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Fuels for the Marine Sector

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THANKS TO OUR SPONSORS

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- US DOT – Galen Hon, Daniel Yuska
- US DOD – Bill Muras, Mark Spector
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THANKS TO OUR COLLABORATORS

- People at Argonne – Chris Kolodziej, Livia Benvenutti, Thathiana Benavides, Michael Wang
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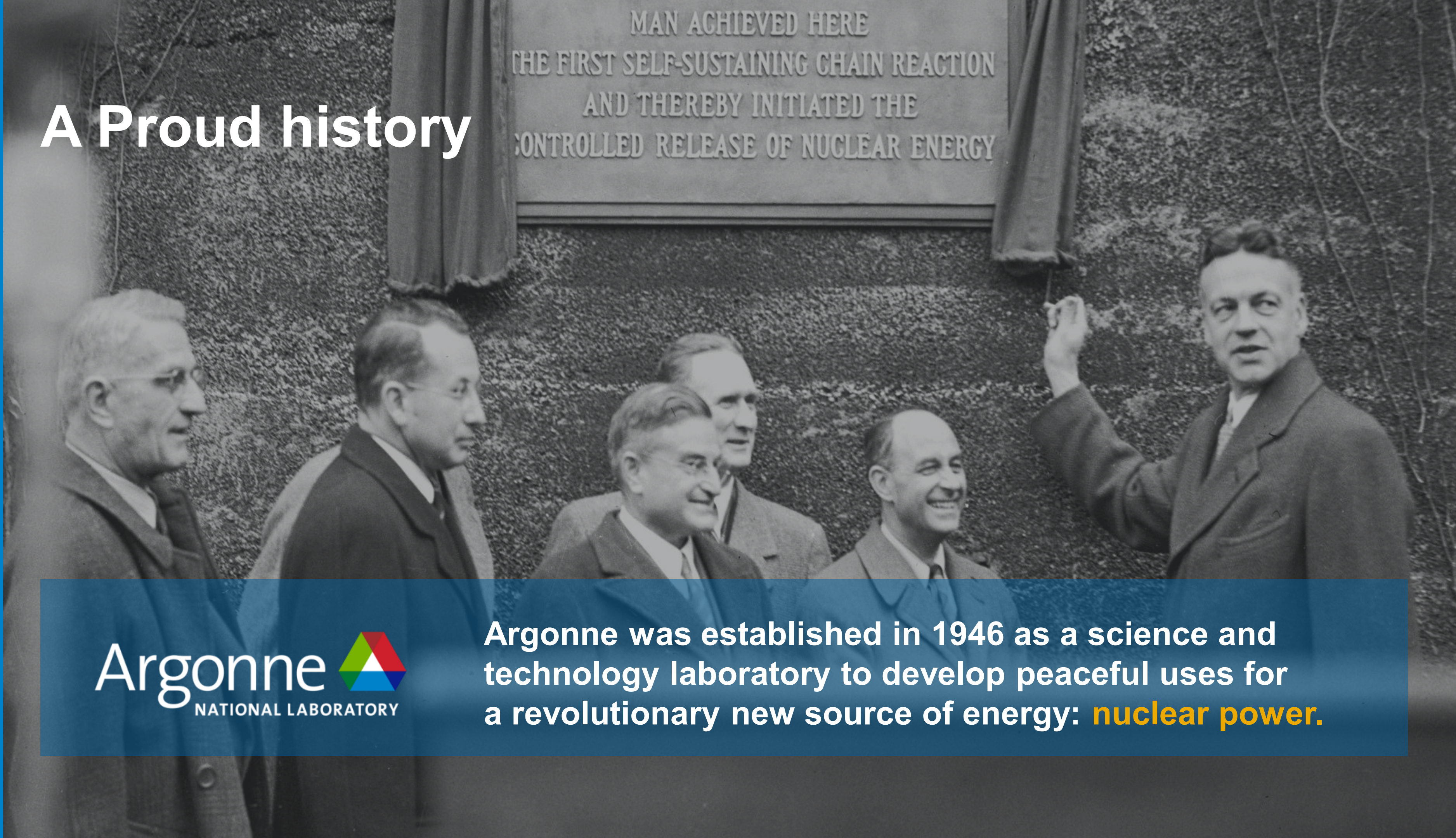
- People at NREL – Eric Tan
- People at ORNL – Mike Kass, Ingrid Busch

A Proud history



Argonne NATIONAL LABORATORY

Argonne was established in 1946 as a science and technology laboratory to develop peaceful uses for a revolutionary new source of energy: **nuclear power.**

