84% | -86% | -78% | -2% | -98% | -8% | -78% | -78% | 79% |
| | Corn Stover / Biochemical / Isobutanol | -80% | -80% | -66% | -132% | -56% | -8% | -76% | -76% | 638% |
| | Forest Residue & Clean Pine / IDL / Liquid Petroleum Gas (LPG) | -78% | -82% | -72% | 142% | -91% | -7% | -77% | -77% | 80% |
| | Corn Stover / Biochemical / Ethanol | -71% | -72% | -53% | -54% | -58% | -7% | -76% | -75% | 842% |
| | Forest Residue / Thermochemical / RD | -70% | -72% | -55% | 4% | -96% | -7% | -77% | -76% | 77% |
| | Clean Pine / Pyro / Upg. Pyro Oil | -70% | -73% | -52% | 157% | -91% | -7% | -77% | -76% | 44% |
| | Soybean Oil / Hydrotreating / Biodiesel | -67% | -74% | -72% | 498% | -92% | -8% | -79% | -78% | 2765% |
| | Sludge / HTL / Biocrude (with NH3 removal) | -61% | -63% | -41% | 9% | -96% | -8% | -77% | -77% | 14% |
| | Algae / HTL / Biodiesel | -54% | -57% | -6% | 18% | -64% | -7% | -77% | -75% | 74% |
| | Sludge / HTL / Biodiesel (with NH3 removal) | -51% | -53% | -22% | 15% | -95% | -8% | -77% | -76% | 69% |
| Fossil & Biomass | Yellow Grease & HFO / Upg. / Diesel | -49% | -49% | -76% | -1% | 164% | -9% | -19% | -19% | -84% |
| | Biomass & NG / Fischer-Tropsch / Diesel | -33% | -36% | 20% | -3% | -92% | -8% | -80% | -79% | 88% |
| | Biomass & Coal / Fischer-Tropsch / Diesel | 20% | 18% | 89% | -2% | -88% | -9% | -77% | -68% | 206% |
| Fossil | Marine Gasoil (1.0% sulfur) | -8% | -8% | -2% | -3% | 82% | -9% | -38% | -37% | -2% |
| | Marine Gasoil (0.5 % sulfur) | -8% | -8% | -1% | -3% | -8% | -9% | -58% | -58% | -1% |
| | Marine Gasoil (0.1 % sulfur) | -7% | -8% | -1% | -3% | -79% | -9% | -75% | -75% | -1% |
| | Marine Distillate Oil (1.92% sulfur) | -5% | -5% | -2% | 1% | 263% | -5% | 5% | 5% | -2% |
| | Liquefied Natural Gas (LNG) | -4% | -28% | 788% | -51% | -95% | -85% | -93% | -93% | -82% |
| | Marine Distillate Oil (0.5% sulfur) | -4% | -4% | -1% | 1% | -4% | -5% | -56% | -56% | -1% |
| | Marine Distillate Oil (0.1% sulfur) | -3% | -4% | 0% | 1% | -79% | -5% | -74% | -73% | 0% |
| | HFO (2.7% sulfur) | -1% | -1% | -2% | 0% | 428% | 0% | 98% | 98% | -2% |
| | HFO (0.5% sulfur) | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| | HFO (0.1% sulfur) | 0% | 0% | 0% | 0% | -78% | 0% | -18% | -18% | 0% |
| | NG / Fischer-Tropsch / Diesel | 3% | 2% | 52% | -2% | -94% | -9% | -80% | -80% | 44% |

Environmental Impacts are scaled relative to HFO (0.5% S). Negative values indicate a *reduction* in environmental impact relative to HFO, while positive values indicate an *increase* in environmental impact relative to HFO. All results are presented on a well-to-hull basis.

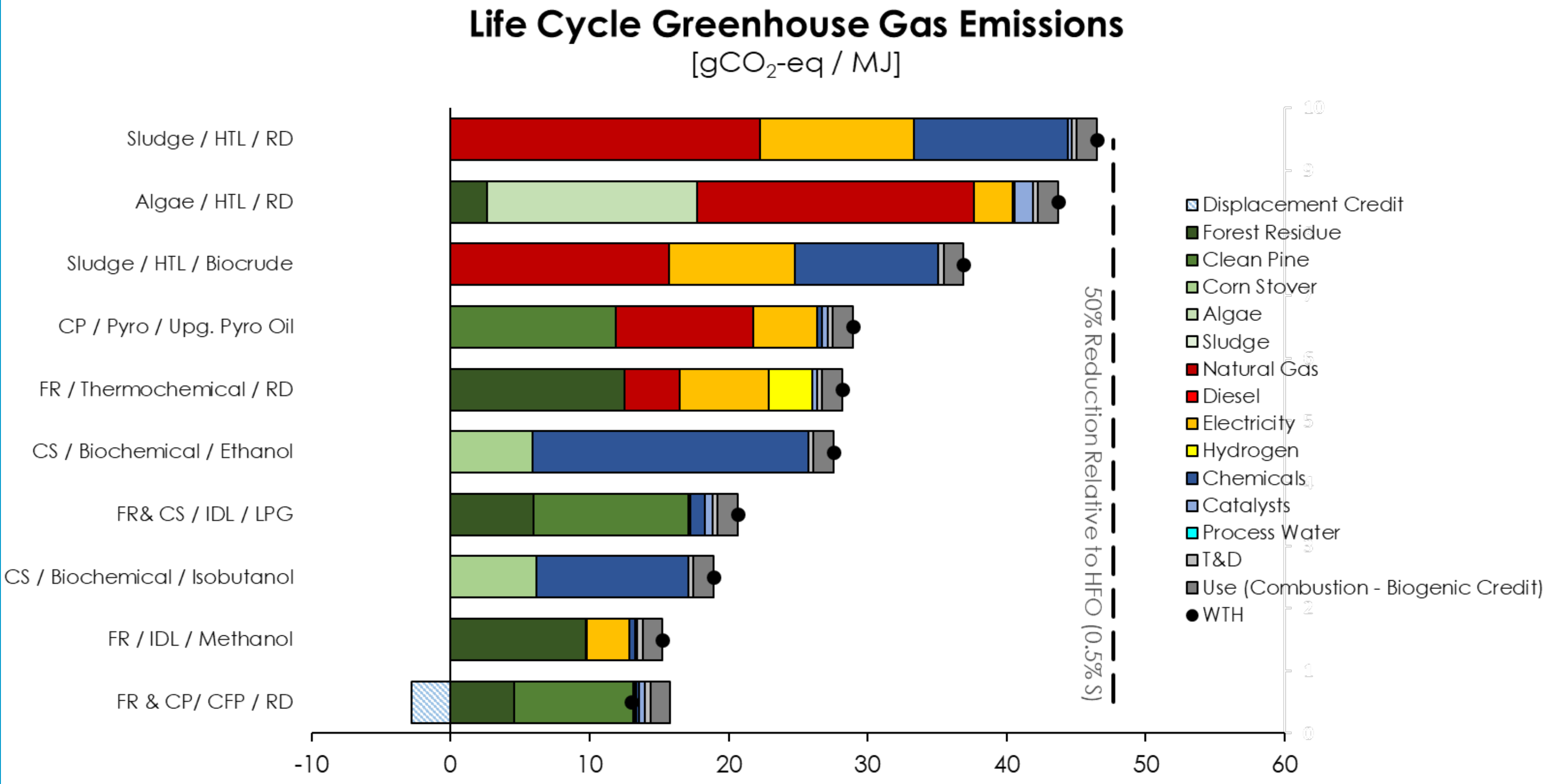
[1]The International Maritime Organization (IMO) has set targets to reduce GHG emissions from international shipping by 50% in 2050, relative to 2008

Progress and Outcomes

# Tasks 1-3: LCAs Show the Benefits of Biofuels & Pathways Towards Meeting or Exceeding the IMO 2050 Target

## Environmental Analysis

- A wide breadth of marine biofuels were considered in FY20, spanning biocrudes, bio-alcohols, blendstocks, drop-in fuels
- Life Cycle GHG emissions ranged from 13 to 46 $gCO_2e/MJ$ across the host of fuel pathways evaluated
- Biofuel pathways demonstrate a high capacity for GHG emissions reductions relative to HFO




Well-to-Hull Life Cycle GHG Emissions for Marine Biofuel Pathways evaluated in FY20. Results are generated using Argonne's GREET Model (GREET2020).

