



Life-Cycle Analysis for Advanced Marine Fuels

Farhad Masum

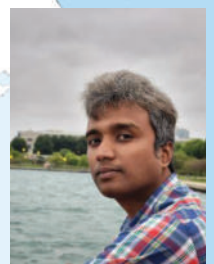
Argonne National Laboratory
June 20, 2023



Argonne National Laboratory is a
U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC.



- Bachelor in Environmental Science, University of Chittagong
- MS in Forest Resources, University of Arkansas
- 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

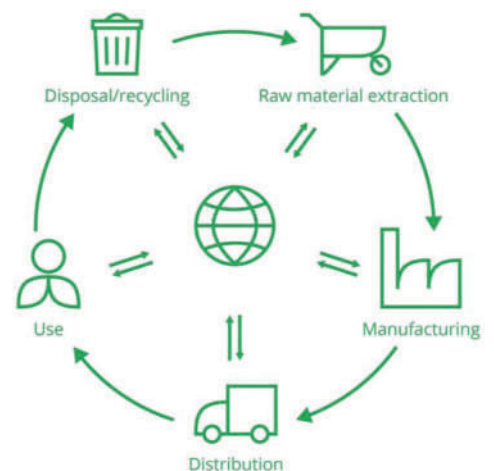
5 national research centers led by Argonne

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



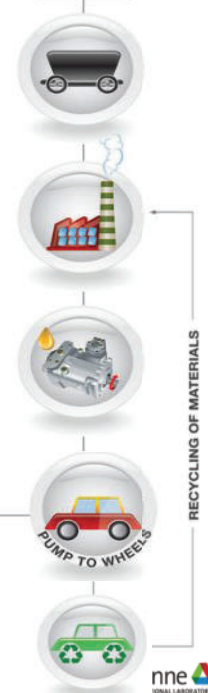
<https://pre-sustainability.com/articles/life-cycle-assessment-lca-basics/>

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

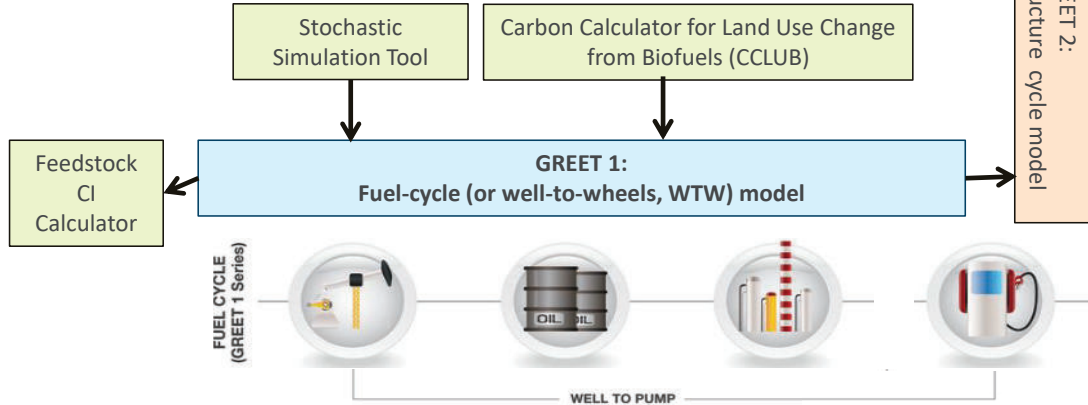
- Argonne has been developing the GREET life-cycle analysis (LCA) model since 1995 with annual updates and expansions
- BETO has been a major GREET sponsor since the beginning
- GREET is available at greet.anl.gov
- GREET Outputs: GHG emissions, Criteria Air Pollutant emissions, Energy Use, and Water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

(Vehicle manufacturing cycle as the example)

VEHICLE CYCLE (GREET 2 Series)



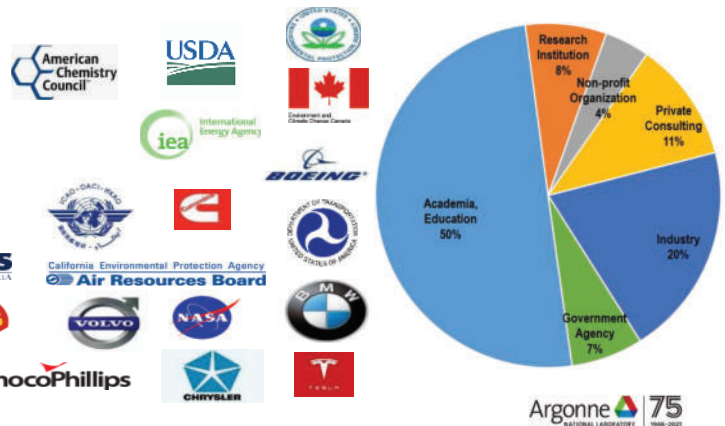
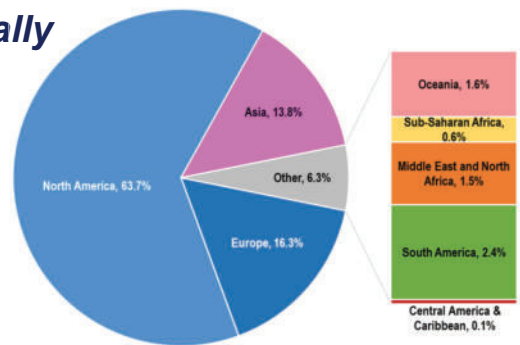
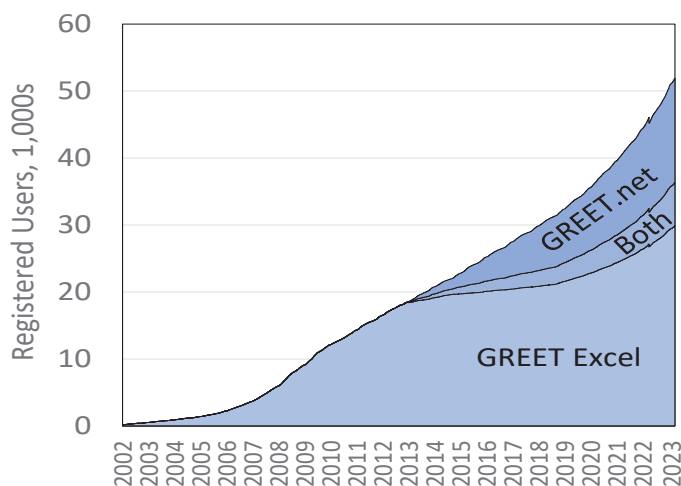
GREET 2: Material/infrastructure cycle model



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

Energy use	Air pollutants	Greenhouse gases	Water consumption
<ul style="list-style-type: none"> 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 	<ul style="list-style-type: none"> VOC, CO, NOx, PM₁₀, PM_{2.5}, and SOx Estimated separately for total and urban (a subset of the total) emissions 	<ul style="list-style-type: none"> CO₂, CH₄, N₂O, black carbon, and albedo CO_{2e} of the five (combined with their global warming potentials) 	<ul style="list-style-type: none"> Addressing water supply and demand (energy-water nexus)

