Life-Cycle Analysis for Advanced Marine Fuels

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- Bachelor in Environmental Science, University of Chittagong
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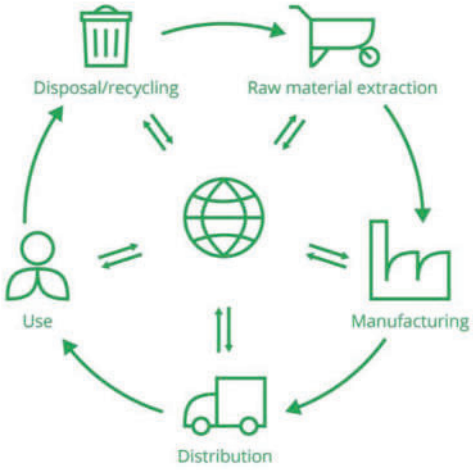
- MS, PhD, Postdoc, University of Georgia
- Argonne National Laboratory

Argonne by the numbers:
World-leading research at scale in suburban Chicago

$1.15	billion-dollar budget
3,500	employees, including 1,800 researchers and 500 students
6,000	researchers supported by 6 DOE-SC and DOE-NE user facilities
5	national research centers led by Argonne
3	locations: Chicago suburbs, City of Chicago, and Washington, D.C.

Life Cycle Assessment (LCA)

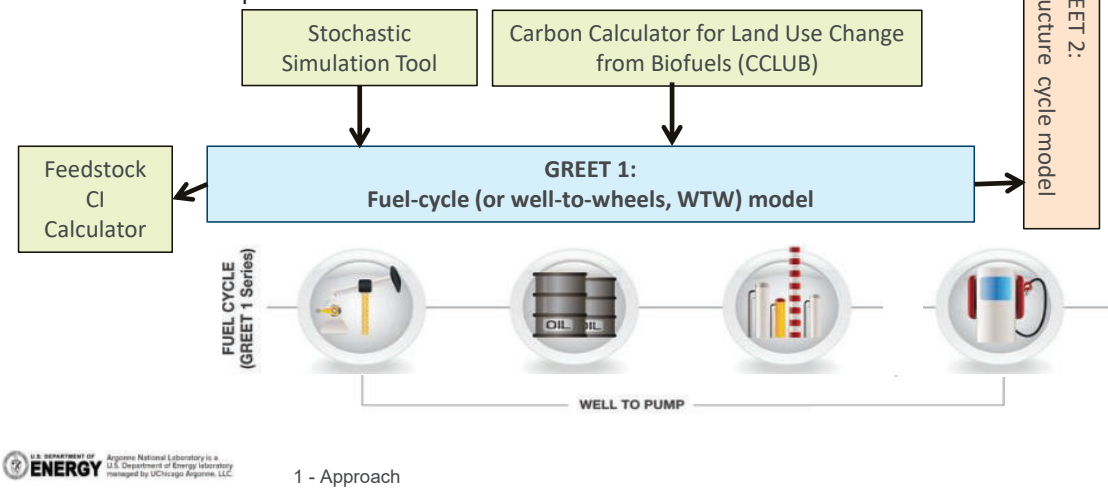
- LCA is a major step to holistically evaluate sustainability of technologies and policies
  - LCA thinking has helped changes in corporation and consumer behaviors
- Recent trends of LCA applications
  - US domestic regulations and programs
    - ✓ Regulations such as the CA LCFS (and several other states) and EPA RFS
    - ✓ The Inflation Reduction Act incentives for clean hydrogen, sustainable aviation fuels, and clean fuels are based on LCA GHG results
  - International activities
    - ✓ International Civil Aviation Organization's CORSIA program for SAFs
    - ✓ International Marine Organization's discussion of potential low-GHG fuel standard
    - ✓ EU Renewable Fuel Directive
    - ✓ Canadian Clean Fuel Standard
    - ✓ Brazilian RenovaBio program



https://pre-sustainability.com/articles/life-cycle-assessment-lca-basics/

The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) Model Framework

- Argonne has been developing the GREET **life-cycle analysis (LCA)** model since 1995 with annual updates and expansions
- BETO has been a major GREET sponsor since the beginning
- GREET is available at greet.anl.gov
- GREET Outputs: GHG emissions, Criteria Air Pollutant emissions, Energy Use, and Water Consumption



(Vehicle manufacturing cycle as the example)

GREET sustainability metrics include energy use, criteria pollutants, greenhouse gases, and water consumption

Energy use

- Total energy: fossil energy and renewable energy
- Fossil energy: petroleum, natural gas, and coal
- Renewable energy: biomass, nuclear energy, hydro-power, wind power, and solar energy

Air pollutants

- VOC, CO, NOx, PM_{10}, $PM_{2.5}$, and SOx
- Estimated separately for total and urban (a subset of the total) emissions

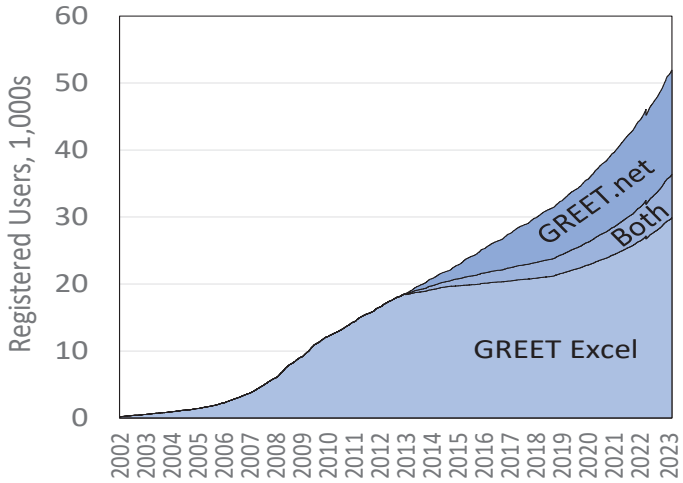
Greenhouse gases

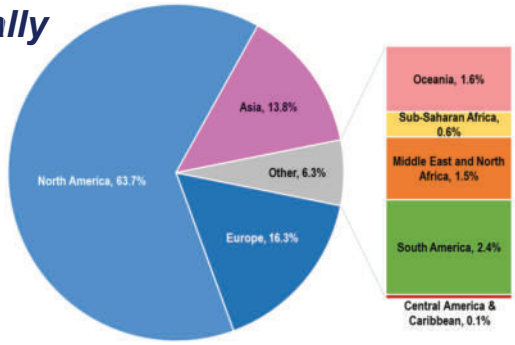
- CO_2, CH_4, N_2O, black carbon, and albedo
- CO_{2e} of the five (combined with their global warming potentials)

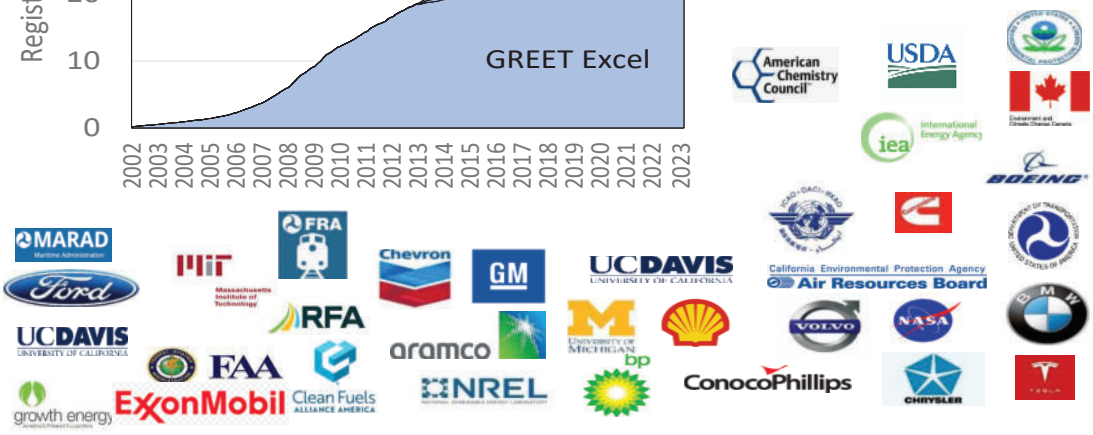
Water consumption

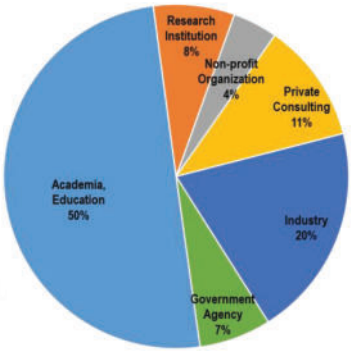
- Addressing water supply and demand (energy-water nexus)

There are over 50,000 registered GREET users globally









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Informing Policies and Regulations