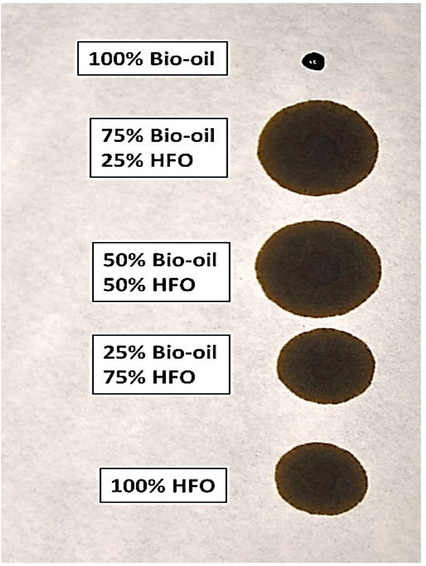
CS: Corn Stover; CP: Clean Pine; CFP: Catalytic Fast Pyrolysis; FR: Forest Residue; IDL: Indirect Liquefaction; LPG: Liquefied Petroleum Gas; HTL: Hydrothermal Liquefaction, RD: Renewable Diesel

Progress and Outcomes

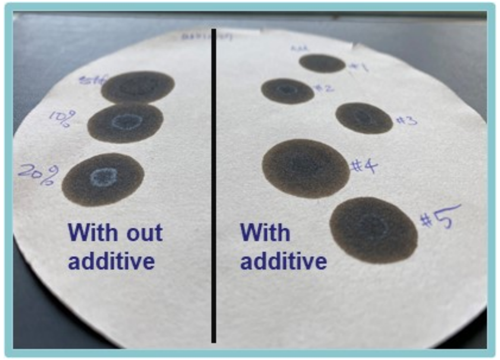
# Tasks 4-5 Technical Accomplishments

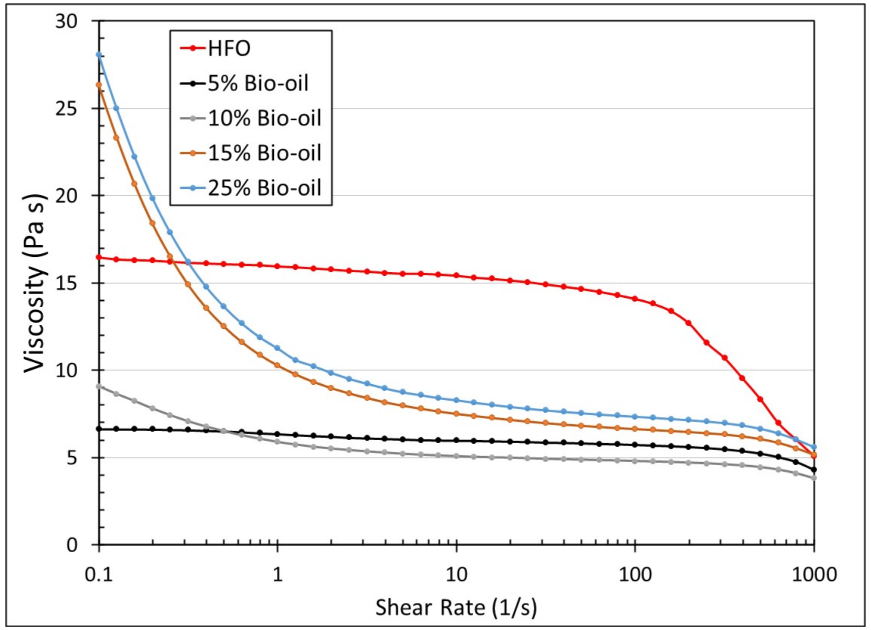
- Bio-oils have demonstrated good compatibility with VLSFO (ASTM 4740)
- Bio-crudes will likely require additives to improve blend stability. Preliminary work is promising
- Both bio-oil and bio-crude effectively lower the viscosity of VLSFO (even at low concentrations).
- Blends of bio-oil and bio-crudes with VLSFO demonstrated good compatibility with fuel system metals

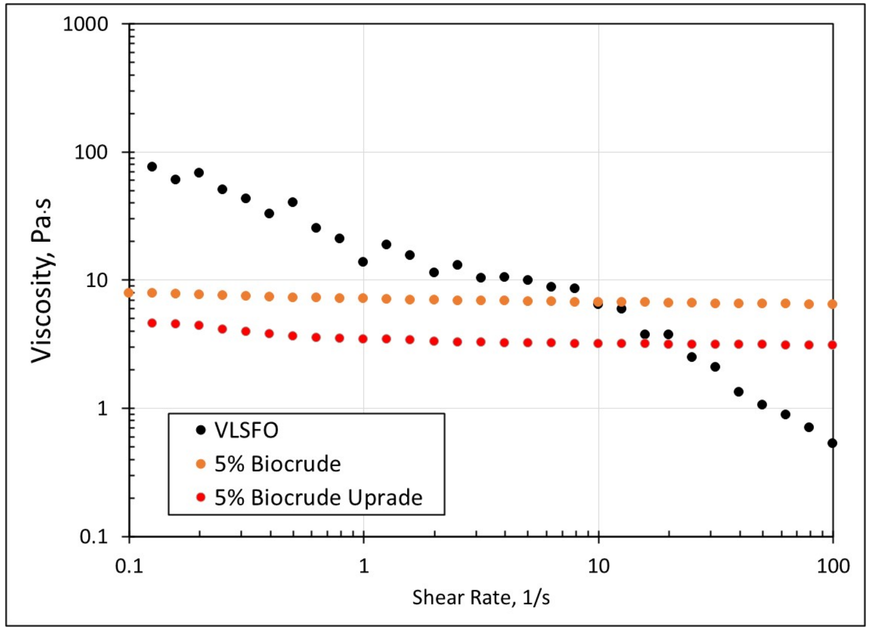
ASTM 4740 spot analysis results from bio-oil




ASTM 4740 spot analysis results from wet waste derived biocrude



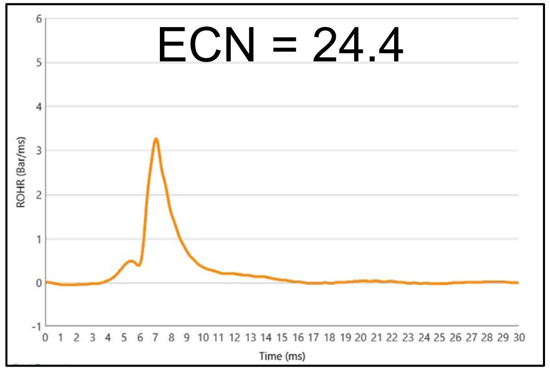



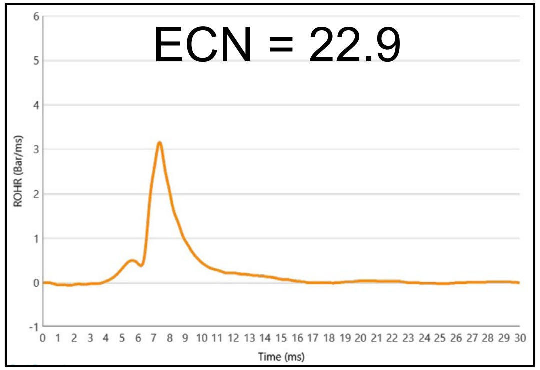
# Bio-intermediates show excellent combustion quality when blended with VLSFO

- Addition of 5% fast pyrolysis (FP) bio-oil and upgraded bio-crude provided excellent combustion
- Addition of up to 10% bio-oil provided excellent combustion
- ECNs all greater than 20