Argonne by the numbers

World-leading research at scale

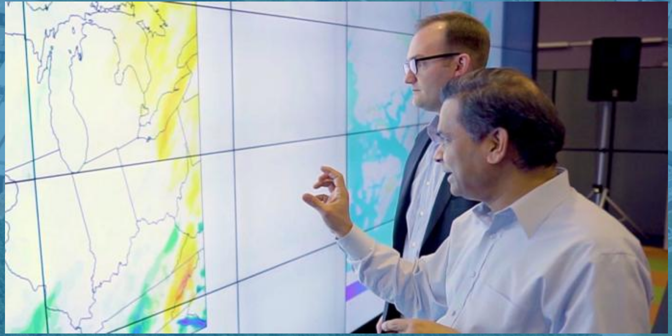
$1.4B
Laboratory budget

3,944
Employees, including 1,850 researchers

7,134
Facility users

6
DOE Office of Science and Office of Nuclear Energy user facilities

690
Students



R&D GREET Model

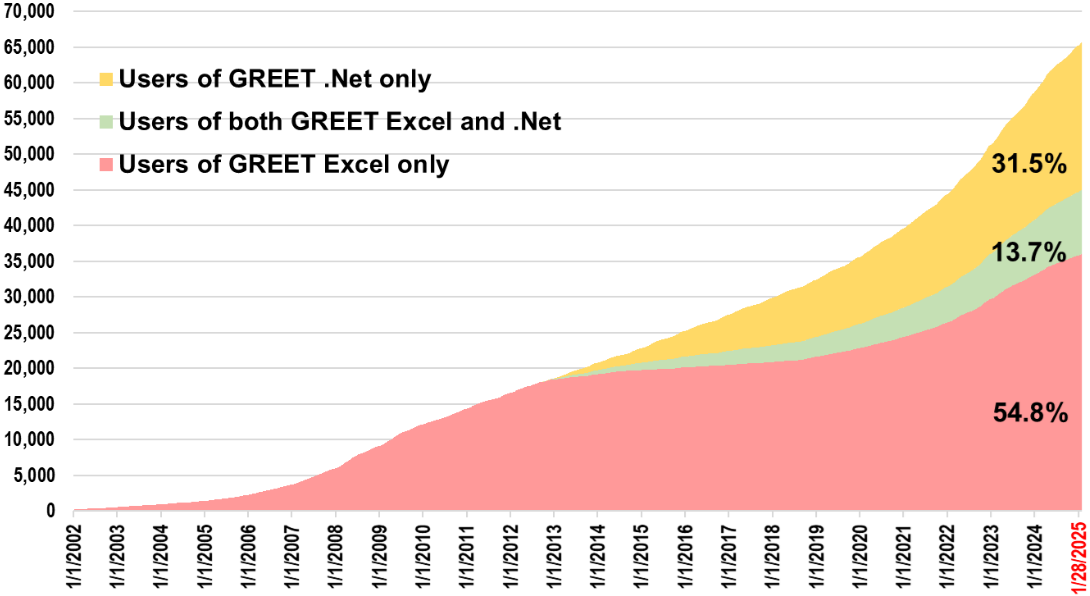
Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies

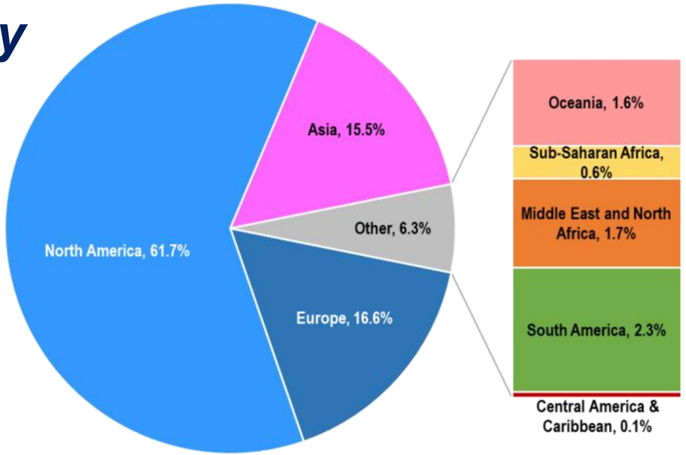
- **LCA database tracking and comparing life cycle performance of energy systems and products.**
  - Used to inform and guide U.S. Dept. of Energy research.
  - Adapted by California Air Resources Board and other states to determine fuel carbon intensities for the Low Carbon Fuel Standard and other fuel regulations.
  - Expanded from transportation focus to detailed analysis of a wide range of technologies including chemicals, plastics, agriculture, metals, concrete, buildings, batteries, electricity infrastructure