There are over 50,000 registered GREET users globally



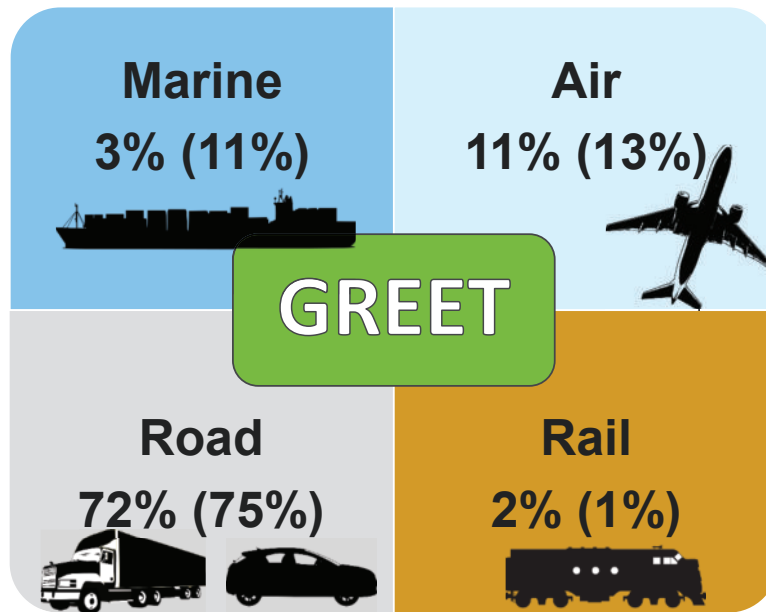
Informing Policies and Regulations

California Environmental Protection Agency
Air Resources Board



- 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

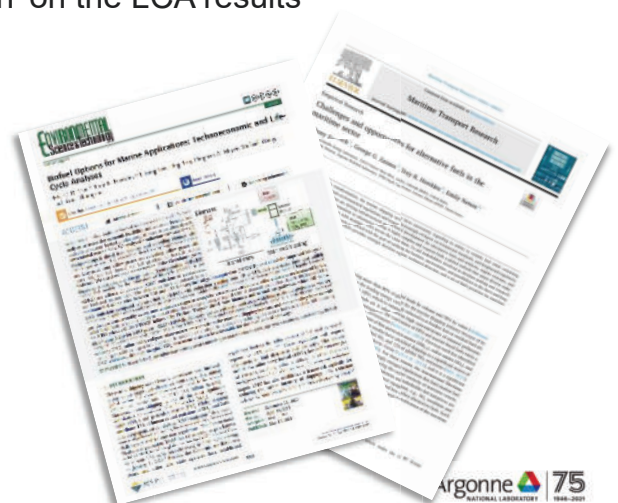
REET Scope - All Transportation Sectors



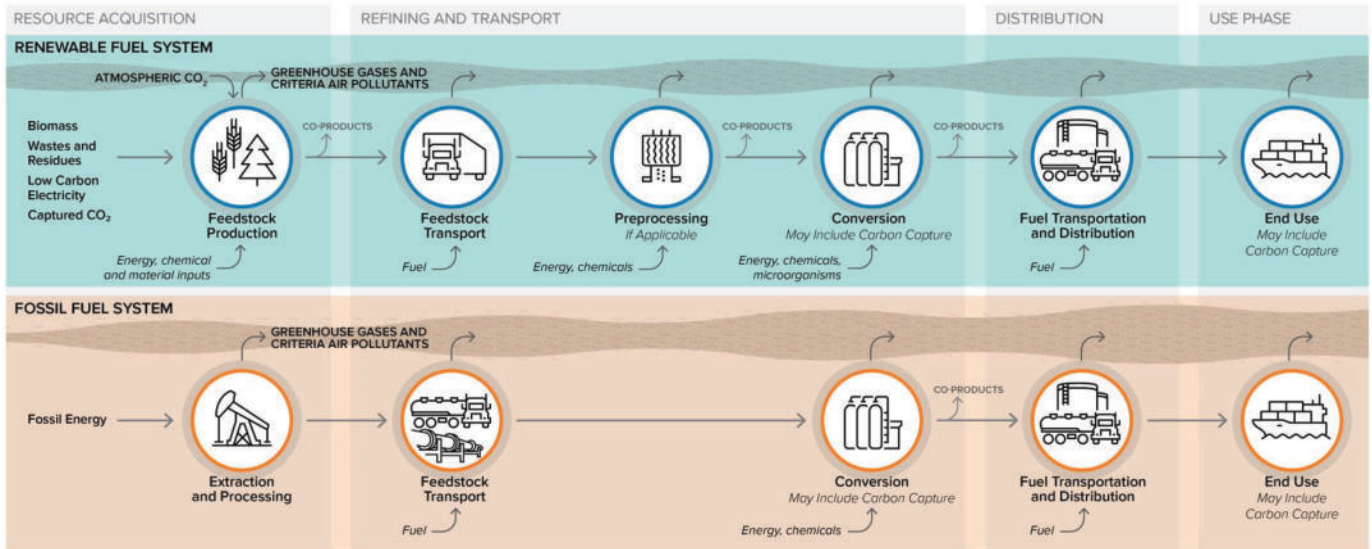
* Share of transportation GHG emissions in the US (and globally in 2019), remaining 12% for US is from pipelines and offroad (EIA, IEA). REET also includes LCA of industry sectors, buildings, and plastics.