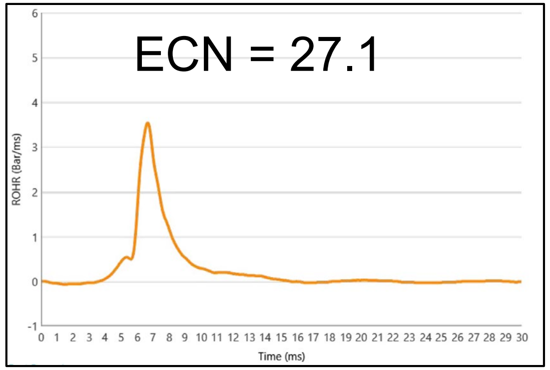
HTL bio-oil
algal feedstock




VLSFO

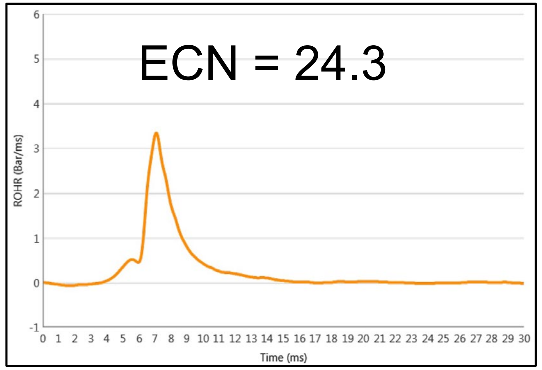



5% Bio-crude

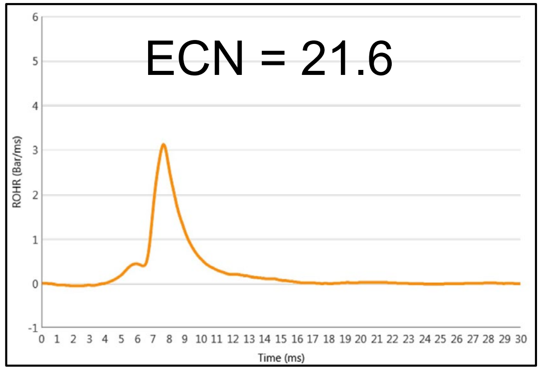



5% Upgraded Biocrude

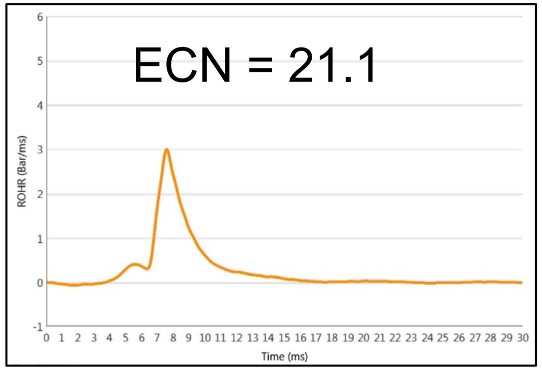
FP Bio-oil
pine feedstock




VLSFO




5% Bio-oil




10% Bio-oil

# Bio-intermediates show excellent compatibility with infrastructure metals

- Metals and alloys were representative of those used in on-board fuel systems (tanks, pumps, and piping).
- Test conditions were 500 hours at 50°C
- Results showed good compatibility with fast pyrolysis bio-oil at blend levels up to 50%
- Dilution of the bio-oil was responsible for the observed behaviors
- Effort leveraged with BETO Bio-oil Evaluation for Marine Use AOP

Metals were evaluated in unstressed and stressed states

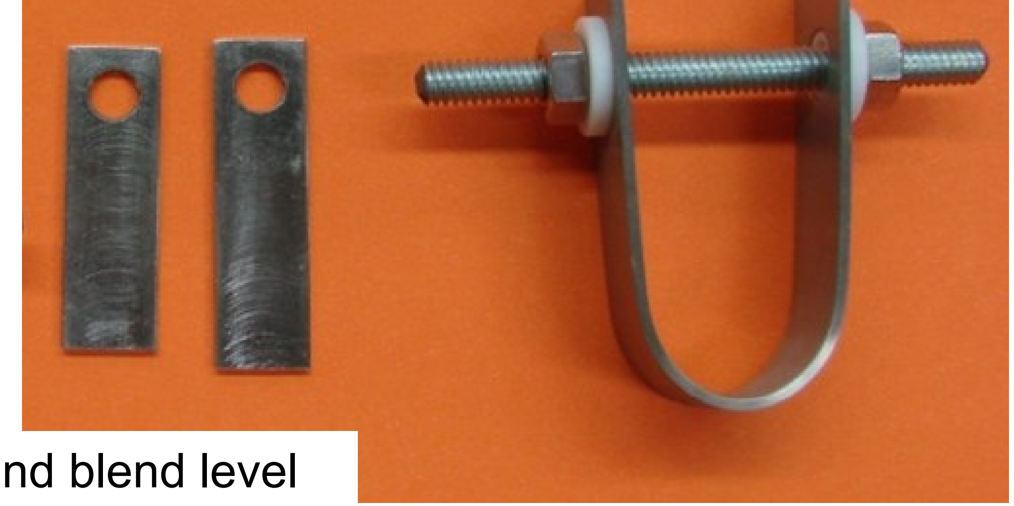


Table showing corrosion rates (mils per year) for each metal and blend level

| Bio-oil content (mass%) | Carbon Steel | | 2.25Cr– 1Mo Steel | | 409 Stainless Steel | | 304L Stainless Steel | | 316L Stainless Steel | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 250h | 500h | 250h | 500h | 250h | 500h | 250h | 500h | 250h | 500h |
| 8 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 19 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 25 | 0.02 | 0.03 | <0.01 | 0.07 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 50 | 0.05 | 0.04 | 0.09 | 0.05 | 0.05 | 0.04 | <0.01 | <0.01 | <0.01 | <0.01 |
| 100 | 1.97 | 1.69 | 4.82 | 2.83 | 1.32 | 0.94 | <0.01 | <0.01 | <0.01 | <0.01 |

# Fuel-Property Matrix was Identified and is Being Populated

| Category | Property | Baseline Fuels | | | | | | Pyrolysis Oil/Blends | | | | | HTL Bio-crude | | | | | Renewable diesel | F-T diesel | Lignin Ethanol Oil |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | HFO | MGO | LNG | Biodiesel | Methanol | Ethanol | FP Bio-oil | FP Bio-oil blend with HFO | FP Bio-oil (2% O) | Ex situ CFP oil | Ex situ CFP oil (Target) | Algal HTL raw | Algal H-treated | Wet waste HTL raw | Wet Waste hydrogenated | HTL distillate | | | |
| Engine/Fuel System/Bunkering Infrastructure | Material compatibility (corrosivity and wear) | Suitable | Suitable | Suitable | Moderate | Moderate | Moderate | Poor | Suitable | Moderate | Poor | Poor | Moderate | TBD | TBD | TBD | TBD | Suitable | Suitable | TBD |
| | Fuel-fuel compatibility & stability | Suitable | Suitable | Suitable | Moderate | Suitable | Moderate | Moderate | Suitable | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | Suitable | Suitable | TBD |
| | Component compatibility (viscosity at 50 & 100C) | Suitable | Suitable | Suitable | Moderate | TBD | TBD | Poor | Suitable | Moderate | TBD | TBD | TBD | TBD | TBD | TBD | TBD | Suitable | Suitable | TBD |
| | Blend limits with HFO or MGO | N/A | N/A | N/A | Suitable | N/A | N/A | N/A | TBD | High | TBD | TBD | TBD | TBD | TBD | TBD | TBD | Suitable | Suitable | TBD |
| | Waste generation/disposal | High | None | None | None | None | None | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | Suitable | Suitable | TBD |
| Fuel Characteristics | Production maturity | Suitable | Suitable | Moderate | Moderate | Moderate | Moderate | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | Moderate | Moderate | TBD |
| | Scalability | Suitable | Suitable | Moderate | Good | Good | Good | TBD | TBD | Good | Good | Good | Moderate | Good | Good | Good | Good | TBD | TBD | TBD |
| | Transport | Suitable | Suitable | Moderate | Moderate | Moderate | Moderate | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | Suitable | Suitable | TBD |
| | Engine use maturity | Suitable | Suitable | Suitable | High | High | High | Low | Low | Low | Low | Low | Low | Low | Low | Low | Low | Suitable | Suitable | TBD |
| Fuel Properties | Composition/impurities | Suitable | Suitable | Suitable | Poor | Suitable | Suitable | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | Suitable | Suitable | TBD |
| | Stability | Suitable | Suitable | Suitable | Moderate | Suitable | Suitable | Moderate | Suitable | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | Suitable | Suitable | TBD |
| | Density | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Poor | Suitable | Suitable | TBD | TBD | Poor | TBD | Poor | TBD | Poor | Suitable | Suitable | TBD |
| | Volumetric energy density | Suitable | Suitable | Poor | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | TBD | TBD | TBD | TBD | TBD | TBD | TBD | Suitable | Suitable | TBD |
| | Estimated Cetane Number | Suitable | Suitable | Suitable | Suitable | N/A | N/A | Poor | Suitable | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | Suitable | Suitable | TBD |
| | Cold filter plugging point | Suitable | Moderate | Suitable | Poor | N/A | N/A | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | Suitable | Suitable | TBD |
| | Viscosity | Suitable | Suitable | Suitable | Suitable | N/A | N/A | Suitable | Suitable | Suitable | TBD | TBD | TBD | TBD | TBD | TBD | TBD | Suitable | Suitable | TBD |
| | Lubricity | Suitable | Suitable | Poor | Suitable | Moderate | Moderate | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | Suitable | Suitable | TBD |
| Economic | MFSP ($/gge) | 2.00 | 4.00 | TBD | TBD | 2.29 | 3.57 | 1.95 | TBD | 3.29 | 3.33 | 2.48 | 4.82-11.35 | TBD | 2.11 | 3.46 | 3.71 | TBD | TBD | TBD |
| | 5% blend @ $2.62/GGE; HVO @ $2.00/GGE | N/A | N/A | N/A | TBD | | | | N/A | | | | | TBD | | | | TBD | TBD | TBD |
| | 20% blend @ $2.52/GGE; HVO @ $2.00/GGE | N/A | N/A | N/A | TBD | | | | N/A | | | | | TBD | | | | TBD | TBD | TBD |
| | 5% blend @ $3.12/GGE; HVO @ $2.50/GGE | N/A | N/A | N/A | TBD | | | | N/A | | | | | TBD | | | | TBD | TBD | TBD |
| | 20% blend @ $3.02/GGE; HVO @ $2.00/GGE | N/A | N/A | N/A | TBD | | | | N/A | | | | | TBD | | | | TBD | TBD | TBD |
| | Price uncertainty | N/A | N/A | N/A | N/A | N/A | N/A | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD |
| | Current fuel reliability | Suitable | Suitable | Suitable | TBD | N/A | N/A | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD |
| | Retrofit cost | None | None | None | TBD | N/A | N/A | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD |
| | Retrofit schedule | None | None | None | TBD | N/A | N/A | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD |
| | Fuel Standards | Suitable | Suitable | Suitable | Suitable | N/A | N/A | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD |
| Environmental | Life cycle GHG | Poor | Poor | Moderate | TBD | TBD | TBD | Favorable | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD |
| | Life cycle SOx emissions | Favorable | Favorable | Favorable | Favorable | Favorable | Favorable | Favorable | Favorable | Favorable | Favorable | Favorable | TBD | TBD | TBD | TBD | TBD | Suitable | Suitable | Suitable |
| | Life cycle NOx emissions | Poor | Poor | Poor | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD |
| | Life cycle PM emissions | Poor | Poor | low | Moderate | Favorable | Favorable | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD |
| | Life cycle water use | Poor | Poor | Poor | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD | TBD |
| | Large spill/release impact | Poor | Poor | Poor | Low | Moderate | Moderate | Low | Low | Low | Low | Low | Low | Low | Low | Low | Low | Suitable | Suitable | Suitable |
| Safety | Human health (toxicity, carcinogen, etc.) | Suitable | Suitable | Suitable | Suitable | Moderate | Moderate | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable |
| | Flammability | Suitable | Suitable | High | Suitable | High | High | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable |
| | Suffocation potential | Suitable | Suitable | High | Suitable | High | High | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable |
| | Explosion risk | Suitable | Suitable | High | Suitable | High | High | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable | Suitable |