California Environmental Protection Agency Air Resources Board

DEQ

NHTSA

USDRIVE

MARAD Maritime Administration

USDA

Environment and Climate Change Canada

ENERGY

US CONGRESS

- **CA-GREET** is an adaptation of Argonne's GREET model
- **Oregon Clean Fuels Program** also uses an adaptation of Argonne's GREET model
- **U.S. EPA** uses GREET with other sources for **Renewable Fuels Standard** pathway evaluations
- **National Highway Traffic Safety Administration** for fuel economy regulation
- **Federal Aviation Administration** and **International Civil Aviation Organization** using GREET to evaluate aviation fuel pathways
- **USDRIVE** Well-to-Wheels Report
- **U.S. Maritime Administration -** renewable marine energy options for IMO GHG intensity and sulfur limits
- **U.S. Dept. of Agriculture bioenergy LCA** and carbon intensity of farming practices
- **Canadian Clean Fuel Standard** for Environment and Climate Change Canada fuel pathways
- LCA results for use in different provisions of the 2021 **Bipartisan Infrastructure Law** and the 2022 **Inflation Reduction Act**

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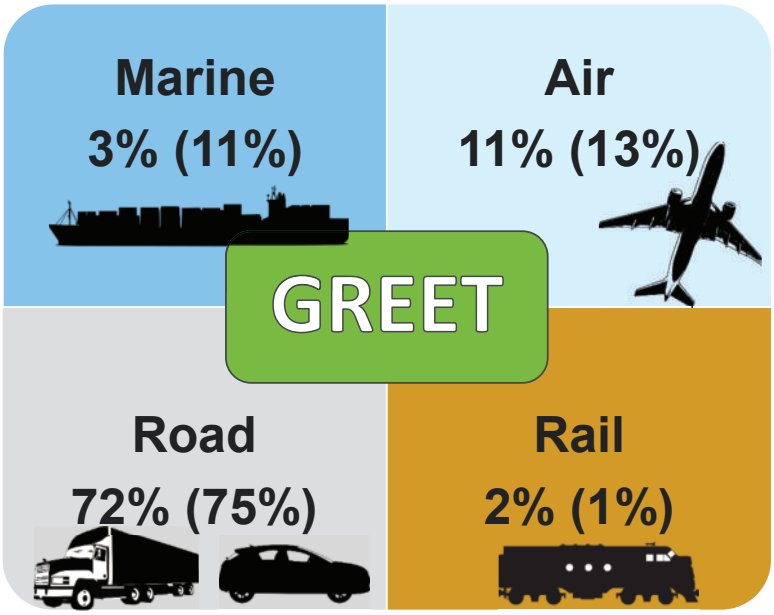
GREET Scope - All Transportation Sectors



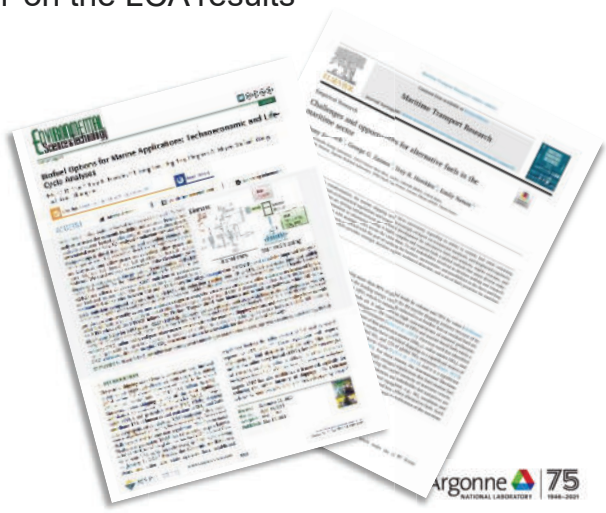
* Share of transportation GHG emissions in the US (and globally in 2019), remaining 12% for US is from pipelines and offroad (EIA, IEA). GREET also includes LCA of industry sectors, buildings, and plastics.

GREET Marine Models

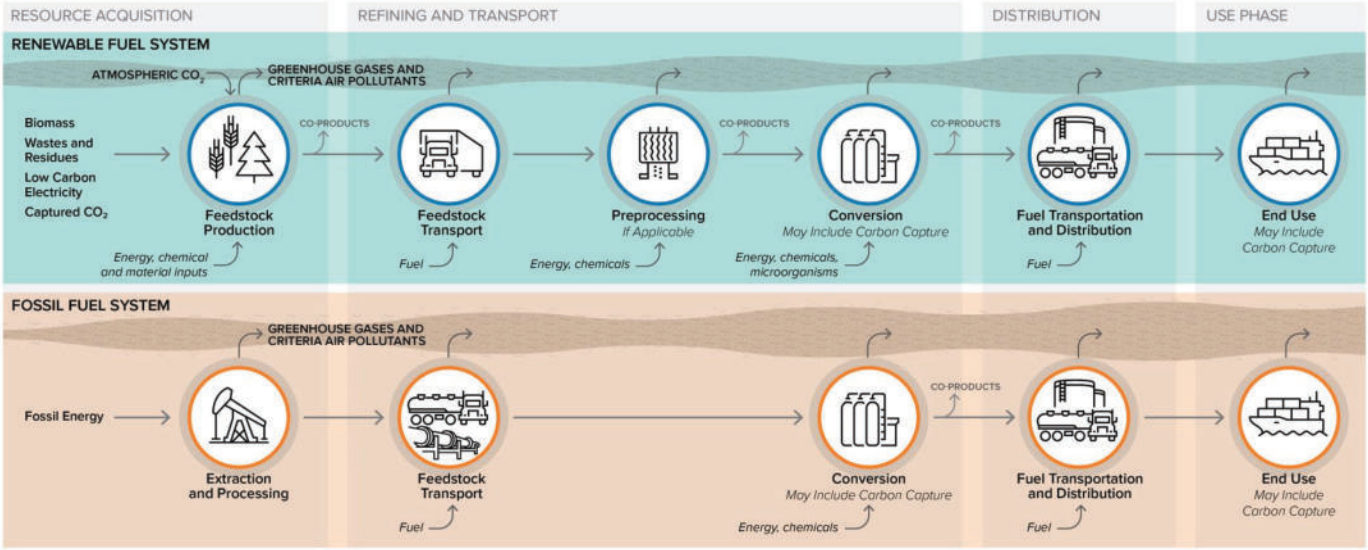
- GREET Marine Model and New Stand-Alone Marine Module
  - Marine Fuel Pathways incl. Fossil, Renewable, Fossil/Biomass Blends
  - Relevant Environmental Metrics incl. GHGs, Energy-use, CAPs, Water-use
  - Standardization enables apples-to-apples comparison across fuel and technology pathways, and capacity to 'drill-down' on the LCA results

- Functional Units
  - Energy-Based (Impacts per unit MJ)
  - Service-Based (Impacts per Trip, Tonne-Km)

- Key Variables
  - Fuel and Engine Types
  - Trip and Vessel Characteristics
  - Emissions Regulations