REET Marine Models

- REET 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

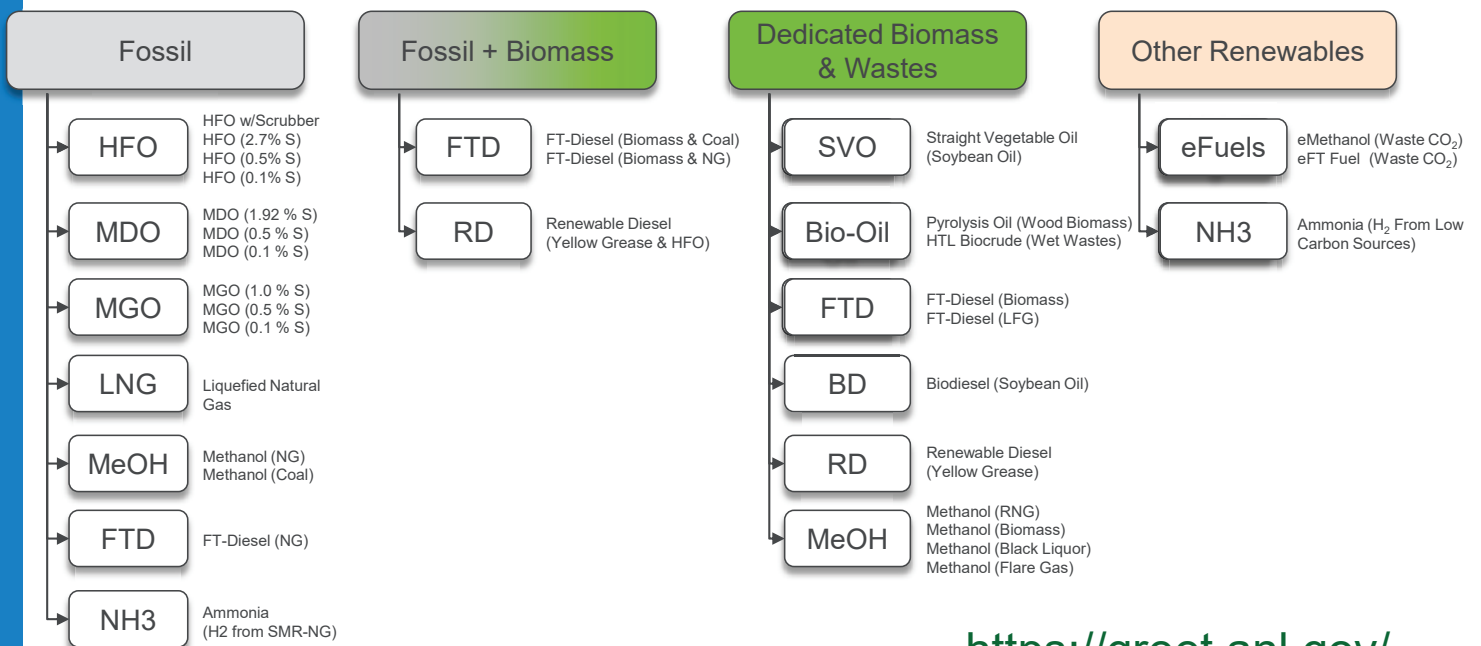


Consistent System Boundary Across Fuel Pathways



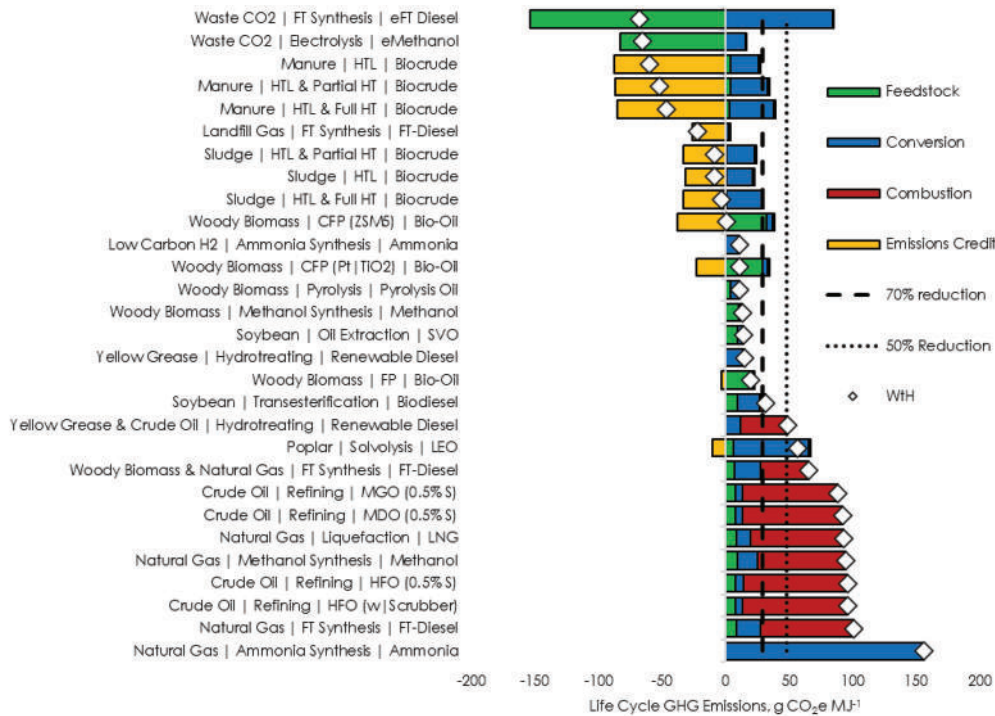
- Compare on an apples-to-apples basis
- Avoid burden shifting across supply chain segments
- Identify key drivers
- Screen across potential environmental impacts

Publicly-Available LCA Models: GREET 2022



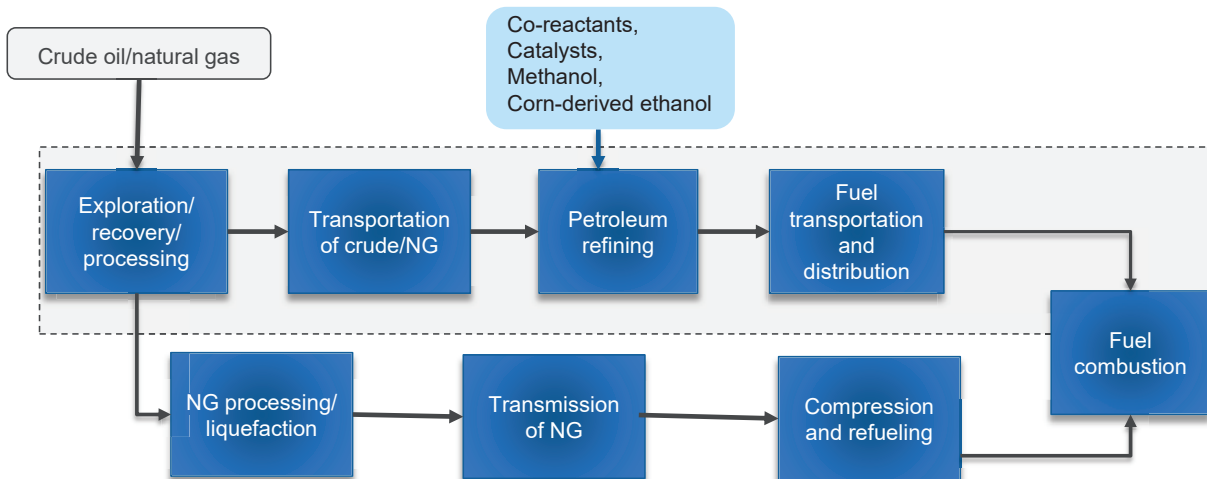
<https://greet.anl.gov/>

Comparison across range of marine fuel pathways



CFP: Catalytic Fast Pyrolysis; ZSMS: 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

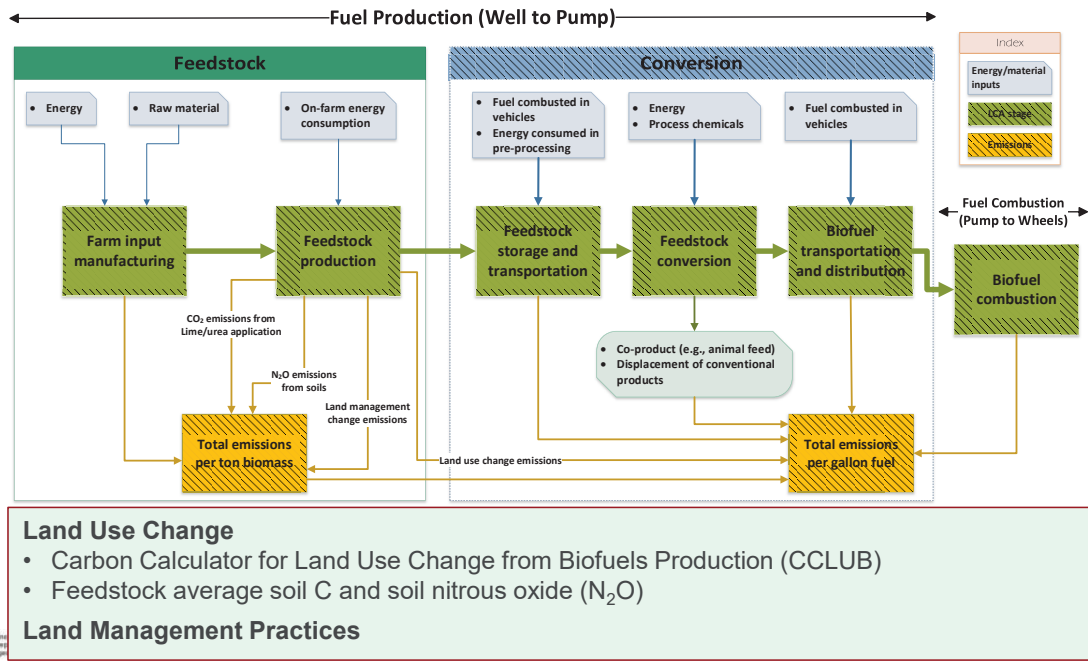
Life cycle of fuels from petroleum and natural gas