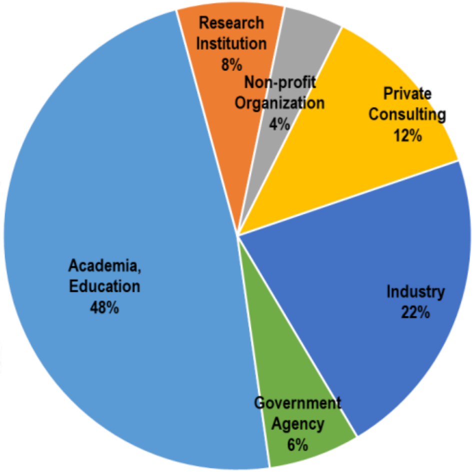
- **Argonne has been developing R&D GREET since 1995 with annual updates and expansions.**

- **Long-term support from U.S. Dept. of Energy**
  - Vehicle Technologies Office
  - Bioenergy Technologies Office
  - Hydrogen Fuel-Cell Technologies Office
  - Office of Technology Transfer

>65,000 Registered R&D GREET Users Globally







Federal, State, and International Agencies Using R&D GREET

California Environmental Protection Agency
Air Resources Board

State of Oregon
DEQ
Department of Environmental Quality

United States Environmental Protection Agency

NHTSA
National Highway Traffic Safety Administration

ICAO • OACI • ИКАО

Federal Aviation Administration

USDRIVE
Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability

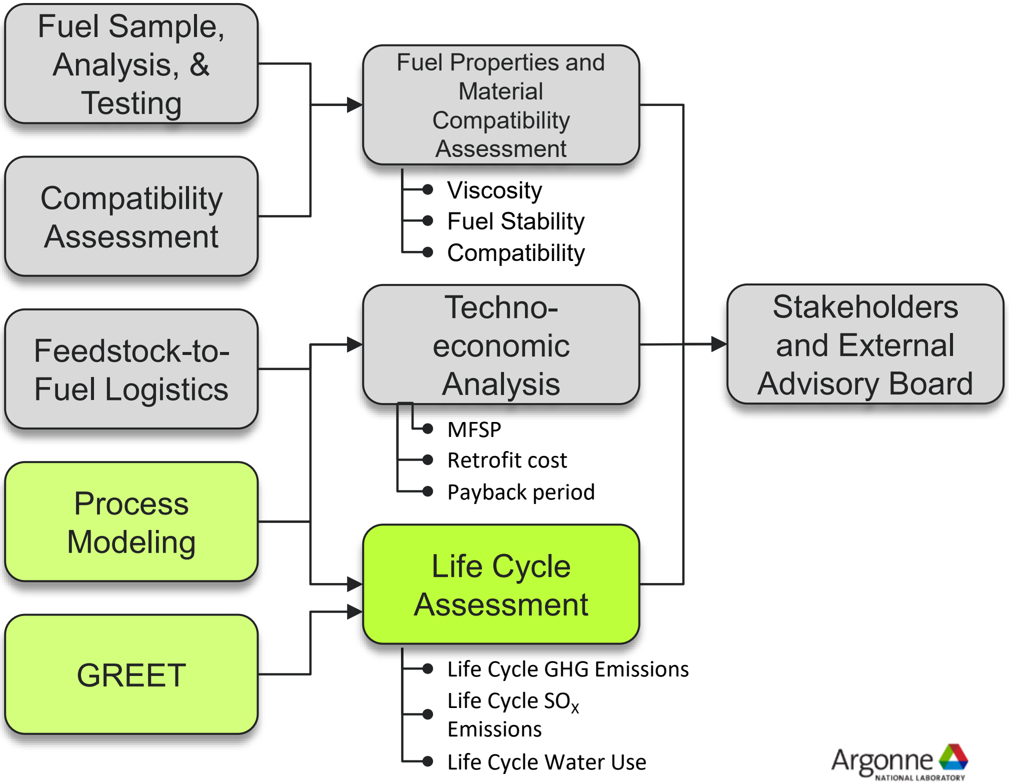
MARAD
Maritime Administration

USDA

Environment and Climate Change Canada

BETO Multi-Laboratory Effort

- **Interdisciplinary Framework**
  - Conduct TEA, LCA, and technical feasibility analyses to determine the viability of biofuels for the maritime sector
- **Novel Marine Biofuel Pathways**
  - Catalytic Fast Pyrolysis: Woody Blend
  - Fischer-Tropsch Synthesis: Landfill Gas
  - Hydrothermal Liquefaction: Waste Streams
  - Lignin-Ethanol Alcohol
- Supported by the U.S. Department of Energy's (DOE) Bioenergy Technology Office (BETO)