- Colored cells represent collected data suitability
- Clear cells awaiting to be populated

# Success Factors and Milestones

**Critical success factors**
- GHG reduction
- Blend stability with VLSFO
- Reduced blend viscosities
- Efficient combustion with lowered PM formation
- Cost effectiveness
- Compatibility with existing infrastructure

| Milestone | Status |
|---|---|
| 1. Provide an initial list of biofuels with a priority ranking based on economic potential (near-term), medium-term/transitional, and carbon reduction (long-term). | Listing completed. Priorities on bio-intermediates, biodiesel, and lignin ethanol oils |
| 2. Deliver to sponsors & stakeholders findings-to-date and status update including data and methods | Ongoing. On schedule for Q2. |
| 3. A draft of the final report will be submitted containing inputs from each task. | In progress. On schedule for Q3. |
| 4. Deliver final report and recommendations to DOE and stakeholder community | On schedule for Q4 |

# Summary

1. The objective is to obtain data on biofuel cost and performance to inform DOE and marine community on the efficacy of biofuels as a marine fuel. This is to be achieved via technoeconomic analyses (TEA), life-cycle analyses (LCA) and technical feasibility analyses
2. Stakeholder community is strongly supportive of a federal program focused on biofuels for marine sector
3. Biofuels offer a pathway toward GHG reduction
4. Studies to-date have shown that biofuels have good compatibility and combustion characteristics
5. This effort directly supports BETO’s overarching commercial viability mission while providing a unique solution to addressing the limited energy options of the marine sector
6. Preliminary TEA show potential cost reductions with bio-intermediates
7. Future work activities include 1) continuing exploration of pathways to reduce emissions and costs, 2) understanding engine performance, 3) assess economic viability

# Quad Chart Overview

## Timeline
- Project start date: October 1, 2020
- Project end date: September 30, 2021

| | FY21 | Active Project |
|---|---|---|
| **DOE Funding** | (10/01/2020 – 9/30/2021) | $1.5M distributed among ORNL, ANL, NREL and PNNL |

## Project Partners
- US DOT Maritime Administration

## Barriers addressed
- Assesses the cost and compatibility of biofuels
- New market opportunities for biofuels

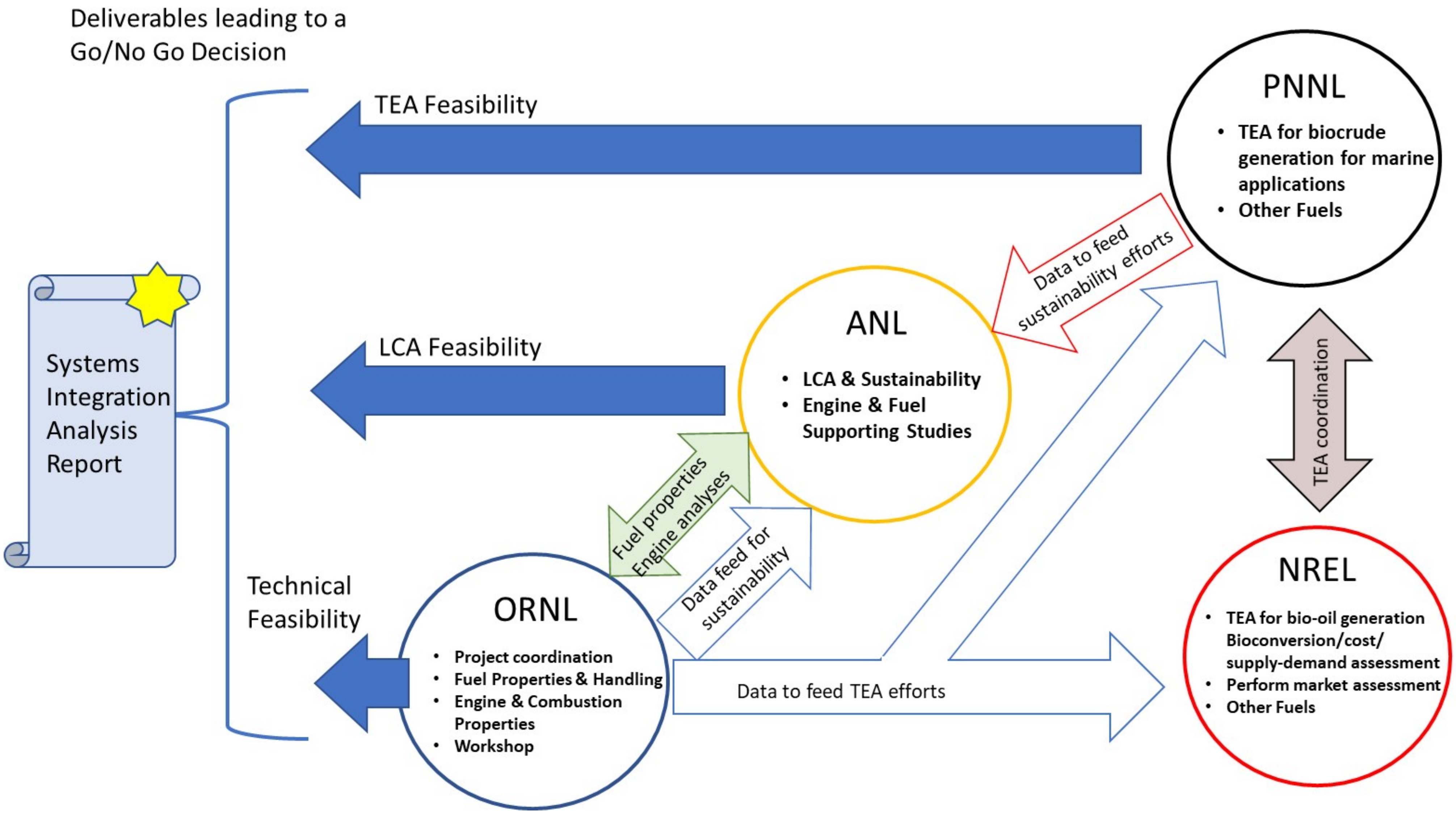
## Project Goal
- To provide information to DOE and the stakeholder community on biofuel cost and performance as a marine fuel.
- To be achieved by conducting TEA, LCA and technical feasibility analyses on biofuels and pathways within the BETO portfolio.
- Fuels to be evaluated for near- and longer-term scenarios and whether the economic and carbon reduction targets can be met with biofuels.