- 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



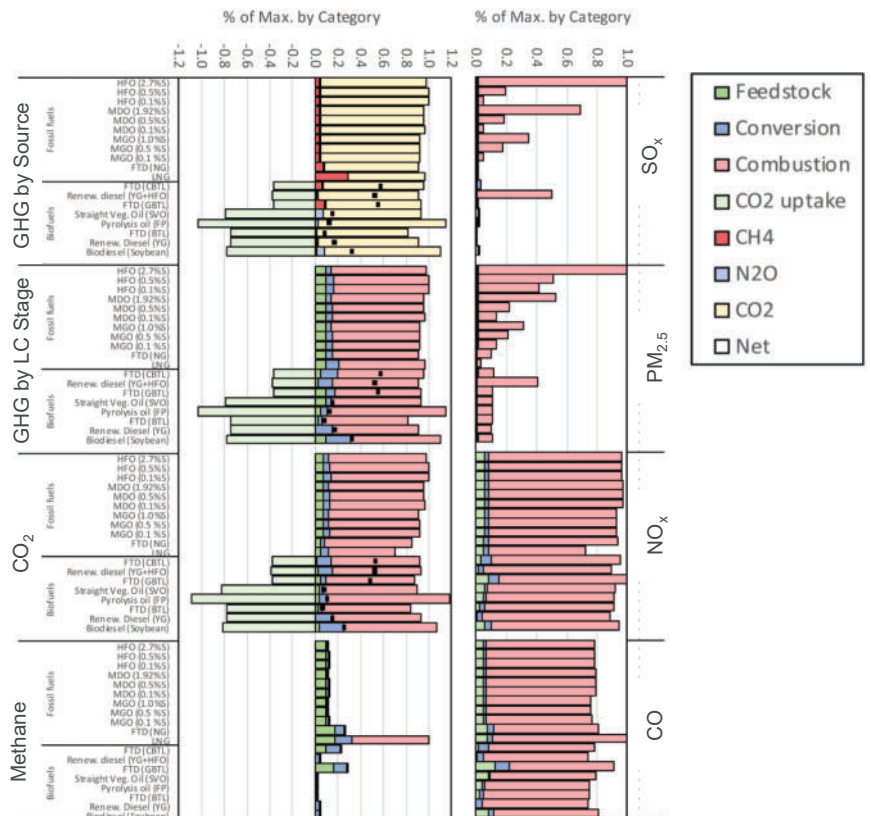
LCA of Alternative Marine Fuel Options

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

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

Read Online

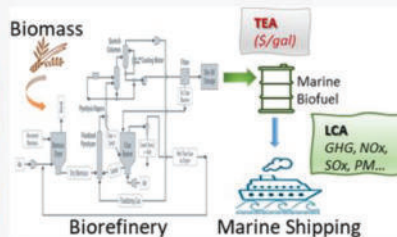
ACCESS

Metrics & More

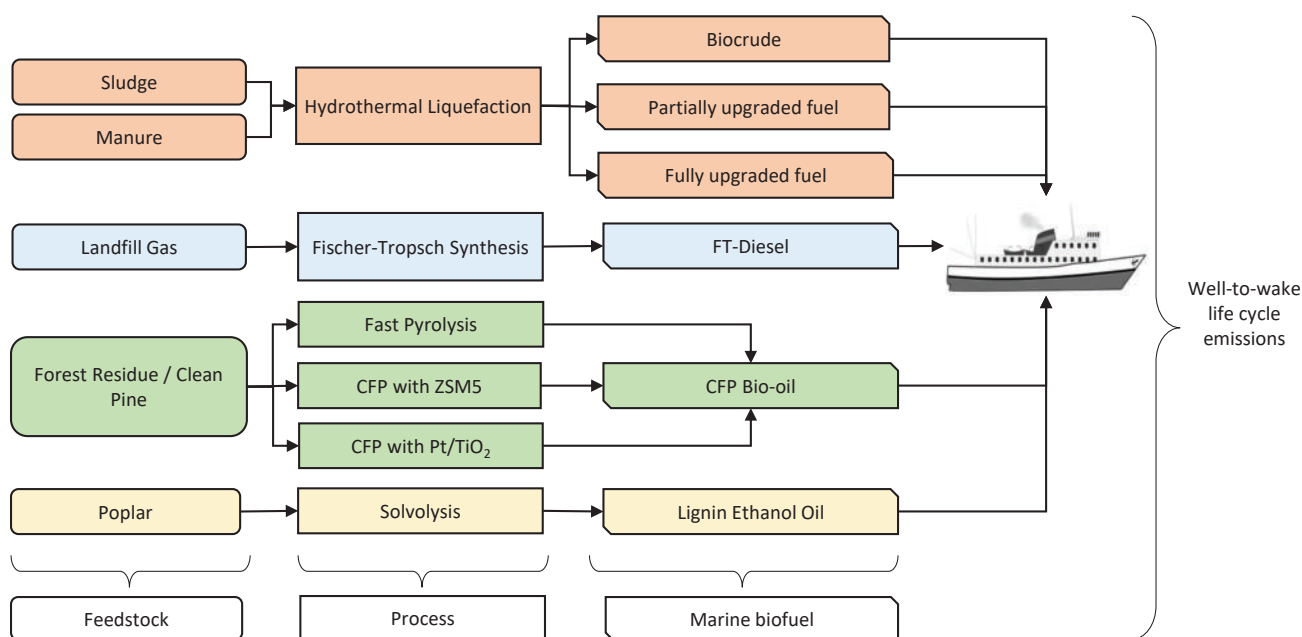
Article Recommendations

Supporting Information

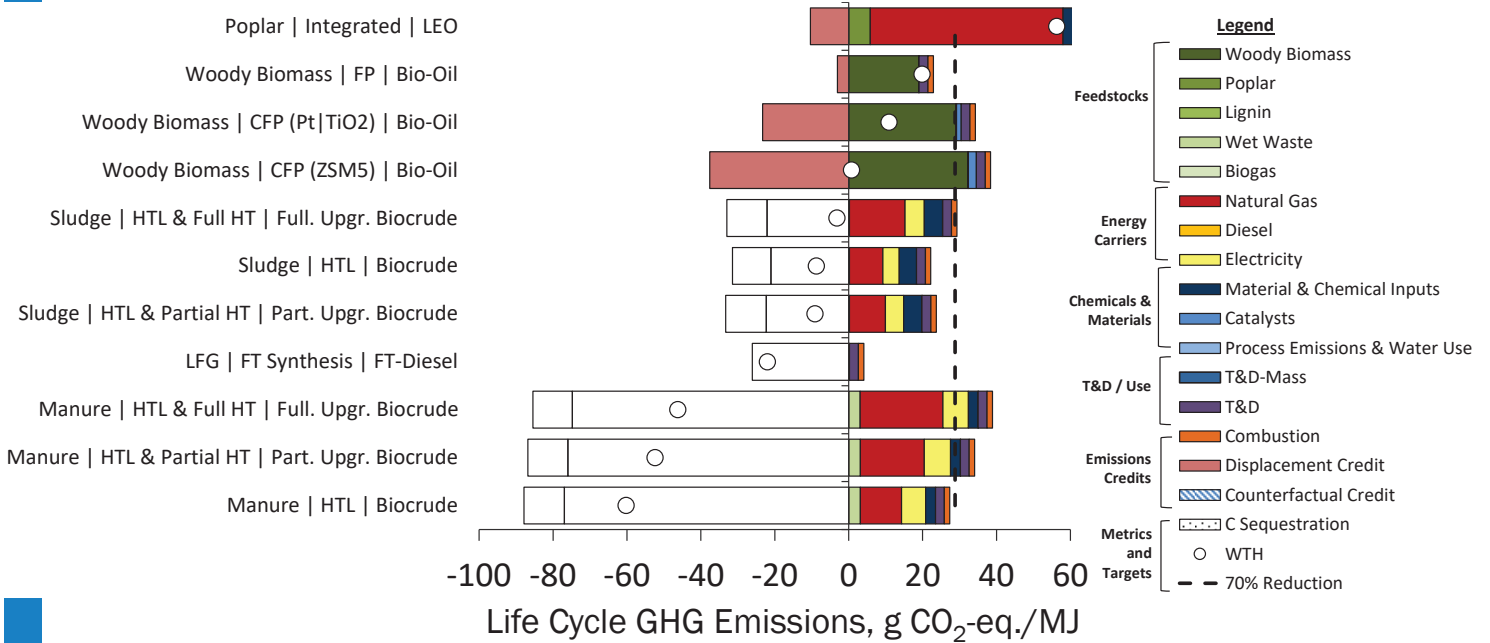
ABSTRACT: This study performed technoeconomic and life-cycle analyses to assess the economic feasibility and emission benefits and tradeoffs of various biofuel production pathways as an alternative to conventional marine fuels. We analyzed production pathways for (1) Fischer–Tropsch diesel from biomass 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 liquefied 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