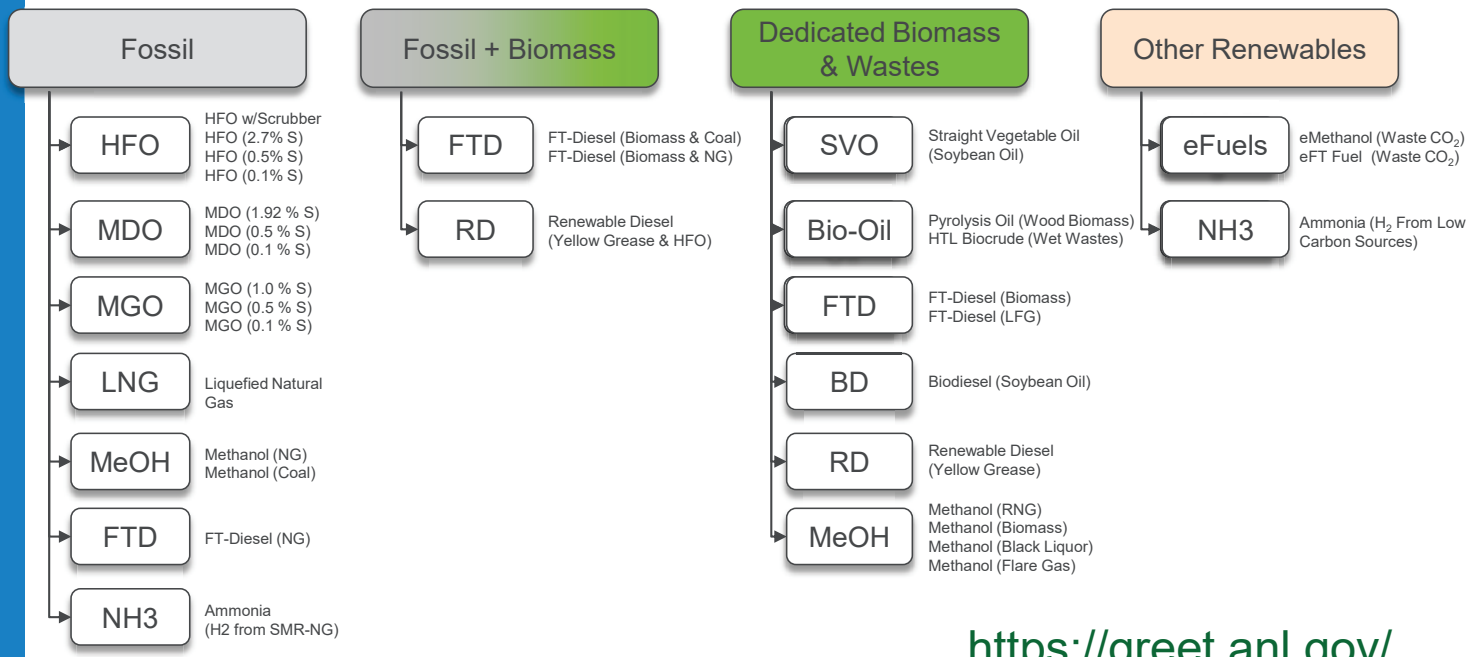


Consistent System Boundary Across Fuel Pathways



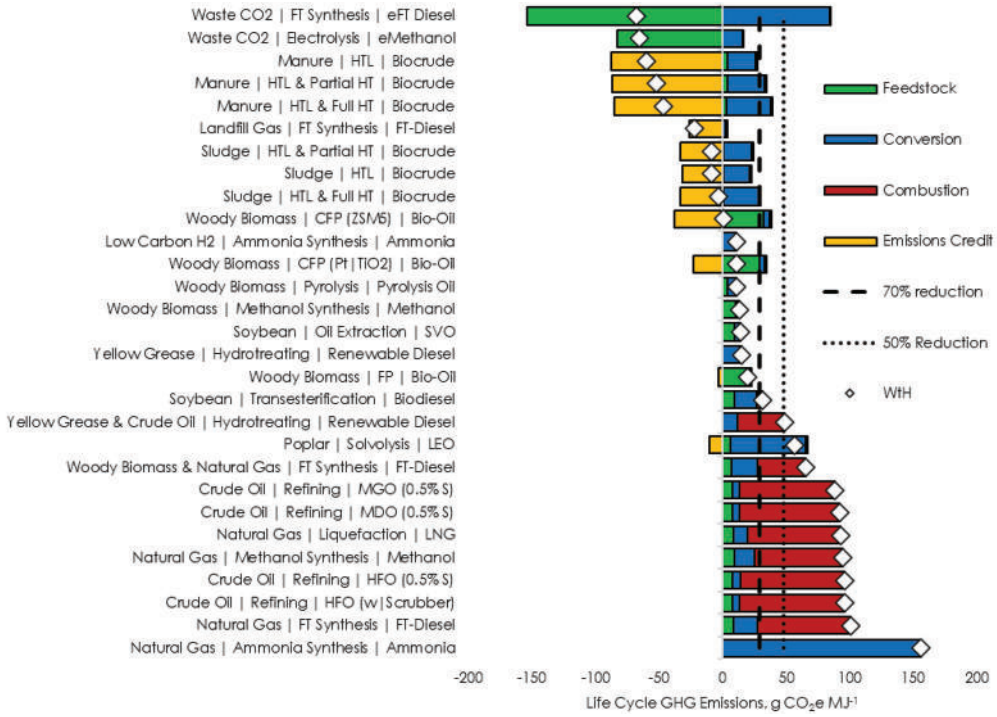
- Compare on an apples-to-apples basis
- Avoid burden shifting across supply chain segments
- Identify key drivers
- Screen across potential environmental impacts

Publicly-Available LCA Models: GREET 2022



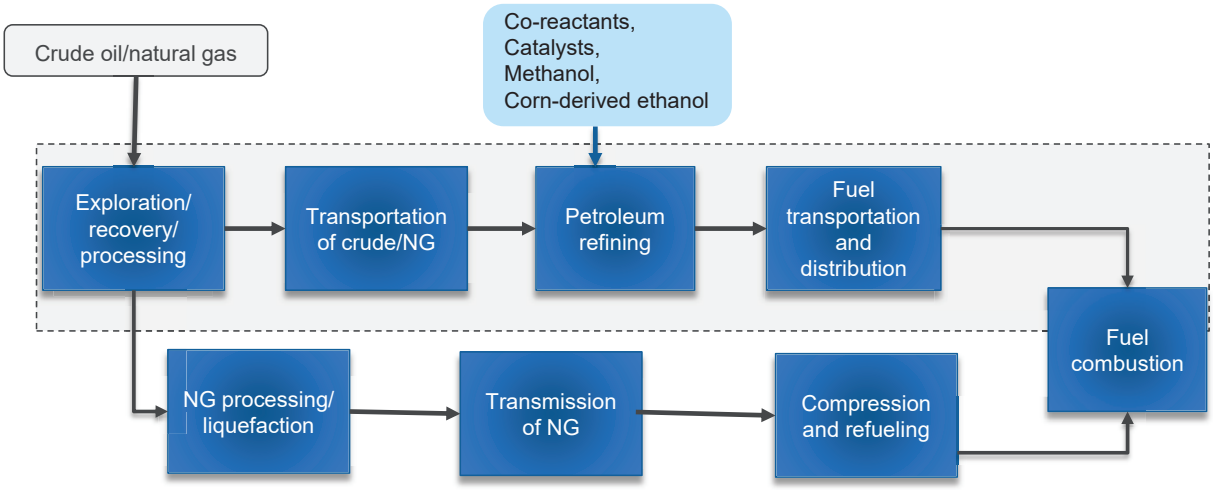
https://greet.anl.gov/

Comparison across range of marine fuel pathways



CFP: Catalytic Fast Pyrolysis; ZSM5: Zeolite Socony Mobil-5; TiO2: Titanium Dioxide; FP: Fast Pyrolysis; HTL: Hydrothermal Liquefaction; HT: Hydrotreating; LFG: Landfill Gas; SVO: Straight Vegetable Oil; LEO: Lignin-Ethanol Oil; MGO: Marine Gas Oil; MDO: Marine Distillate Oil; HFO: Heavy Fuel Oil; LNG: Liquefied Natural Gas; FT: Fischer-Tropsch; S: Sulfur; T&D: Transportation and Distribution; WtH: Well-to-Hull

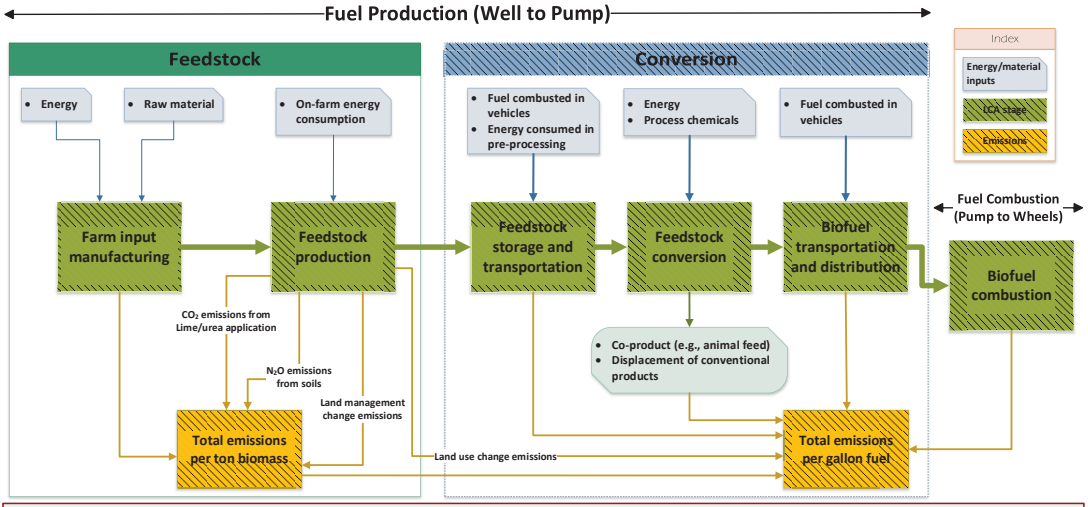
Life cycle of fuels from petroleum and natural gas



- All direct activities and emissions in the above flowcharts are included
- **Land disturbance** of oil/NG recovery was assessed and included in GREET (up to 2 g/MJ)
- Methane leakage of the NG supply chain is based on combined bottom-up (EPA GHG Inventory) and top-down (individual studies) approach

Biofuel Pathways

Detailed modeling of feedstocks and conversion



Land Use Change

- Carbon Calculator for Land Use Change from Biofuels Production (CCLUB)
- Feedstock average soil C and soil nitrous oxide (N_2O)