## End of Project Milestone
Deliver final report and recommendations to DOE and stakeholder community. The report will provide a final listing of biofuel types most suitable for near- and long-term targets. A minimum of 3 promising pathways for biofuel production and infrastructure upgrades will be reviewed along with a priority list of research needs.

## Funding Mechanism
AOP

# Additional Slides

# Tasks and research activities at the four participating labs is highly interdependent and collaborative



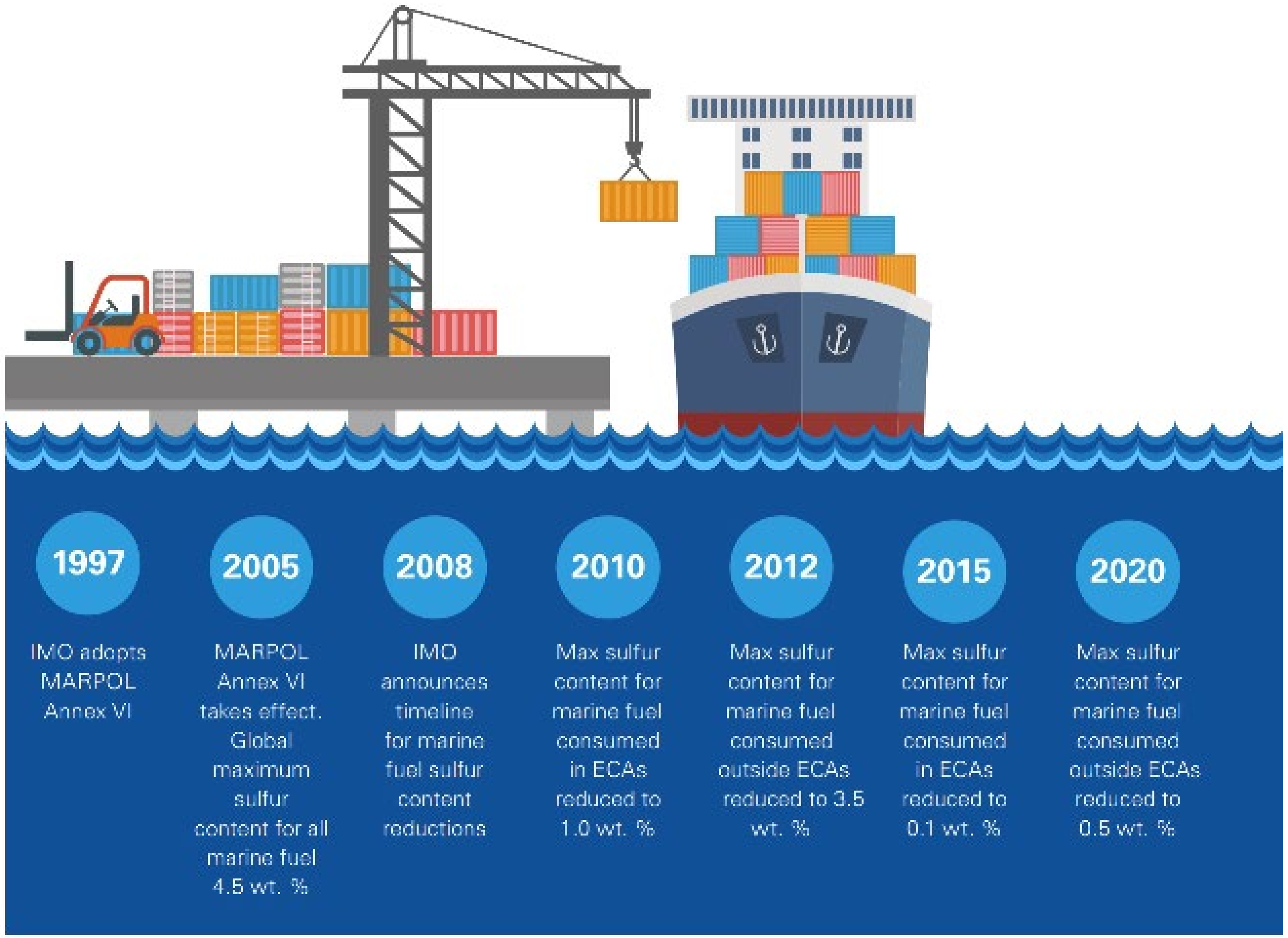

Team has close working relationship with the Department of Transportation Maritime Administration (MARAD)

# Additional Details Concerning Regulatory Focus on GHG Emissions

- Pressure to reduce carbon intensity of shipping
  - IMO framework to reduce carbon intensity ($CO_2$ per ton-mile) by 40% for new ships by 2030 and 70% by 2050, relative to 2008
  - IMO goal to reduce GHG emission from international shipping by 50% in 2050, relative to 2008
  - Peak GHG emissions as soon as possible, with decarbonization attained by the end of century
- Situation complicated by many competing options and constraints
  - Extremely slim operating margins
  - Alternatives include expanded use of distillates, LNG, biofuels, and employing S scrubbers amongst others
- Biofuels could offer emissions reductions, improved energy security, and reductions in the carbon intensity of marine shipping.

# Chronology of Maritime Regulations [Backup Slides]

- IMO has progressively limited marine fuel sulfur wt % over time
  - In 2015, fuel sulfur restricted to 0.1% in Emission Control Areas (ECA), coastal regions of US and northern Europe
- In 2020 IMO restricted marine fuel to 0.5% S wt.
  - Carriage ban on all non-compliant fuel

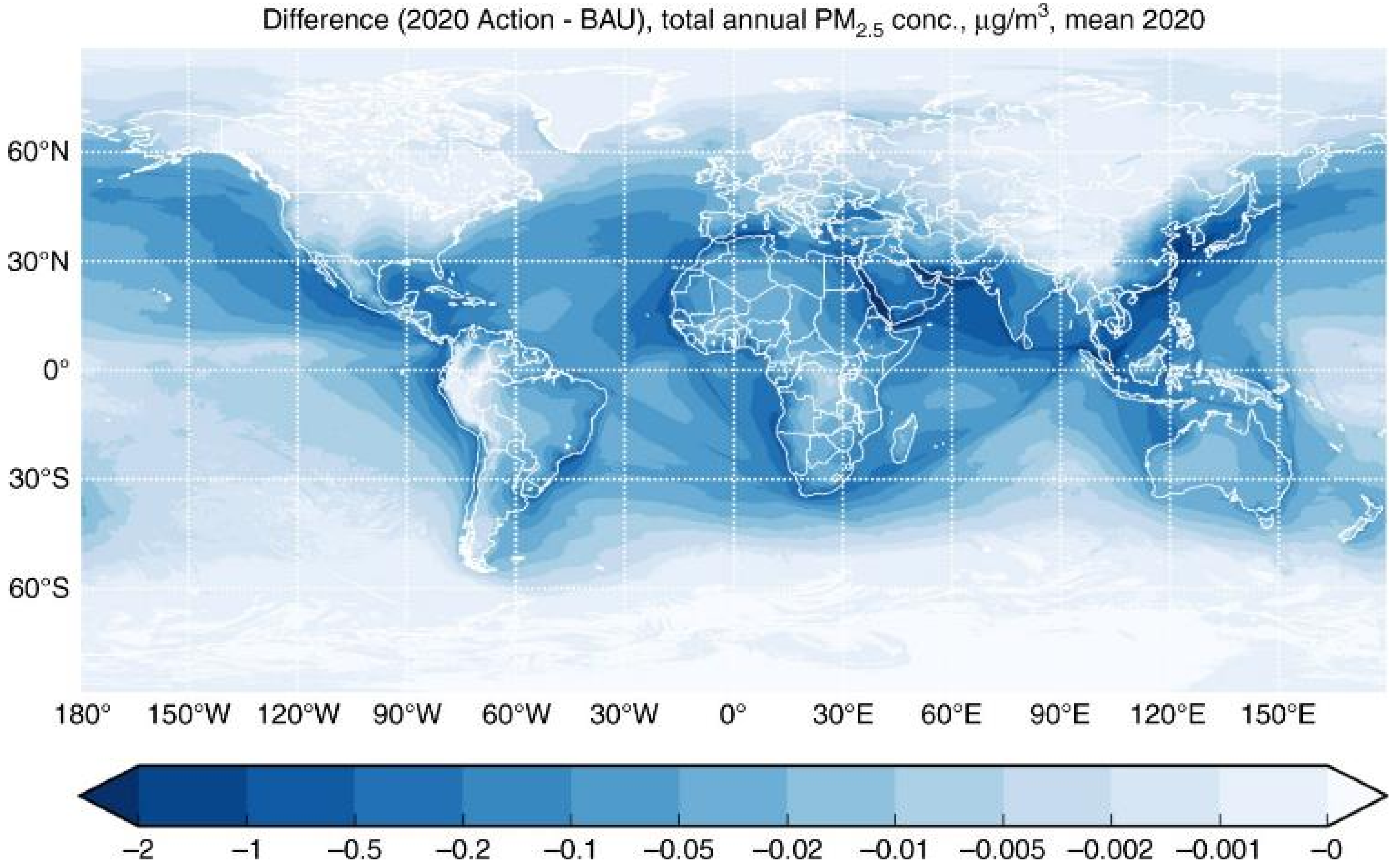



KPMG, IMO 2020 – Value Proposition (2019). https://www.maritimecyprus.com/wp-content/uploads/2019/08/kpmg-imo-2020-1.pdf