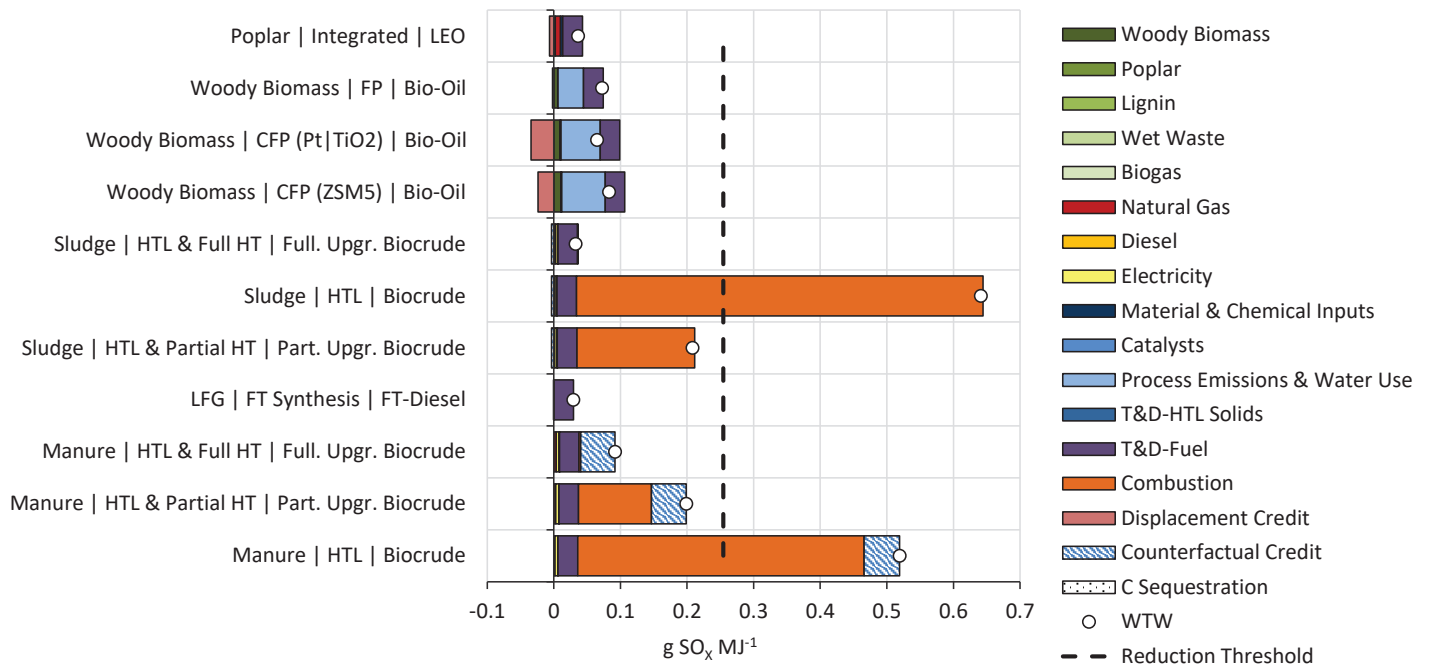


Marine Bio-Oils: Life Cycle GHG Emissions



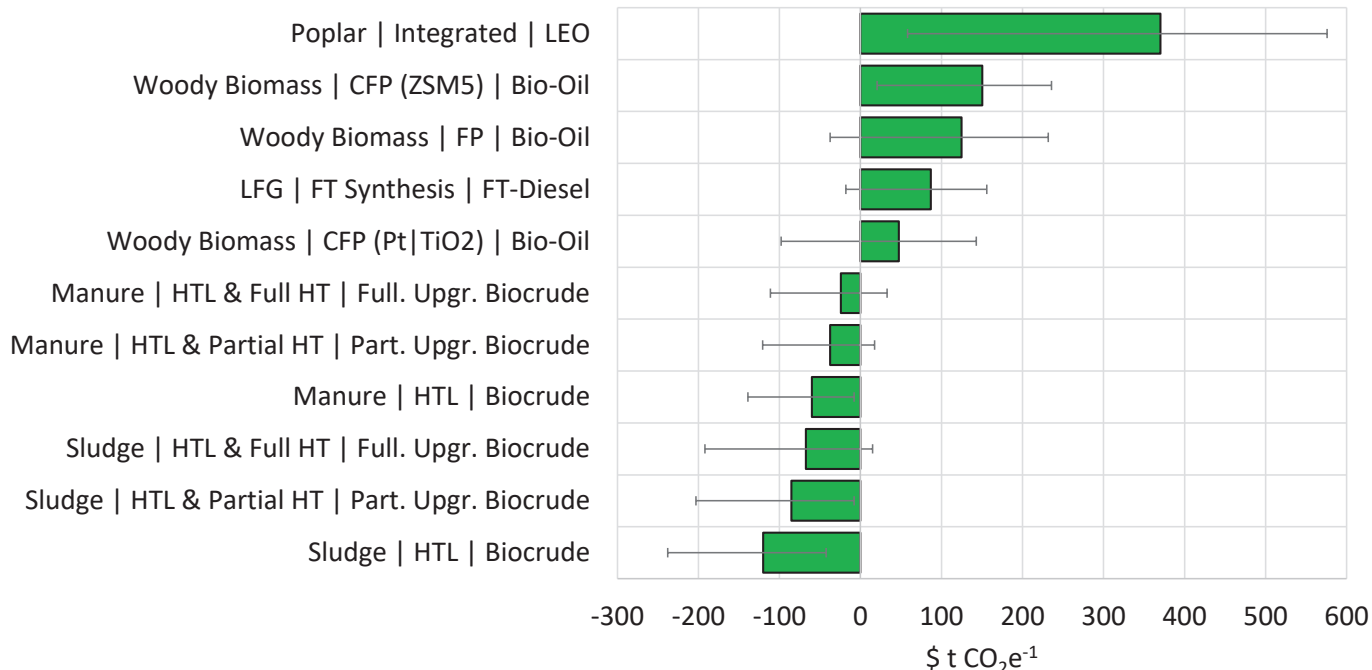
CFP: Catalytic Fast Pyrolysis; ZSM5: Zeolite Socony Mobil-5; TiO₂: Titanium Dioxide; FP: Fast Pyrolysis; HTL: Hydrothermal Liquefaction; HT: Hydrotreating; LFG: Landfill Gas; T&D: Transportation and Distribution; WTH: Well-to-Hull

Marine Bio-Oils: Life Cycle SO_x 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: Marginal Carbon Abatement Cost



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 GHG Emissions



pubs.acs.org/est

Article

1 Comparing Life-Cycle Emissions of Biofuels for Marine Applications: 2 Hydrothermal Liquefaction of Wet Wastes, Pyrolysis of Wood, 3 Fischer–Tropsch Synthesis of Landfill Gas, and Solvolysis of Wood