Land Management Practices

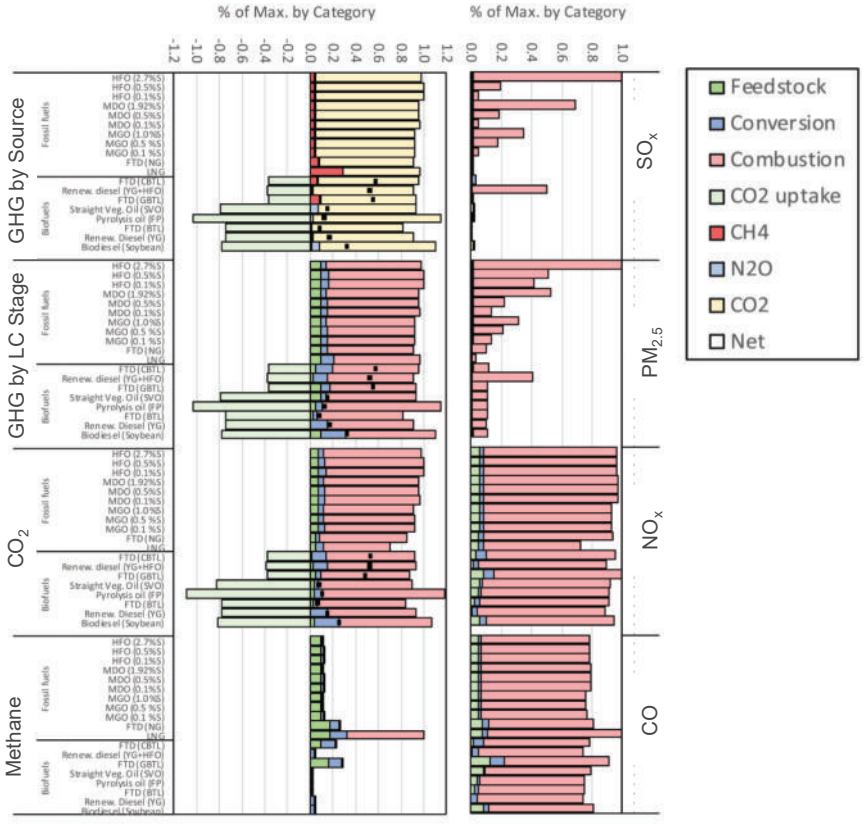
LCA of Alternative Marine Fuel Options

Includes Multiple LCA Metrics:

- GHGs by type
- Criteria air pollutants
- Energy use
- Water consumption

Leverages existing GREET pathways and builds new ones:

- Conventional heavy fuel oil, marine distillate oil, and marine gas oil
- Fischer-Tropsch distillate
- Pyrolysis oil
- Renewable Diesel
- Biodiesel



LCA of Alternative Marine Fuel Options

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Article

Biofuel Options for Marine Applications: Technoeconomic and Life-Cycle Analyses

Eric C. D. Tan,* Troy R. Hawkins,* Uisung Lee, Ling Tao, Pimphan A. Meyer, Michael Wang, and Tom Thompson

Cite This: Environ. Sci. Technol. 2021, 55, 7561−7570

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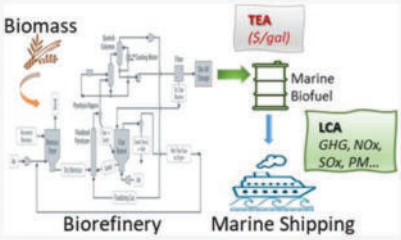
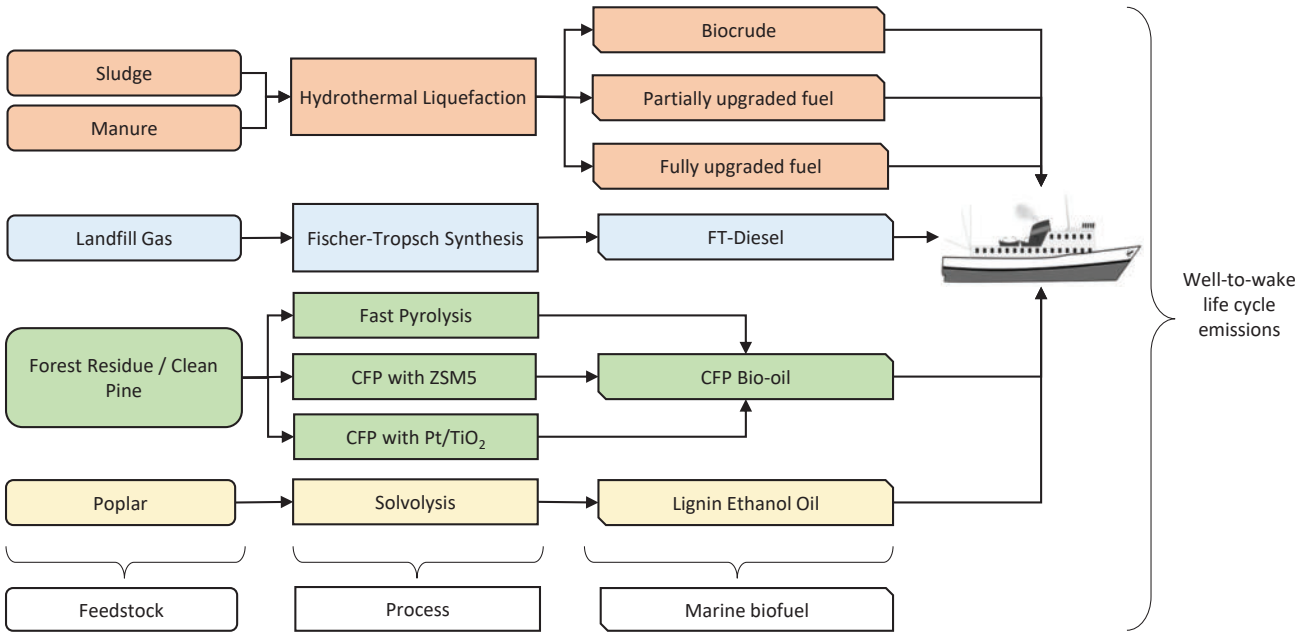
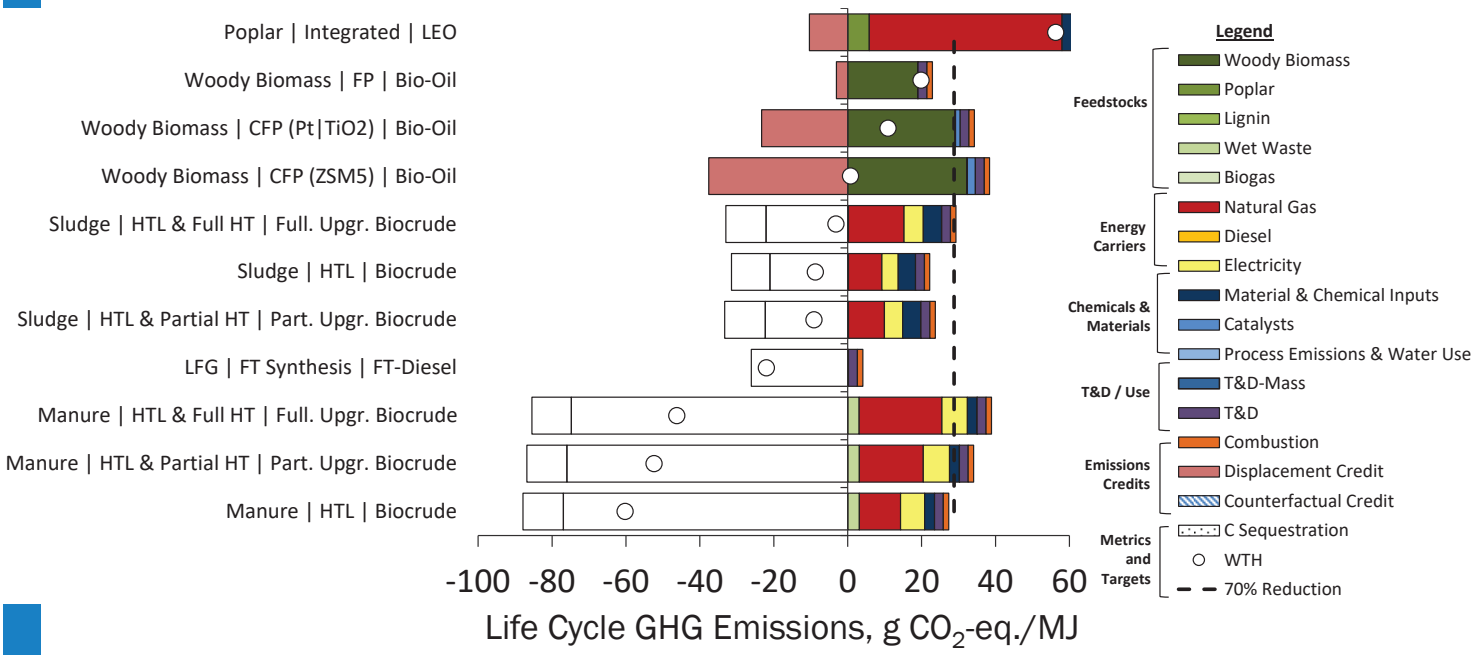
ABSTRACT: This study performed technoeconomic and life-cycle analyses to assess the economic feasibility and emission benefits and tradeoffs of various biofuel production pathways as an alternative to conventional marine fuels. We analyzed production pathways for (1) Fischer−Tropsch diesel from biomass and cofeeding biomass with natural gas or coal, (2) renewable diesel via hydroprocessed esters and fatty acids from yellow grease and cofeeding yellow grease with heavy oil, and (3) bio-oil via fast pyrolysis of low-ash woody feedstock. We also developed a new version of the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) marine fuel module for the estimation of life-cycle greenhouse gas (GHG) and criteria air pollutant (CAP) emissions of conventional and biobased marine fuels. The alternative fuels considered have a minimum fuel selling price between 2.36 and 4.58 $/heavy fuel oil gallon equivalent (HFOGE), and all exhibit improved life-cycle GHG emissions compared to heavy fuel oil (HFO), with reductions ranging from 40 to 93%. The alternative fuels also exhibit reductions in sulfur oxides and particulate matter emissions. Additionally, when compared with marine gas oil and liquified natural gas, they perform favorably across most emission categories except for cases where carbon and sulfur emissions are increased by the