# Chronology of Maritime Regulations [Backup Slides]

- IMO has progressively limited marine fuel sulfur wt % over time
  - In 2015, fuel sulfur restricted to 0.1% in Emission Control Areas (ECA), coastal regions of US and northern Europe

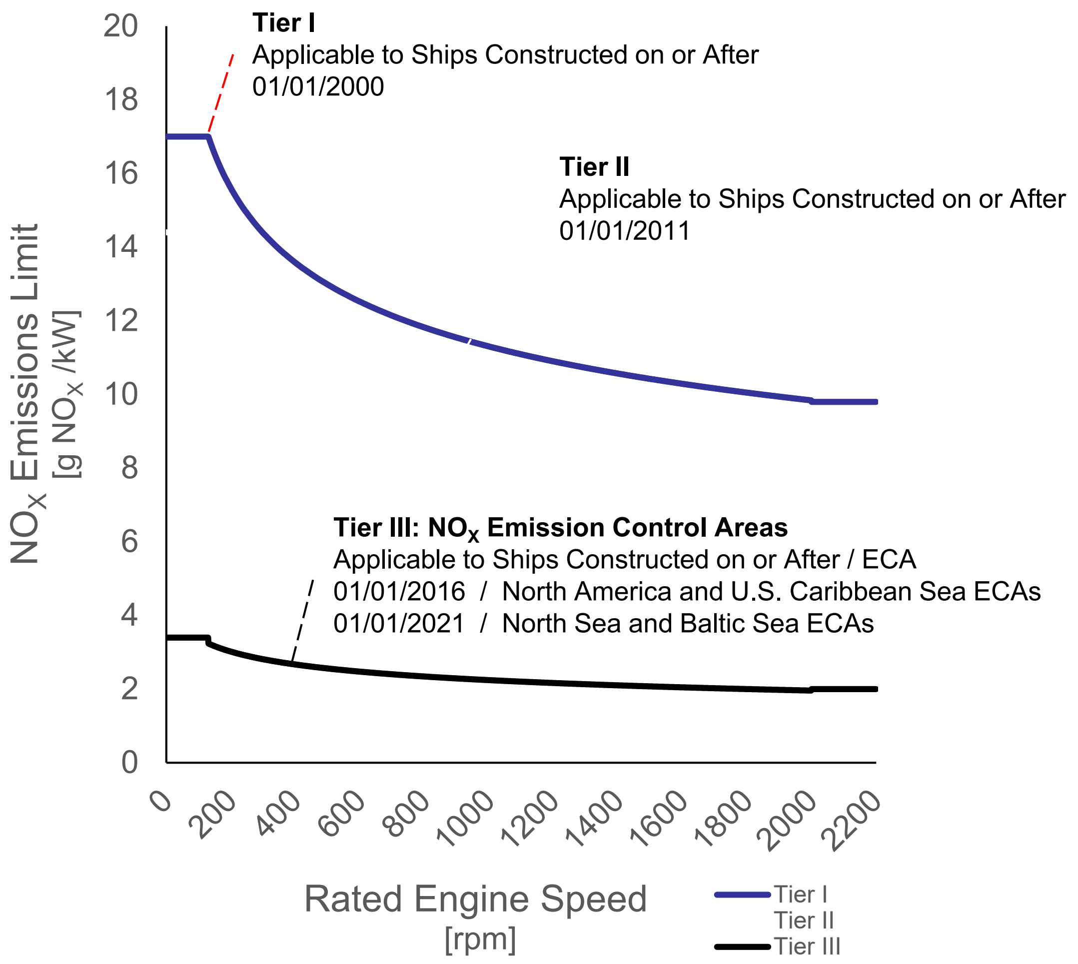
- In 2020 IMO restricted marine fuel to 0.5% S wt.
  - Carriage ban on all non-compliant fuel




Sofiev, Mikhail, et al. "Cleaner fuels for ships provide public health benefits with climate tradeoffs." Nature communications 9.1 (2018): 1-12.
https://www.nature.com/articles/s41467-017-02774-9/figures/2

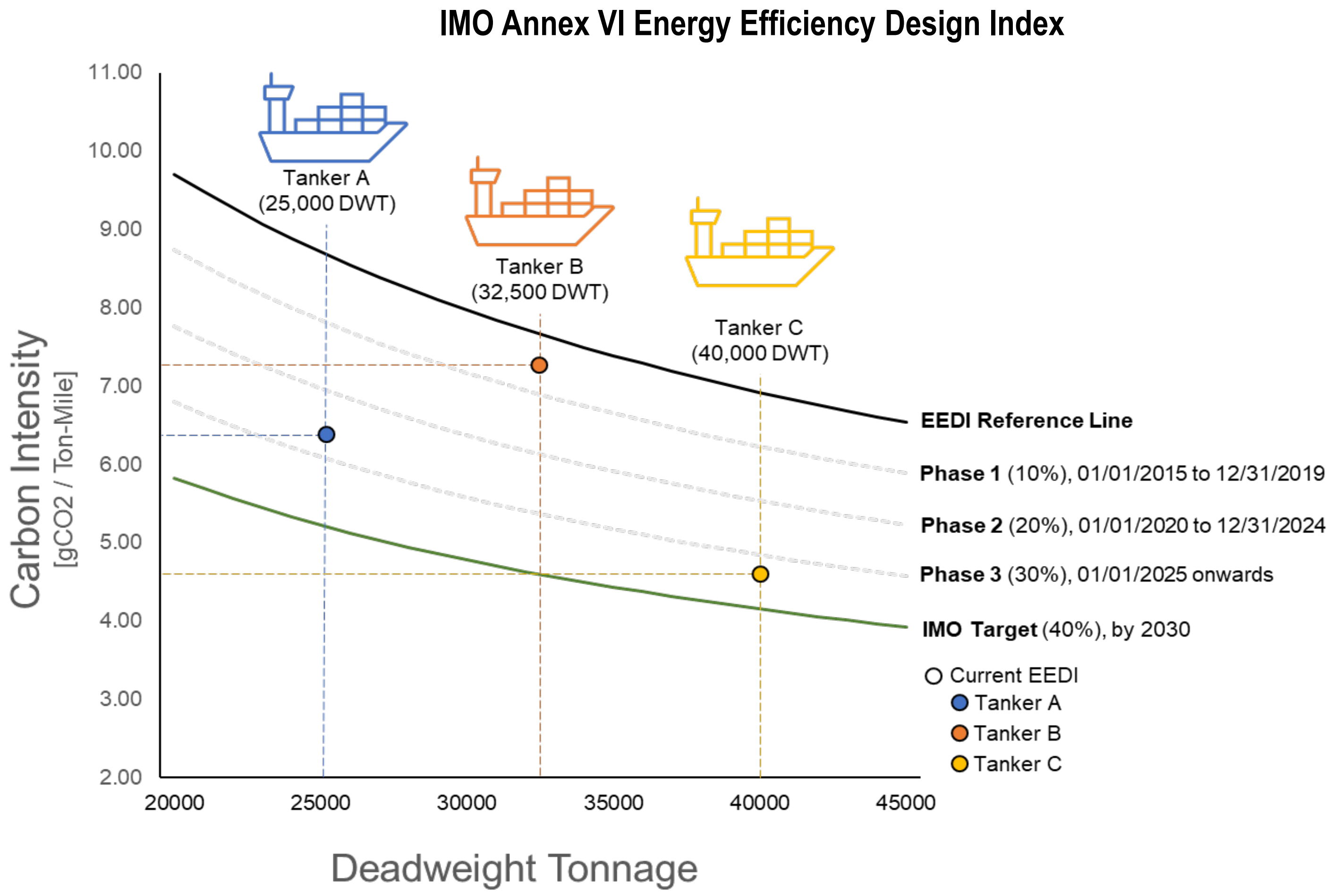
# Chronology of Maritime Regulations [Backup Slides]