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

Cite This: <https://doi.org/10.1021/acs.est.3c00388>

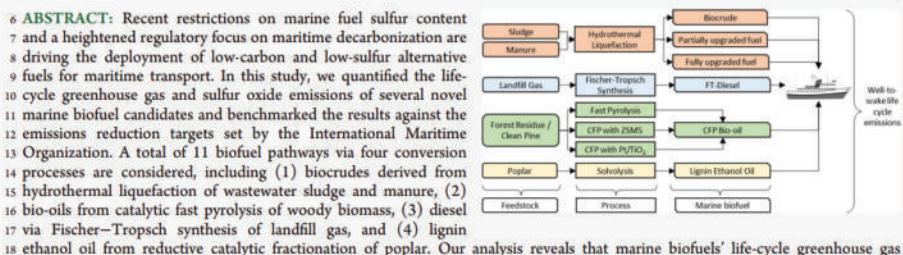
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Metrics & More

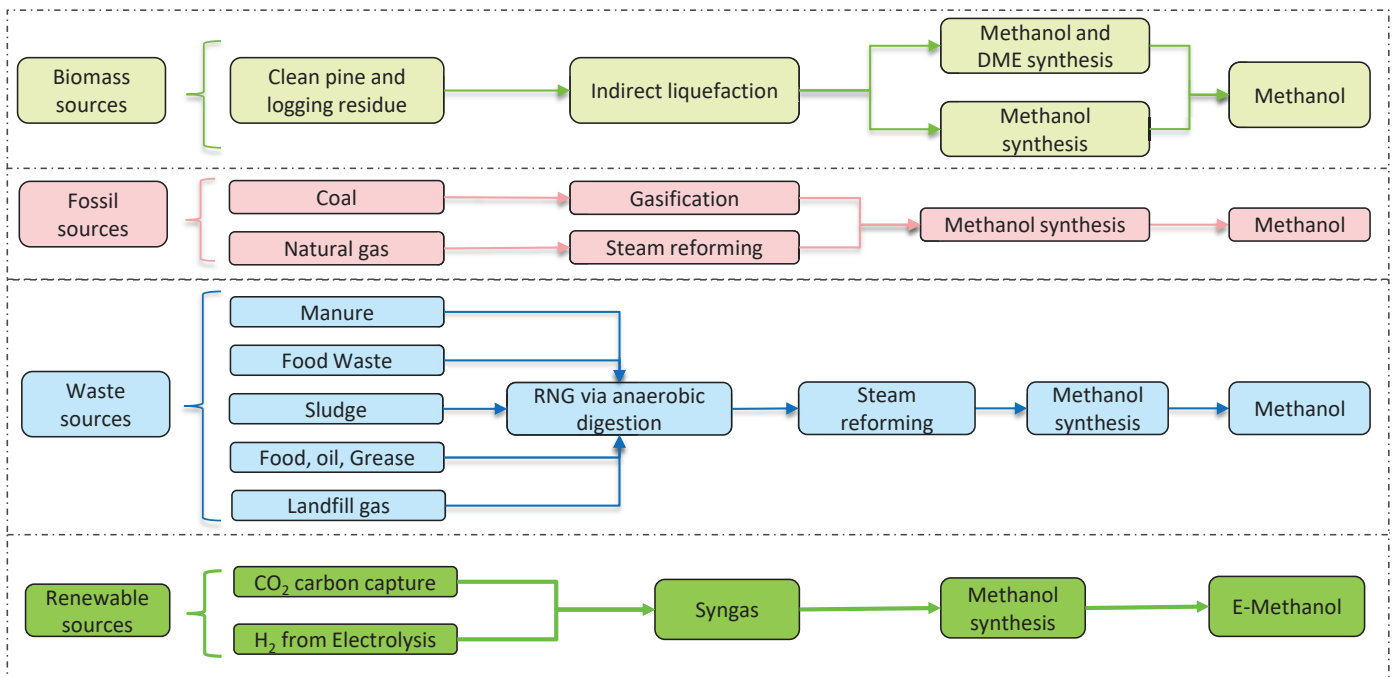
Article Recommendations

Supporting Information



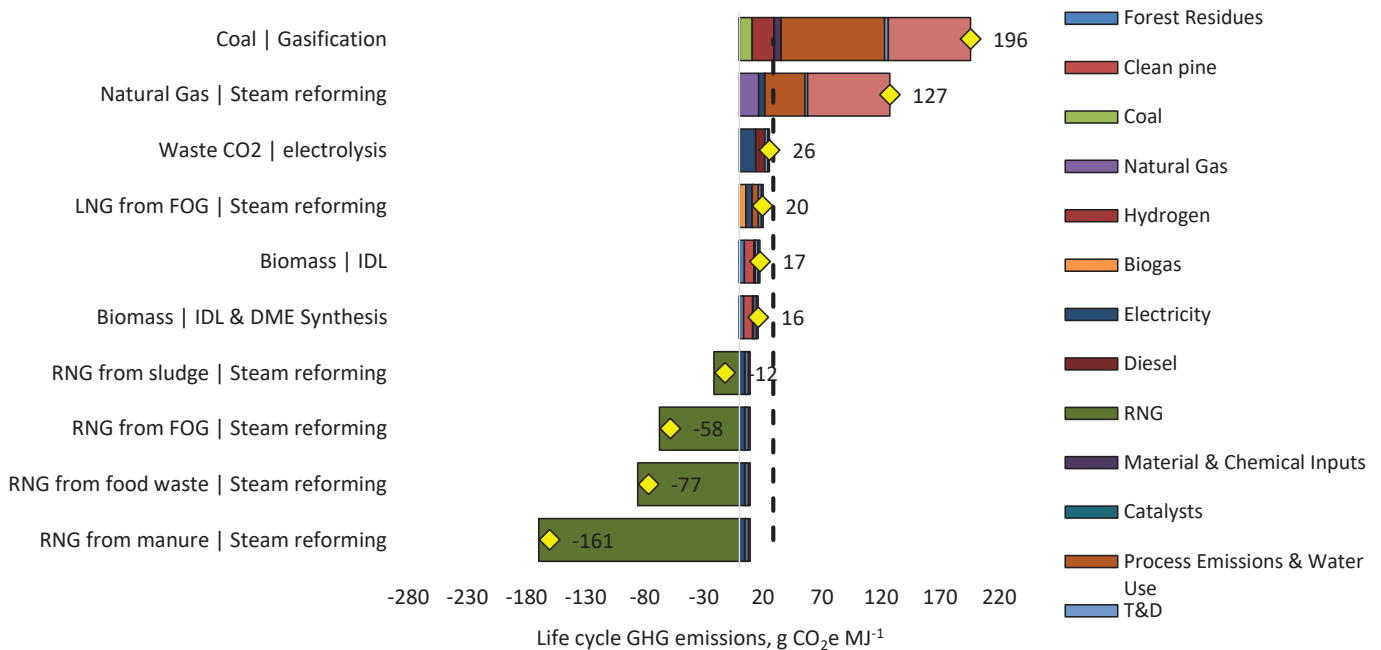
6 **ABSTRACT:** Recent restrictions on marine fuel sulfur content
7 and a heightened regulatory focus on maritime decarbonization are
8 driving the deployment of low-carbon and low-sulfur alternative
9 fuels for maritime transport. In this study, we quantified the life-
10 cycle greenhouse gas and sulfur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