Marine Bio-Oil Pathways

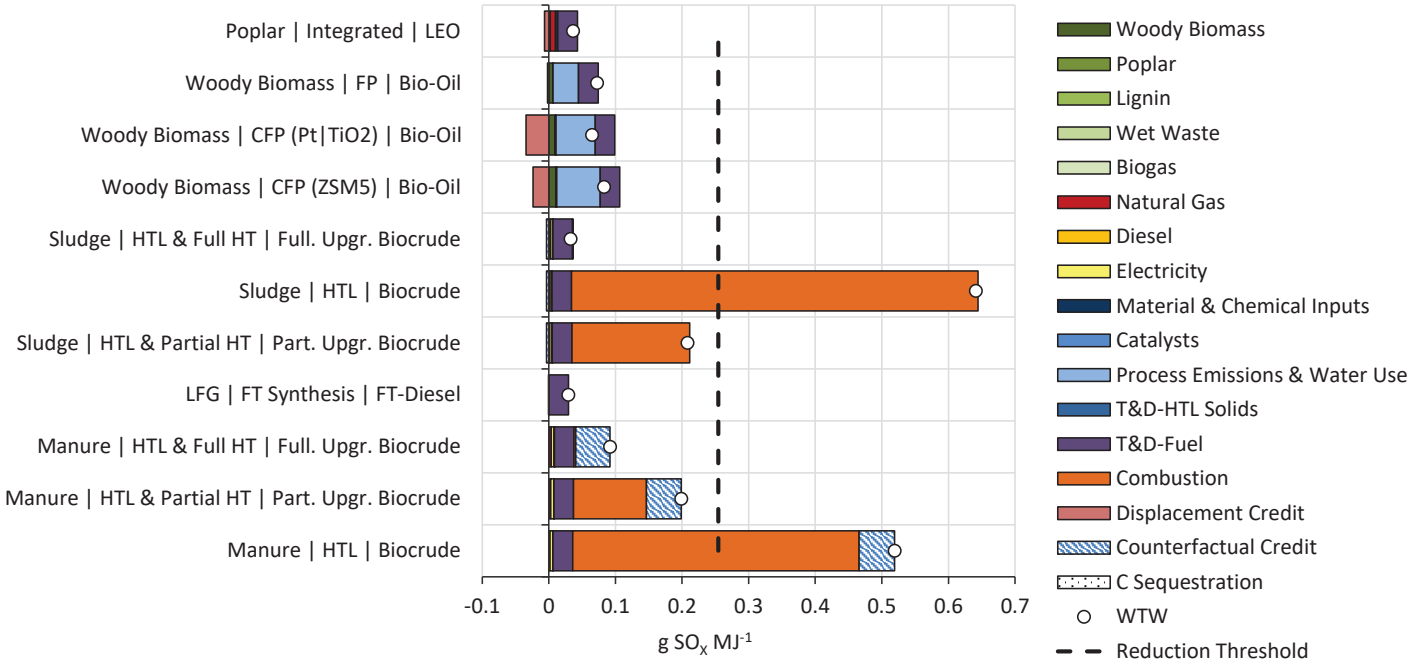


Marine Bio-Oils: Life Cycle GHG Emissions



CFP: Catalytic Fast Pyrolysis; ZSM5: Zeolite Socony Mobil-5; TiO2: Titanium Dioxide; FP: Fast Pyrolysis; **HTL**: Hydrothermal Liquefaction; HT: Hydrotreating; LFG: Landfill Gas; T&D: Transportation and Distribution; **WTH**: Well-to-Hull

Marine Bio-Oils: Life Cycle SOx Emissions



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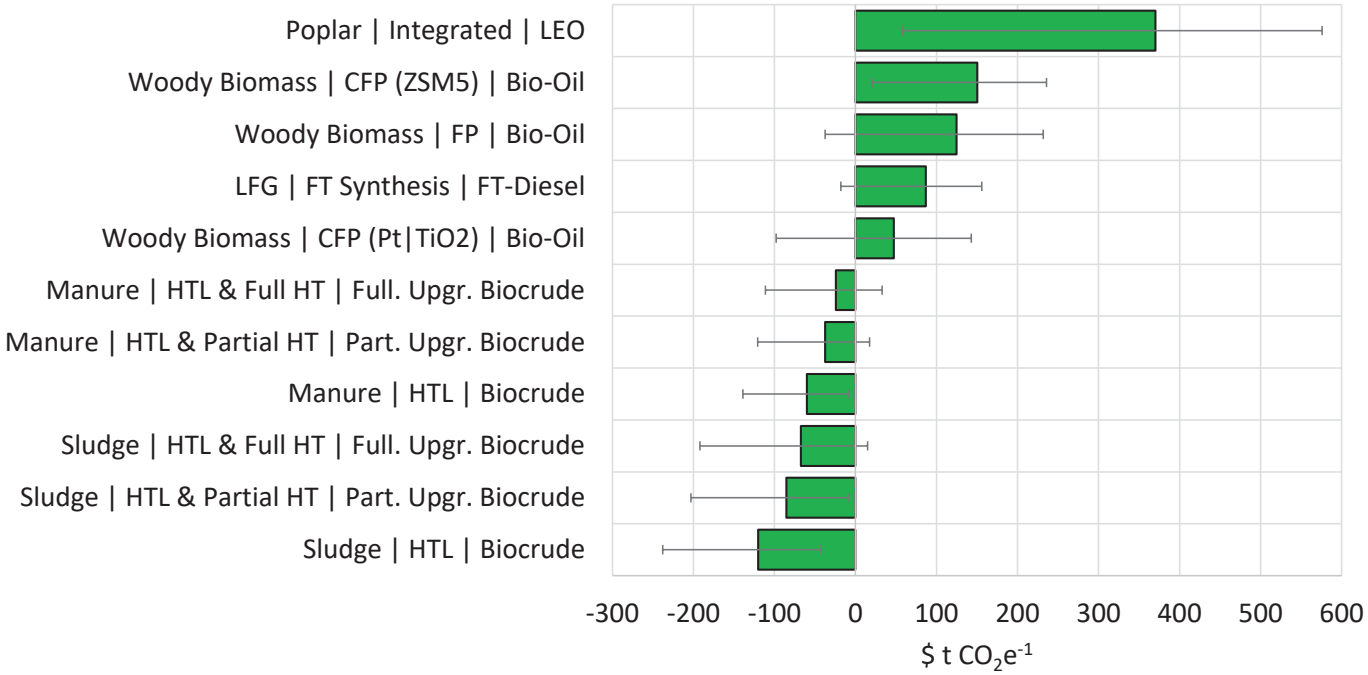
Marine Bio-Oils: Marginal Carbon Abatement Cost