- IMO NOx Regulations
  - NOx emission limits are based on control requirements (‘Tiers’) and maximum engine operating speed
- Future Regulations on the Horizon
  - Invasive species / Hull bio-fouling
  - Particulate matter (PM) & NOx
  - Underwater noise
  - Plastic waste
  - HFO ban in the Arctic
- An increasing number of port and local regulations

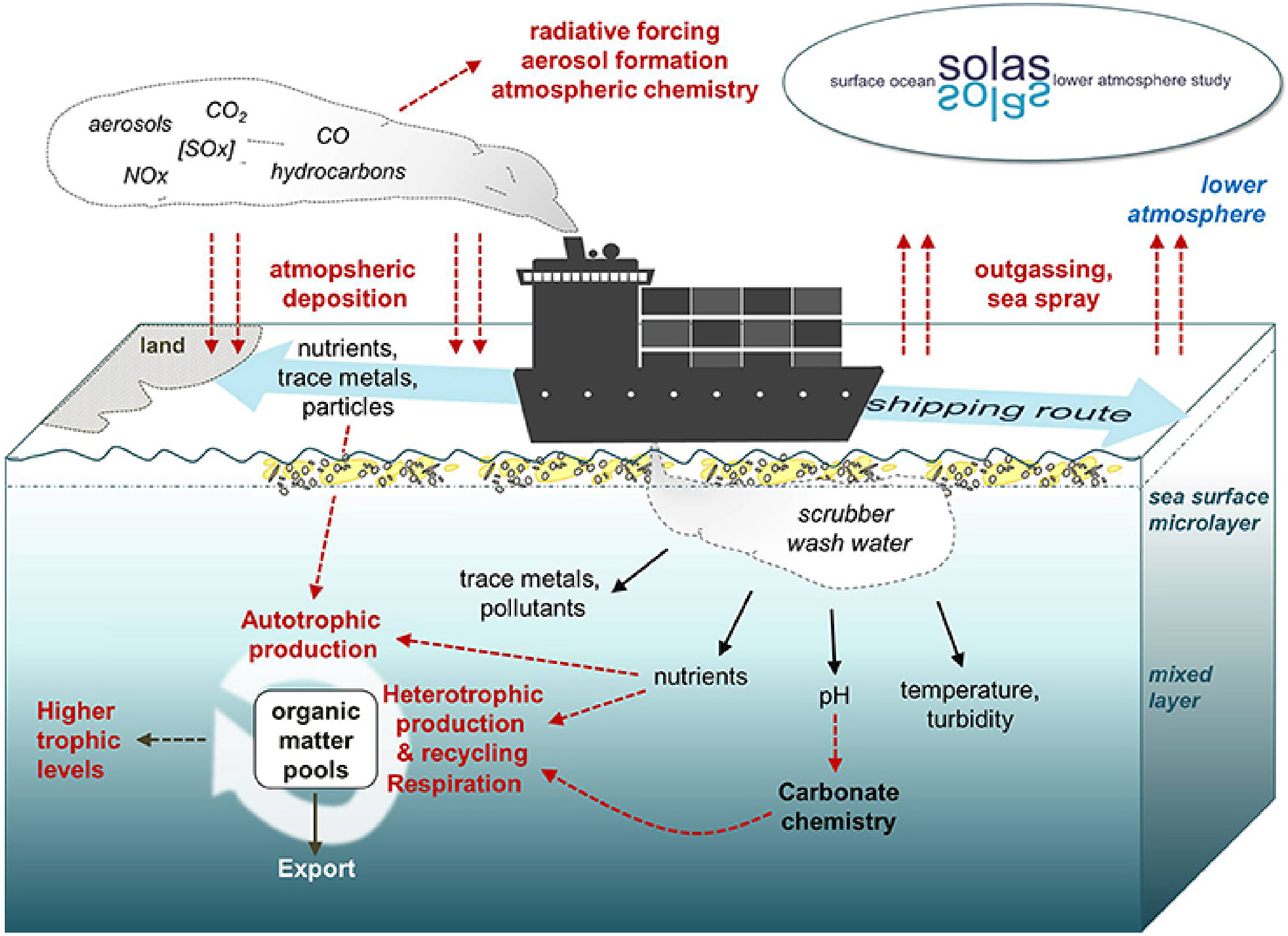


# IMO GHG Strategy [Backup Slides]

- Short-Term (2018 – 2023)
  - Energy Efficiency Design Index (EEDI) & Ship Energy Efficiency Management Plan (SEEMP)
  - Energy Efficiency Indicators
  - Speed Reduction
  - National Action Plans
- Mid-Term (2023 – 2030)
  - Energy Efficiency Existing Ship Index (EEXI)
  - Carbon Pricing & Market Based Measures (MBM)
  - Fuel Switching / Low-Carbon Fuels
- Long-Term (2030+)
  - Carbon Neutral Fuels
  - Novel emissions reductions strategies



# Exhaust Gas Cleaning Systems [Backup Slides]




Endres, Sonja, et al. "A new perspective at the ship-air-sea-interface: the environmental impacts of exhaust gas scrubber discharge." *Frontiers in Marine Science* 5 (2018): 139.

- Scrubber Technologies
  - Open Loop
  - Closed Loop
  - Hybrid Systems
- Impact of scrubber wash water discharge on marine chemistry and biodiversity is contested
  - Scrubber wash water constituents such as polycyclic aromatic hydrocarbons (PAH) and metals may negatively affect growth, consumption, and reproduction of marine biota
  - Water discharge from Open-Loop scrubbers is regulated by IMO
  - Scrubber wash water discharge is restricted and/or prohibited in select Sea/Port areas
- Key Concerns
  - Potential environmental and human health impacts
  - PAHs, organic carbon (OC), and heavy metals can be persistent in the marine environment, and potentially consumed indirectly by humans via the food-web
- IMO to provide further recommendations by 2021

# Bio-crude stability with VLSFO improved with polar additives

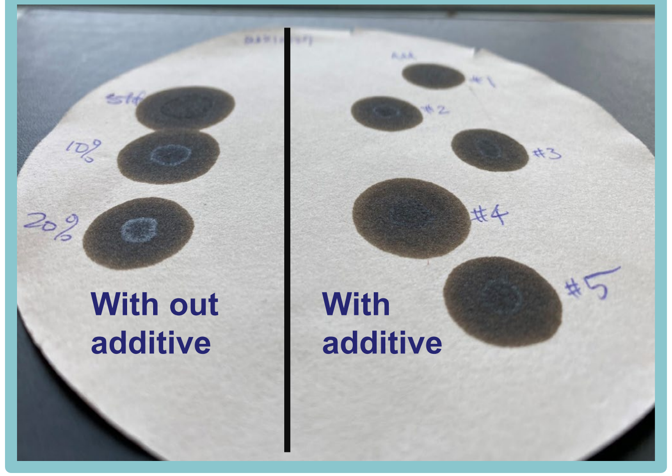
### Spot test analysis on wet waste generated ***biocrude***

| Additive | % Biocrude in Heavy Fuel Oil | Spot Test Pass/Fail |
|---|---|---|
| No Additive | 5% | Yes |
| | 10% | No |
| | 20% | No |
| Additive 1 | **10%** | **Yes** |
| | 20% | No |
| Additive 2 | 10% | No |
| | 20% | No |
| Additive 3 | 10% | No |
| | 20% | No |
| Additive 4 | **10%** | **Yes** |
| | **20%** | **Yes** |
| Additive 5 | 10% | No |
| | 20% | No |

### Spot test analysis on wet waste generated ***biocrude (hydrotreated)***

| Additive | % Biocrude in Heavy Fuel Oil | Spot Test Pass/Fail |
|---|---|---|
| No Additive | 5% | Yes |
| | 10% | Yes |
| | 20% | No |
| Additive 1 | 10% | Yes |
| | **20%** | **Yes** |
| Additive 2 | 10% | Yes |
| | 20% | No |
| Additive 3 | 10% | Yes |
| | 20% | No |
| Additive 4 | 10% | Yes |
| | 20% | No |
| Additive 5 | 10% | Yes |
| | 20% | No |