Methanol Pathways



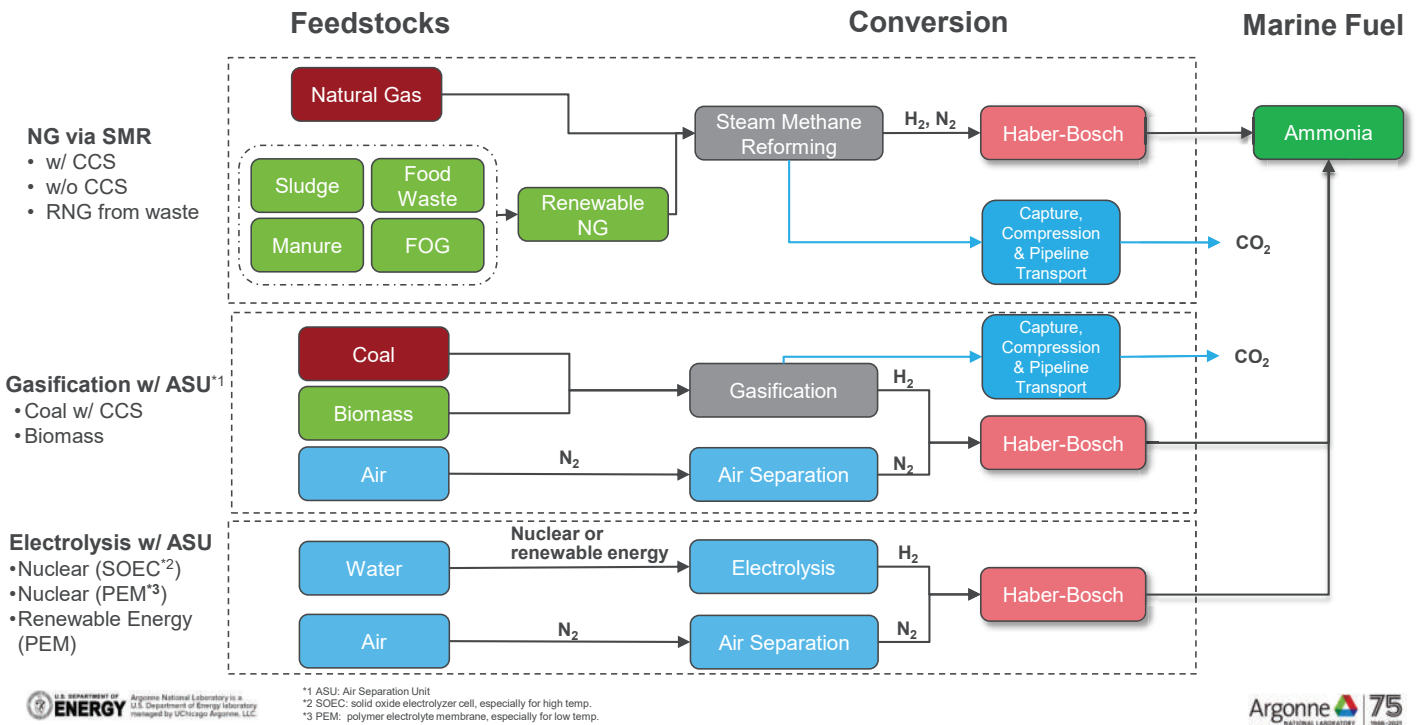
Methanol: Life Cycle GHG Emissions

Draft: Do not cite



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

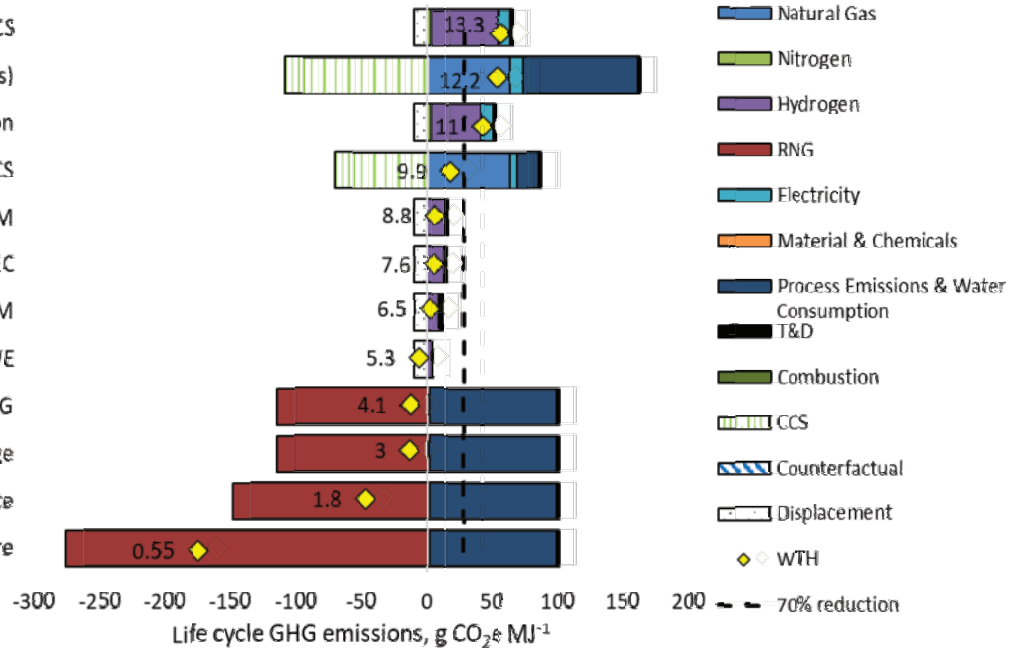
AMMONIA PATHWAYS



Ammonia: Life Cycle GHG Emissions

Draft: Do not cite

- Hydrogen from Coal gasification with CCS
- NG-SMR with CCS (process)
- Hydrogen from Poplar Gasification
- NG-SMR with CCS
- Hydrogen from Nuclear, PEM
- Hydrogen from Nuclear, SOEC
- Hydrogen from Solar/ Wind, PEM
- Hydrogen from Solar/ Wind, AWE
- RNG from FOG
- RNG from Sludge
- RNG from Waste
- RNG from Manure

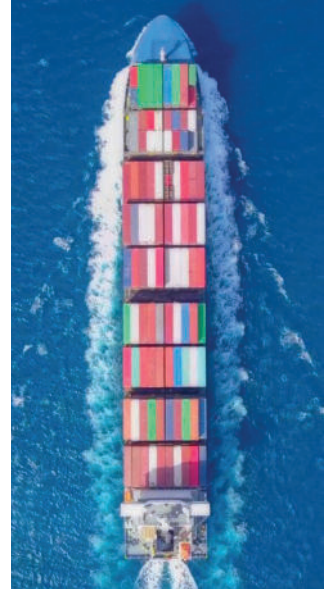


CCS: Carbon Capture and Storage; SMR: Steam Methane Reforming; PEM: Polymer electrolyte membrane; SOEC: Solid Oxide Electrolyzer Cell; RNG: Renewable Natural Gas; FOG: Fats, Oils, and Grease

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.)

REET Marine Module: Main Dashboard

REET Interactive Marine Module (v1.1.0)

Pathway

Select a Fuel and Feedstock

Reset Selection

Fuel

- Biooil
- Ammonia
- Bioethanol
- Biodiesel
- FT-Diesel
- Heavy Fuel Oil
- Heavy Fuel Oil (2.7...)
- Liquefied Natural Gas
- Marine Diesel Oil
- Marine Gas Oil

Feedstock

- Woody Biomass
- Woody Biomass (PvTL...)
- Woody Biomass (ZSM5)

Input Parameters

Feedstock	Type	Input	User-defined	Default	Unit	Note
Logging Residue	Input	Diesel			185,360 bu / dry ton	Landing Phase
Logging Residue	Input	Electricity			11,423 bu / dry ton	Receiving & H...
Logging Residue	Input	Diesel			8,720 bu / dry ton	Storage
Logging Residue	Input	Electricity			276,460 bu / dry ton	Preprocessing
Logging Residue	Input	NG			594,130 bu / dry ton	Preprocessing
Clean Pine	Input	Diesel			133,910 bu / dry ton	Harvest And C...
Clean Pine	Input	Diesel			23,840 bu / dry ton	Landing Phase
Clean Pine	Input	Electricity			42.0 bu / dry ton	Receiving & H...
Clean Pine	Input	Diesel			3,960 bu / dry ton	Storage
Clean Pine	Input	Electricity			348,230 bu / dry ton	Preprocessing
Clean Pine	Input	NG			594,130 bu / dry ton	Preprocessing