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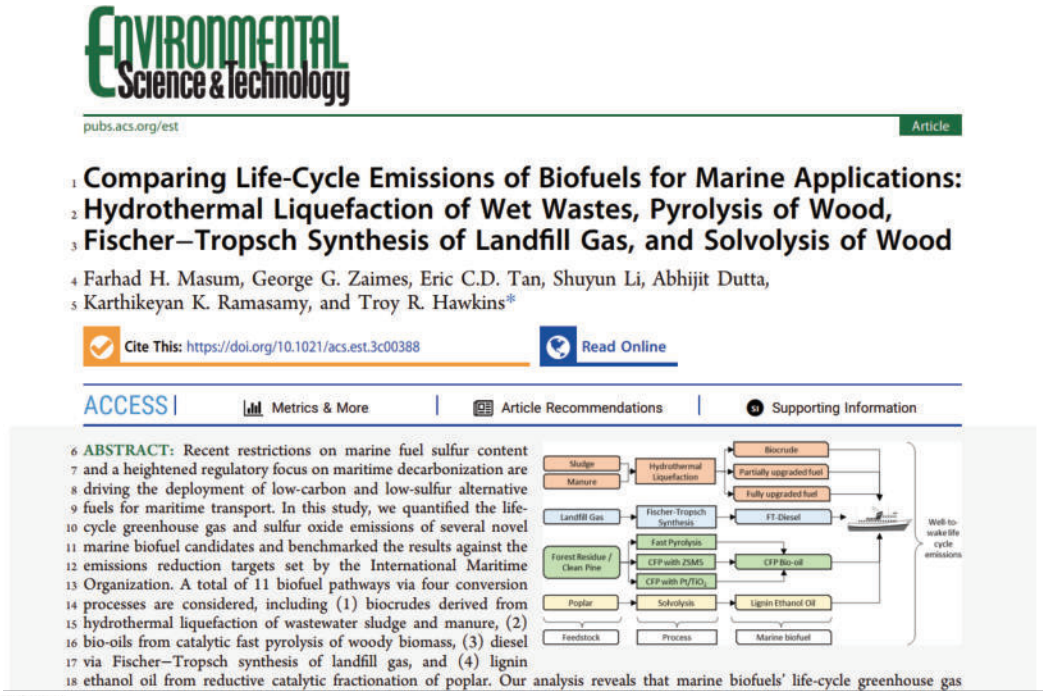
Marine Bio-Oils: Life Cycle GHG Emissions



Environmental Science & Technology

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Comparing Life-Cycle Emissions of Biofuels for Marine Applications: Hydrothermal Liquefaction of Wet Wastes, Pyrolysis of Wood, Fischer–Tropsch Synthesis of Landfill Gas, and Solvolysis of Wood

Farhad H. Masum, George G. Zaimes, Eric C.D. Tan, Shuyun Li, Abhijit Dutta, Karthikeyan K. Ramasamy, and Troy R. Hawkins*

Cite This: https://doi.org/10.1021/acs.est.3c00388 Read Online

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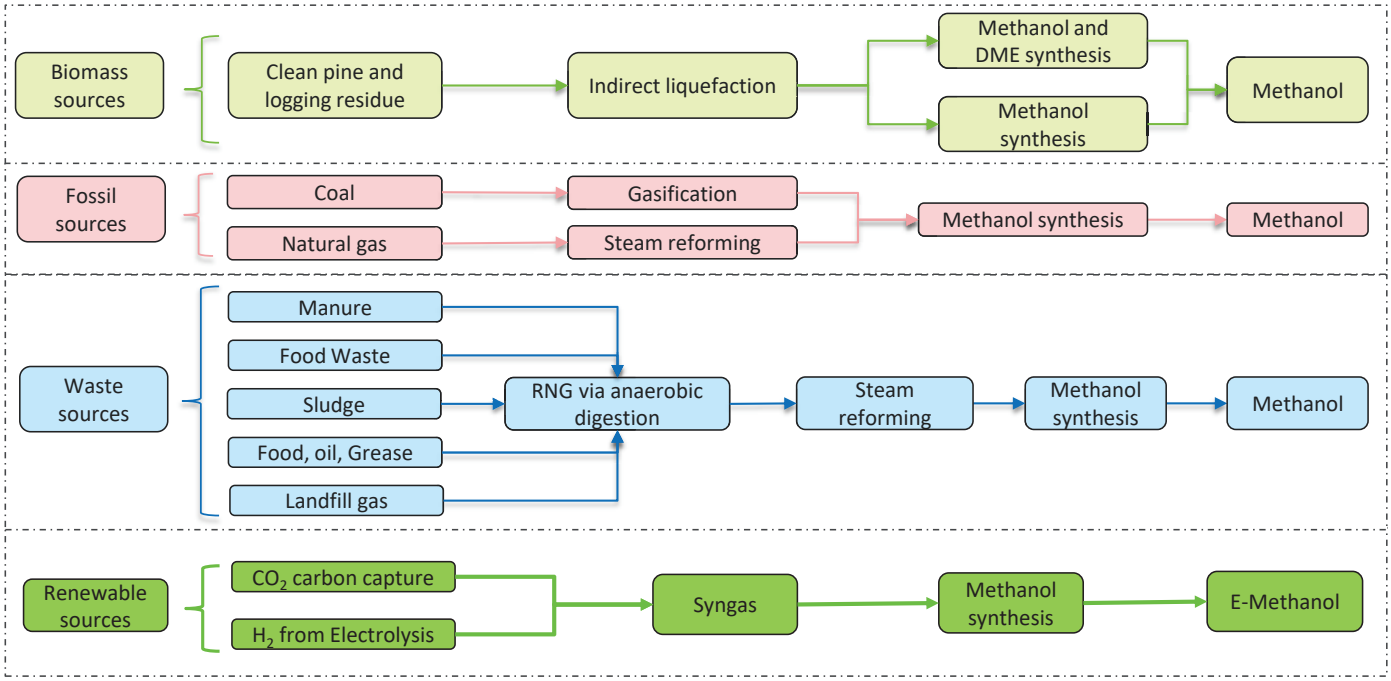
ABSTRACT: Recent restrictions on marine fuel sulfur content and a heightened regulatory focus on maritime decarbonization are driving the deployment of low-carbon and low-sulfur alternative fuels for maritime transport. In this study, we quantified the life-cycle greenhouse gas and sulfur oxide emissions of several novel marine biofuel candidates and benchmarked the results against the emissions reduction targets set by the International Maritime Organization. A total of 11 biofuel pathways via four conversion processes are considered, including (1) biocrudes derived from hydrothermal liquefaction of wastewater sludge and manure, (2) bio-oils from catalytic fast pyrolysis of woody biomass, (3) diesel via Fischer–Tropsch synthesis of landfill gas, and (4) lignin ethanol oil from reductive catalytic fractionation of poplar. Our analysis reveals that marine biofuels' life-cycle greenhouse gas