- Asphaltene present in the heavy fuel oil can precipitate and cause plugging issue due the incapability between the blending component (e.g., biocrude)
- Spot test was conducted based on ASTM D4740 and



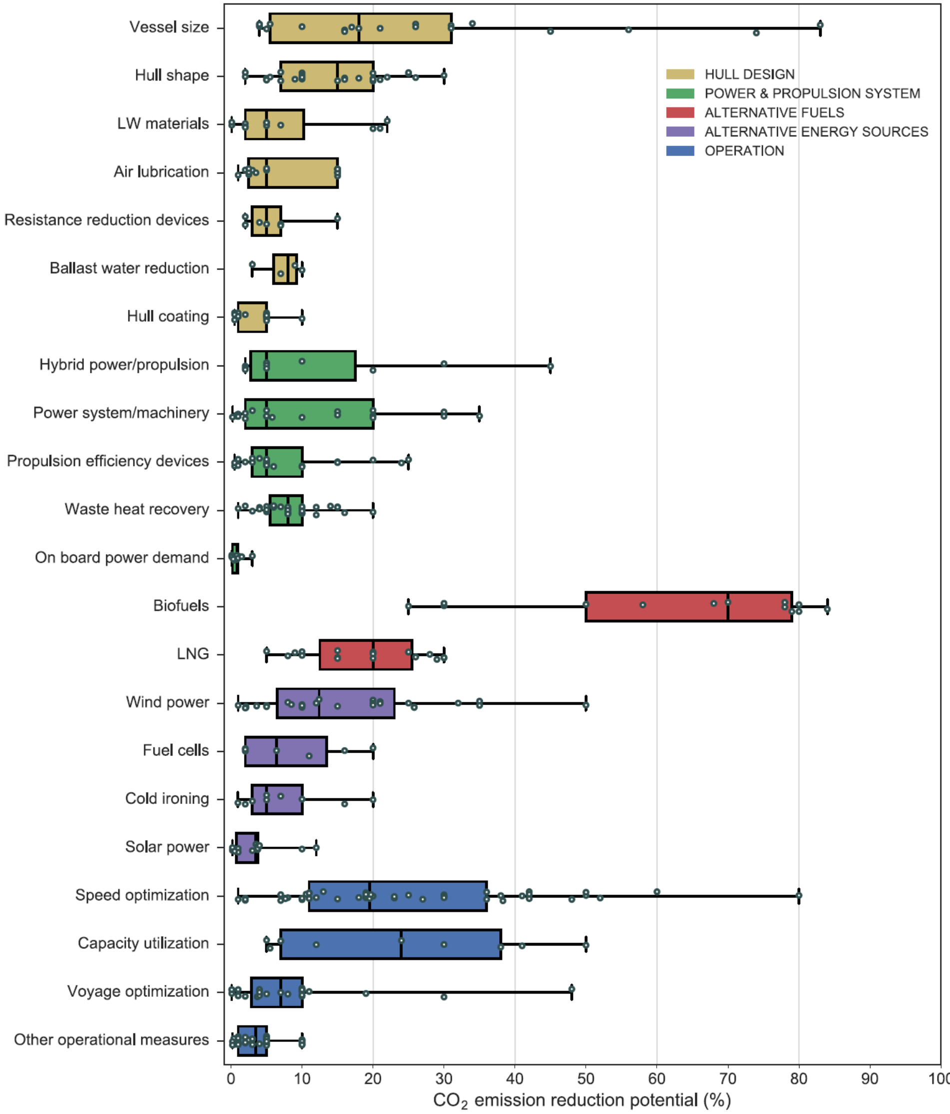

Spot analysis results from the wet waste derived biocrude

- Wet waste derived biocrude is limited to 10% blending limit (with out additive)
- Preliminary result shows the addition of additives can improve the blending limit beyond 20% level
- More work is in progress to identify the additive that can increase the blending levels of HTL derived fuels beyond 20% in heavy fuel oil

# Why Biofuels? [Backup Slides]

## Bouman et al. 2017

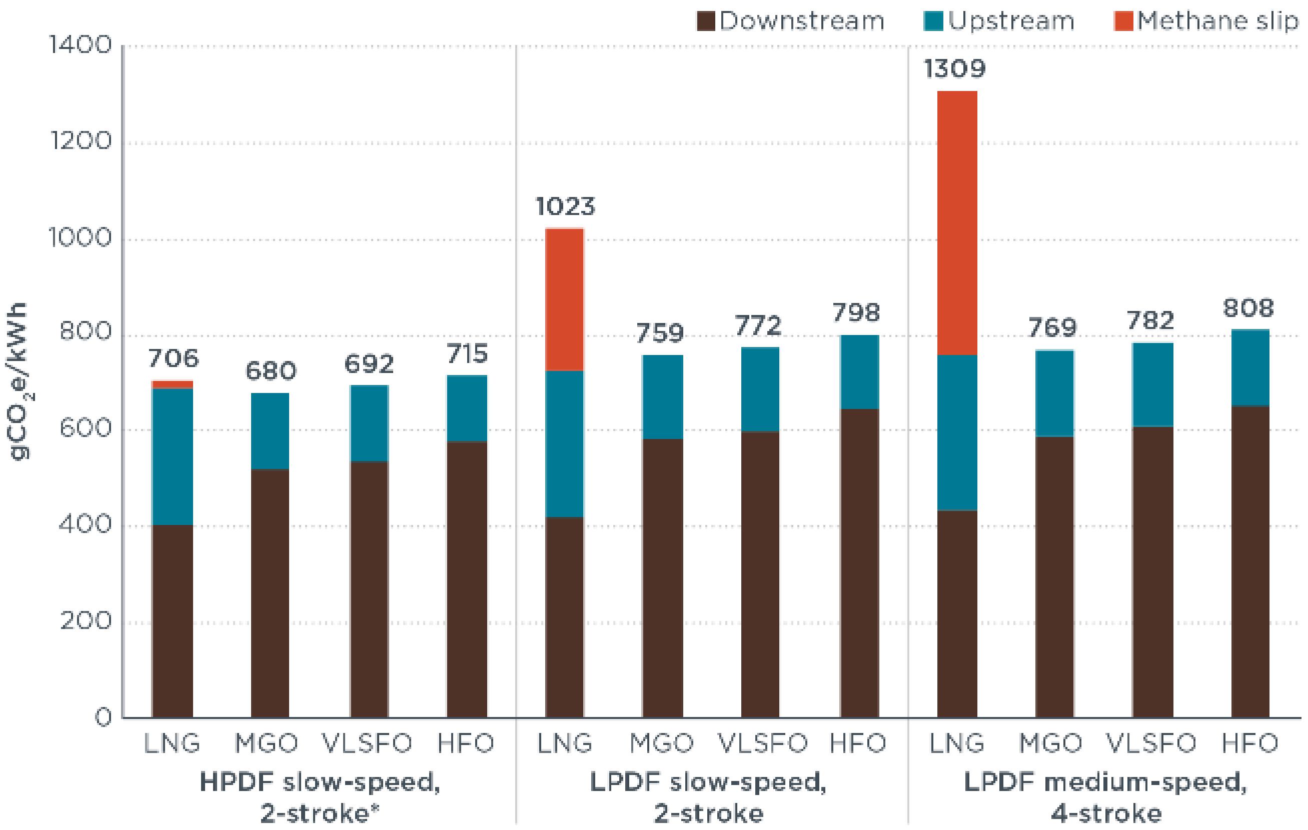
- Reviewed over 150 studies to determine the carbon reduction potential across different measures:
  - Hull Design
  - Power & Propulsion Systems
  - Alternative Fuels
  - Alternative Energy Sources
  - Operational Changes
- Biofuels demonstrated the **single greatest potential** for $CO_2$ emissions reduction across all examined measures




Bouman et al. (2017)
https://doi.org/10.1016/j.trd.2017.03.022

# Liquefied Natural Gas (LNG) [Backup Slides]

- Potential Benefits
  - Cost competitive, high fuel production volume, and low-sulfur
- Carbon Footprint of LNG
  - High near-term (20-year) radiative forcing potential of methane
  - Methane slippage can negate the GHG benefits of LNG, leading to potentially higher GHG emissions relative to HFO
  - Limited capacity for meeting long-term IMO GHG Targets
- Carbon Lock-in
  - The high capital costs for LNG bunkering infrastructure may deter future divestment
  - Potential concerns over (1) carbon lock-in and/or (2) stranded assets
  - 'Path dependence' could alter the trajectory of the marine sector (e.g. re-vector to Bio-LNG, synthetic LNG)

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https://theicct.org/publications/climate-impacts-LNG-marine-fuel-2020