Misc

Type	Input	User Defined	Default
Utility	Electricity: Natural gas		36.5%
Utility	Electricity: Coal		23.8%
Utility	Electricity: Residual oil		0.3%
Utility	Electricity: Nuclear power		19.6%
Utility	Electricity: Biomass		0.3%
Utility	Electricity: Hydroelectric		6.53%
Utility	Electricity: Geothermal		0.33%
Utility	Electricity: Wind		9.48%
Utility	Electricity: Solar PV		2.67%
Utility	Electricity: Others		0.45%

Conversion

Type	Input	User-defined	Default	Unit	Note
Input	Clean Pine		0.0748	ton / mmbtu	
Input	Forest Residues		0.0748	ton / mmbtu	
Input	Diesel		2,273	bu / mmbtu	
Input	Sand makeup		0.0	g / mmbtu	
Input	Cooling tower chemical		0.739	g / mmbtu	
Input	Boiler chemical		0.0	g / mmbtu	
Input	Boiler feed water chemicals		148	g / mmbtu	
Input	Caustic		170.43	g / mmbtu	
Input	Hydrocracking catalyst, CoMo		0.0	g / mmbtu	
Input	Hydrocracking Catalyst (sulfided CoMo)		0.0001	g / mmbtu	
Input	Hydrocracking Catalyst (sulfided Ni-Al with rare earth m...		0.0	g / mmbtu	
Input	Fixed-Bed VPU Catalyst (Ti: Pt/TiO2)		10.33	g / mmbtu	
Output	Displaced electricity		101,122	btu / mmbtu	

Metric

- CO
- NOx
- PM10
- PM2.5
- SOx
- BC
- OC
- CH4
- N2O
- CO2
- CO2 (w/ C in VOC ...)
- VOC: Urban
- CO: Urban
- NOx: Urban
- PM10: Urban

Update Results

Save Results

Results: Biooil - Catalytic Fast Pyrolysis of Woody Biomass (Pt/TiO2)

Select units from drop-downs

Energy	Water	Emissions
Unit: MJ	Unit: L	Unit: g
Functional Unit: trip	Functional Unit: Marine Fuel	
GWP Factors: AR6/GWP/20		

Life Cycle Result: 1.39E+1 g GHGs / MJ Fuel

	Feedstock	Conversion	Combustion	Total
Total energy (MJ)	3.5E-01	-4.3E-01	1.0E+00	3.6E-01
Fossil fuels (MJ)	3.6E-01	-3.9E-01	-	-2.9E-02
Coal (MJ)	4.0E-02	-7.2E-02	-	-3.2E-02
Natural gas (MJ)	2.4E-01	-2.2E-01	-	2.0E-02
Petroleum (MJ)	8.4E-02	-3.4E-02	-	-1.0E-02
Water consumption (L)	5.2E-02	-1.5E-01	-	-9.6E-02
VOC (g)	2.5E-02	-1.1E-03	5.7E-02	8.6E-02
CO (g)	1.3E-01	-7.1E-03	1.3E-01	2.4E-01
NOx (g)	1.5E-01	2.4E-02	1.2E+00	1.4E+00
PM10 (g)	3.8E-03	-4.5E-04	1.8E-02	2.1E-02

REET Marine Module: Trip Dashboard

REET Interactive Marine Module (v1.1.0)

Trip Selection

Select a fuel for each leg of the complete trip. Only the fuel pathway currently selected on the Dashboard tab (indicated by a *) will reflect user-defined parameters, if supplied; all other fuel pathways will reflect default life cycle results.

1) Fuel Selections

Leg: Selected fuels:

- Cruise (Global waters) Marine Gas Oil (1.0%) - Petroleum Refining of Crude Oil
- RSZ (1) Marine Gas Oil (1.0%) - Petroleum Refining of Crude Oil
- RSZ (2) Marine Gas Oil (1.0%) - Petroleum Refining of Crude Oil
- Hotel (1) Marine Gas Oil (1.0%) - Petroleum Refining of Crude Oil
- Hotel (2) Marine Gas Oil (1.0%) - Petroleum Refining of Crude Oil

2) Trip Selections

Selected trip: Bulk-Domestic, Pacific (Domestic-Domestic)

Pre- or User-defined: Predefined (Regional characteristics) -- Select "User-defined" to enter custom values below

Vessels: Bulk

Travel: Domestic

Region: Pacific

	Selected: Predefined (Regional characteristics)				User-defined			
	Distance (nm)	Speed (knots)	Log Time (hours)	Load Factors	Distance (nm)	Speed (knots)	Log Time (hours)	Load Factors
Cruise (Global waters)	584	14	41	0.8	584	14	41	0.8
RSZ (1)	69	14	5	0.8	69	14	5	0.8
RSZ (2)	85	14	5	0.8	85	14	5	0.8
Hotel (1)			117	0.1			117	0.1
Hotel (2)			117	0.1			117	0.1
Payload (wet ton)	57,541				57,541			
million tonne-km	71				71			

Trip Dashboard

Results: Bulk-Domestic, Pacific (Domestic-Domestic); Default

Select units from drop-downs

Energy	Water	Emissions
Unit: MJ	Unit: L	Unit: g
Functional Unit: trip		
GWP Factors: AR6/GWP/20		

Total Life Cycle Result: 3.42E+8 g GHGs / trip

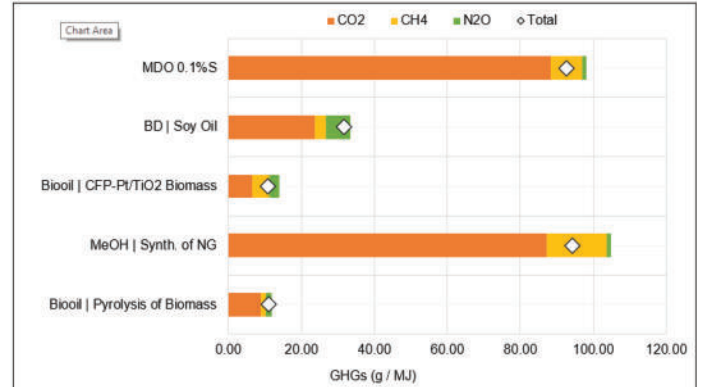
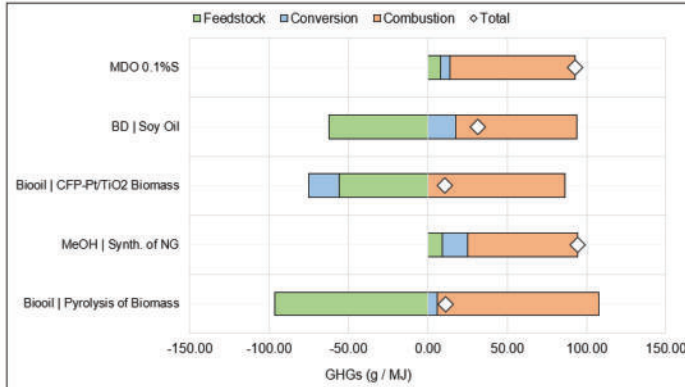
	Feedstock	Conversion	Combustion
Cruise	3.42E+08	-	-
RSZ (1)	-	-	-
RSZ (2)	-	-	-
Hotel (1)	-	-	-
Hotel (2)	-	-	-

GREET Marine Module: Fuel Comparison

Choose Fuel Pathways and Metric

Pathway	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

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

Questions regarding marine LCA with GREET?

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