Methanol Pathways



Methanol: Life Cycle GHG Emissions

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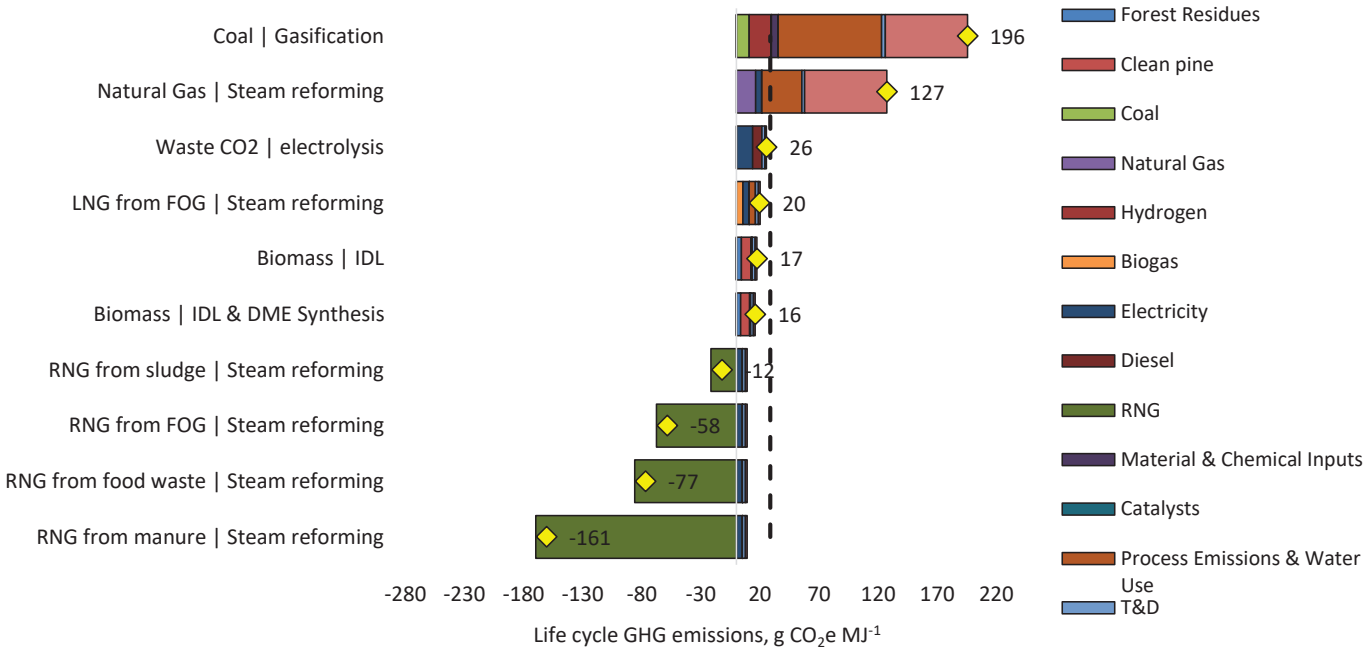
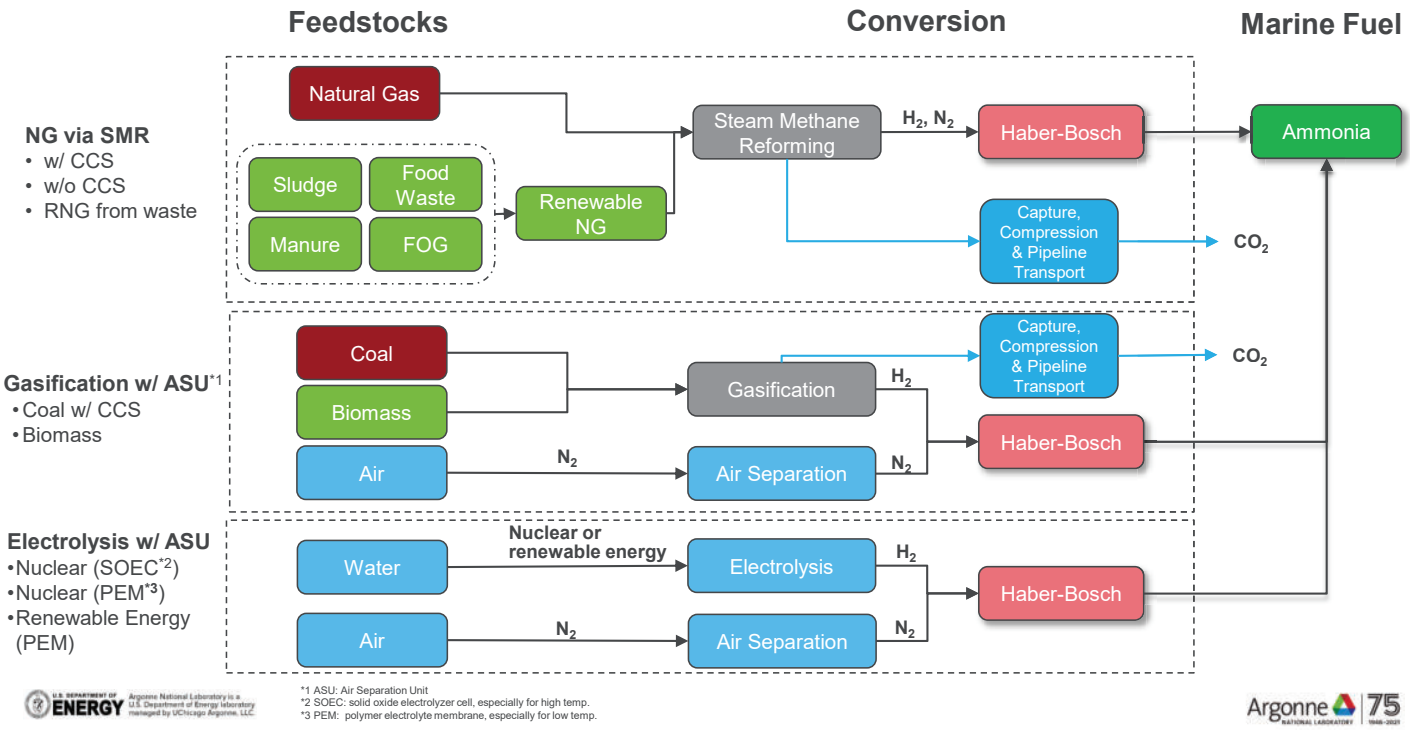


LNG: Liquefied Natural Gas; FOG: Fats, Oils, and Grease; IDL: Indirect Liquefaction; DME: Dimethyl Ether; RNG: Renewable Natural Gas

AMMONIA PATHWAYS



*1 ASU: Air Separation Unit
*2 SOEC: solid oxide electrolyzer cell, especially for high temp.
*3 PEM: polymer electrolyte membrane, especially for low temp.

Ammonia: Life Cycle GHG Emissions

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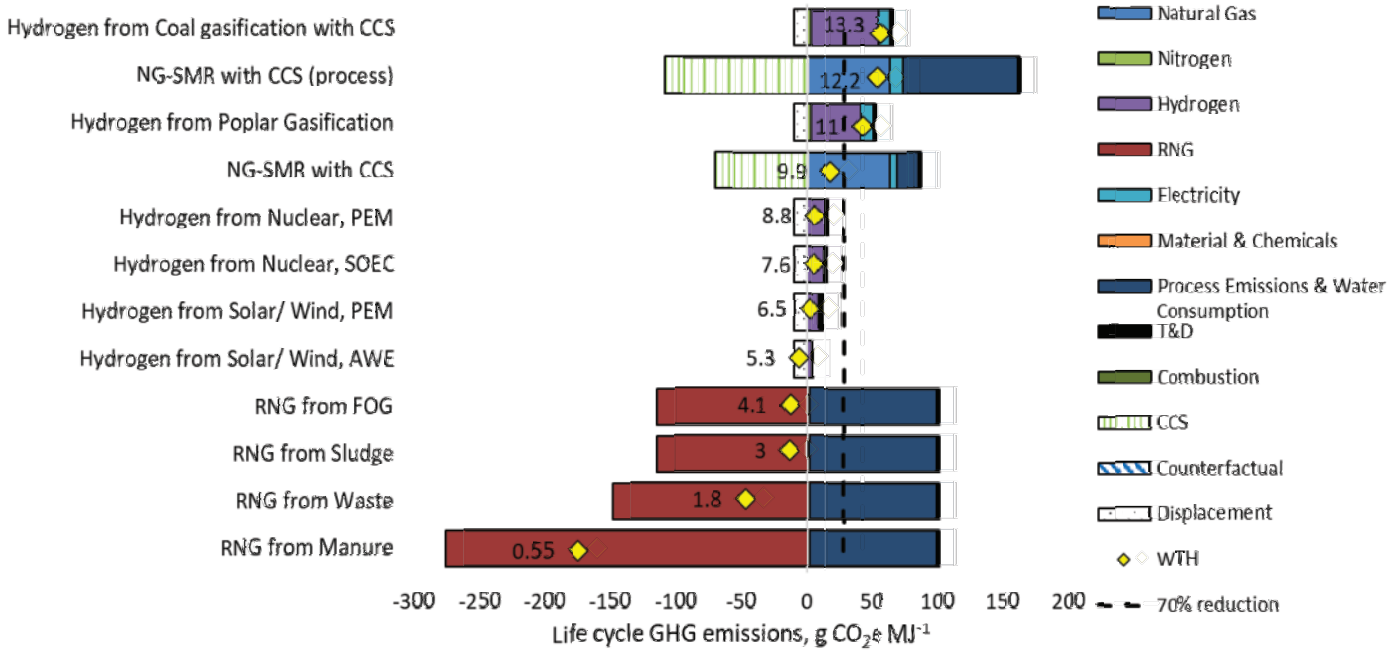
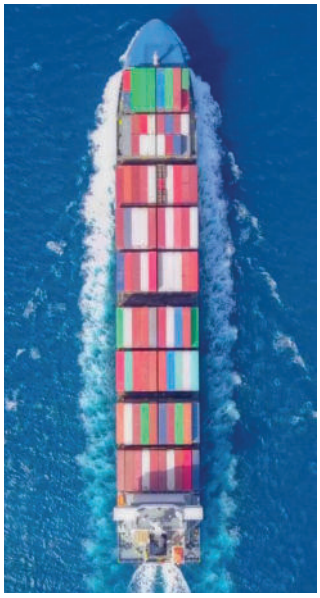


CCS: Carbon Capture and Storage; SMR: Steam Methane Reforming; PEM: Polymer electrolyte membrane; SOEC: Solid Oxide Electrolyzer Cell; RNG: Renewable Natural Gas; FOG: Fats, Oils, and Grease

Marine Module Default Fuel Consumption per Trip

- Trip Fuel Consumption (MJ or J/MT-km):
  - **Vessel Type**: Bulk Carrier, Tanker, and Container Ship
  - **Vessel Operations**: Distance, Speed*, Time, Engine Load Factor, and Fuel^
  - **Main and Aux. Engine Power Ratings**
  - **Energy Conversion Efficiency**
    - Main propulsion: SSD, MSD, Steam Turbine (ST), or Gas Turbine (GT)
    - Aux. engines: MSD or HSD
  - **Region**: Pacific, Atlantic, Gulf of Mexico, or Great Lakes
  - **Travel**: Foreign vs. Domestic
  - **Trip**: Cruise, RSZ, and Hotel



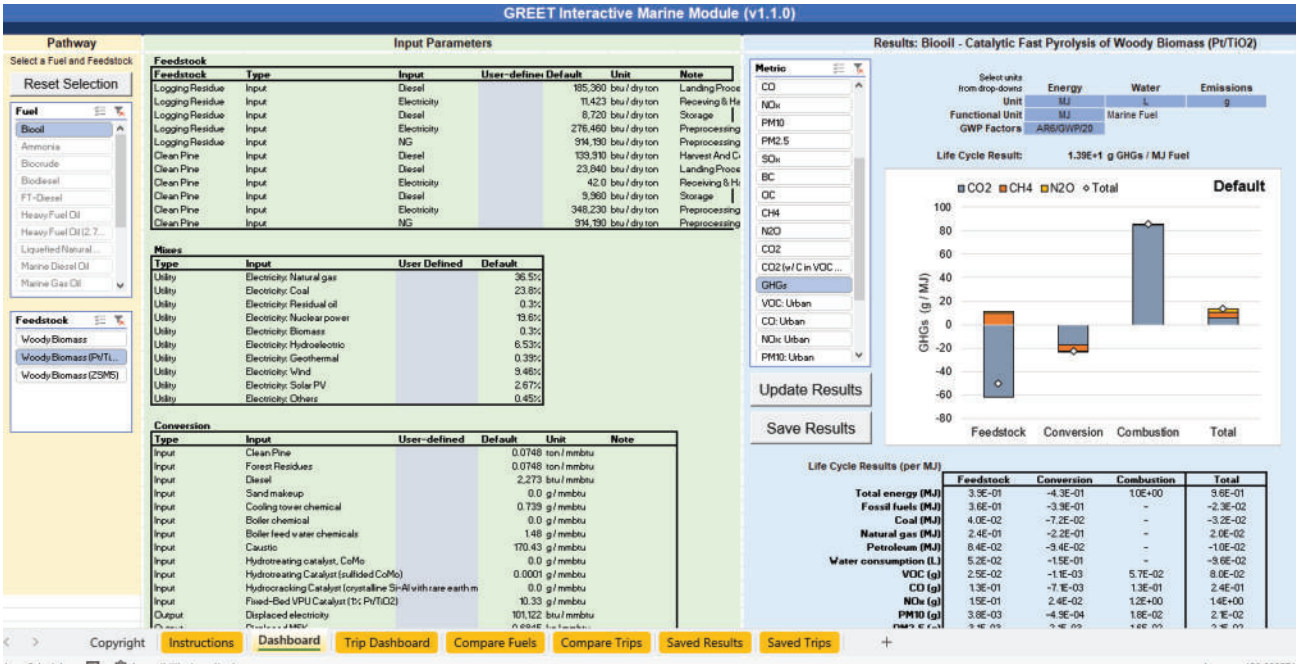
Fuel consumption used for emissions calculations

* Slow steaming assumed.
^ Fuel can be selected for each portion of trip.

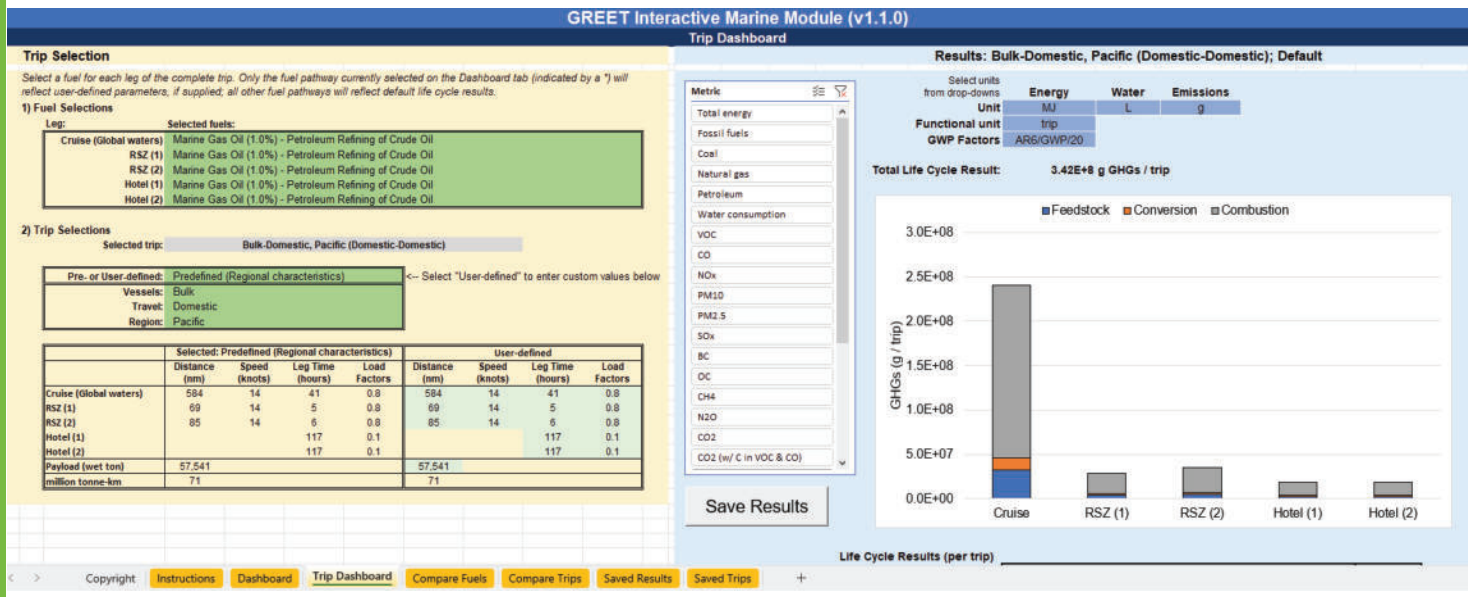
Additional Lifecycle Considerations

- Changes to routine maintenance schedule (and material consumption) with alternative fuels:
  - Oil change interval
  - Other
  - How much effect on fuel consumption and emissions?
- Additional inputs to engine, fueling system, emissions control, etc.?
- Fugitive emissions (leaks, purging, etc.)

GREET Marine Module: Main Dashboard



GREET Marine Module: Trip Dashboard



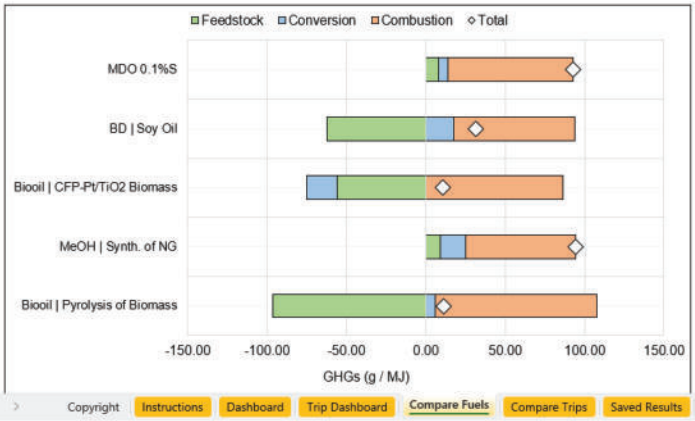
GREET Marine Module: Fuel Comparison

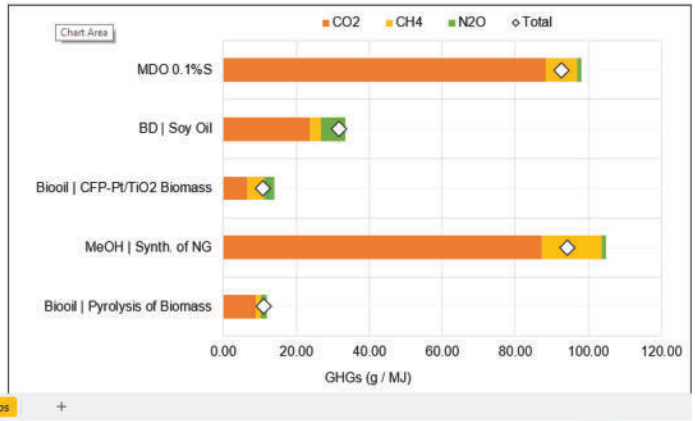
Choose Fuel Pathways and Metric

	Pathway Name	Figure Label
Pathway 1	[default] Marine Diesel Oil (0.1%) - Petroleum Refining of Crude Oil	MDO 0.1%S
Pathway 2	[default] Biodiesel - Transesterification of Soybean	BD | Soy Oil
Pathway 3	[default] Biooil - Catalytic Fast Pyrolysis of Woody Biomass (Pt/TiO2)	Biooil | CFP-Pt/TiO2 Biomass
Pathway 4	[default] Methanol - Methanol Synthesis of Natural Gas	MeOH | Synth. of NG
Pathway 5	[default] Pyrolysis Oil - Pyrolysis of Biomass	Biooil | Pyrolysis of Biomass

Metric: GHGs

Results by Stage	Feedstock	Conversion	Combustion	Total
MDO 0.1%S	7.89	6.09	78.66	92.64
BD | Soy Oil	-62.1663	17.56	76.28	31.68
Biooil | CFP-Pt/TiO2 Biomass	-56.1369	-19.1335	86.21	10.94
MeOH | Synth. of NG	9.12	15.74	69.52	94.38
Biooil | Pyrolysis of Biomass	-96.4473	5.76	101.7	11.02





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Questions regarding marine LCA with GREET?

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