R&D GREET Marine Models

- R&D GREET Marine Models and Stand-Alone Modules
  - Wide range of fuel pathways
  - Relevant environmental metrics including emissions, energy use, CAPs, water use
  - Standardization enables apples-to-apples comparison across fuel and technology pathways, and the capacity to ‘drill down’ on the LCA results
- Functional Units
  - Energy-based (impacts per unit MJ)
  - Service-based (impacts per trip, tonne-km, average passenger-luggage km)
- Key Variables
  - Fuel and engine types
  - Vessel types
  - Trip and vessel characteristics
  - Emissions regulations

R&D GREET Marine Module

R&D GREET Interactive Marine Module 2024

Pathway

Select a Fuel and Feedstock

Reset Selection

Fuel
- Biooil
- Ammonia
- Biocrude
- Biodiesel
- Ethanol
- FT-Diesel
- Heavy Fuel Oil
- Heavy Fuel Oil (2.7...
- Liquefied Natural ...
- Marine Diesel Oil

Feedstock
- Woody Biomass
- Woody Biomass (ZSM5)

Input Parameters

Feedstock

Feedstock	Type	Input	User-defined	Default	Unit	Note
Logging Residue	Input	Diesel		185,360	btu / dry ton	Landing Proce
Logging Residue	Input	Electricity		11,423	btu / dry ton	Receving & Ha
Logging Residue	Input	Diesel		8,720	btu / dry ton	Storage
Logging Residue	Input	Electricity		276,460	btu / dry ton	Preprocessing
Logging Residue	Input	NG		914,190	btu / dry ton	Preprocessing
Clean Pine	Input	Diesel		139,910	btu / dry ton	Harvest And Cc
Clean Pine	Input	Diesel		23,840	btu / dry ton	Landing Proce
Clean Pine	Input	Electricity		42.0	btu / dry ton	Receiving & Ha
Clean Pine	Input	Diesel		9,960	btu / dry ton	Storage
Clean Pine	Input	Electricity		348,230	btu / dry ton	Preprocessing
Clean Pine	Input	NG		914,190	btu / dry ton	Preprocessing

Mixes

Type	Input	User Defined	Default
Utility	Electricity: Residual oil		0.26%
Utility	Electricity: Natural gas		38.5%
Utility	Electricity: Coal		20.59%
Utility	Electricity: Nuclear power		18.88%
Utility	Electricity: Biomass		0.27%
Utility	Electricity: Hydroelectric		6.73%
Utility	Electricity: Geothermal		0.38%
Utility	Electricity: Wind		10.7%
Utility	Electricity: Solar PV		3.28%
Utility	Electricity: Others		0.42%

Conversion

Type	Input	User-defined	Default	Unit	Note
Input	Clean Pine		0.083	ton / mmbtu	
Input	Forest Residues		0.083	ton / mmbtu	
Input	Diesel		2,358	btu / mmbtu	
Input	Sand makeup		128.51	g / mmbtu	
Input	Cooling tower chemical		0.8201	g / mmbtu	
Input	Boiler chemical		0.0	g / mmbtu	
Input	Boiler feed water chemicals		1.64	g / mmbtu	
Input	Caustic		189.13	g / mmbtu	
Input	Hydrotreating catalyst, CoMo		0.0	g / mmbtu	
Input	Hydrotreating Catalyst (sulfided CoMo)		0.0001	g / mmbtu	
Input	Hydrocracking Catalyst (crystalline Si-Al with rare earth me		0.0	g / mmbtu	
Input	Zeolite catalyst		187.49	g / mmbtu	

Results: Biooil - Catalytic Fast Pyrolysis of Woody Biomass (ZSM5)

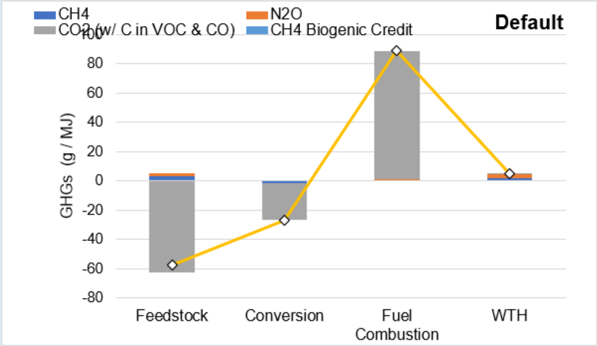
Metric
- SOx
- BC
- OC
- CH4
- N2O
- CO2
- CO2 (w/ C in VOC...
- GHGs
- VOC: Urban
- CO: Urban
- NOx: Urban
- PM10: Urban
- PM2.5: Urban
- SOx: Urban
- BC: Urban
- OC: Urban

Update Results

Save Results

select units from drop-downs	Energy	Water	Emissions
Unit	Btu	L	g
Functional Unit	MJ	of Marine Fuel	
GWP Factors	AR6/GWP/100		

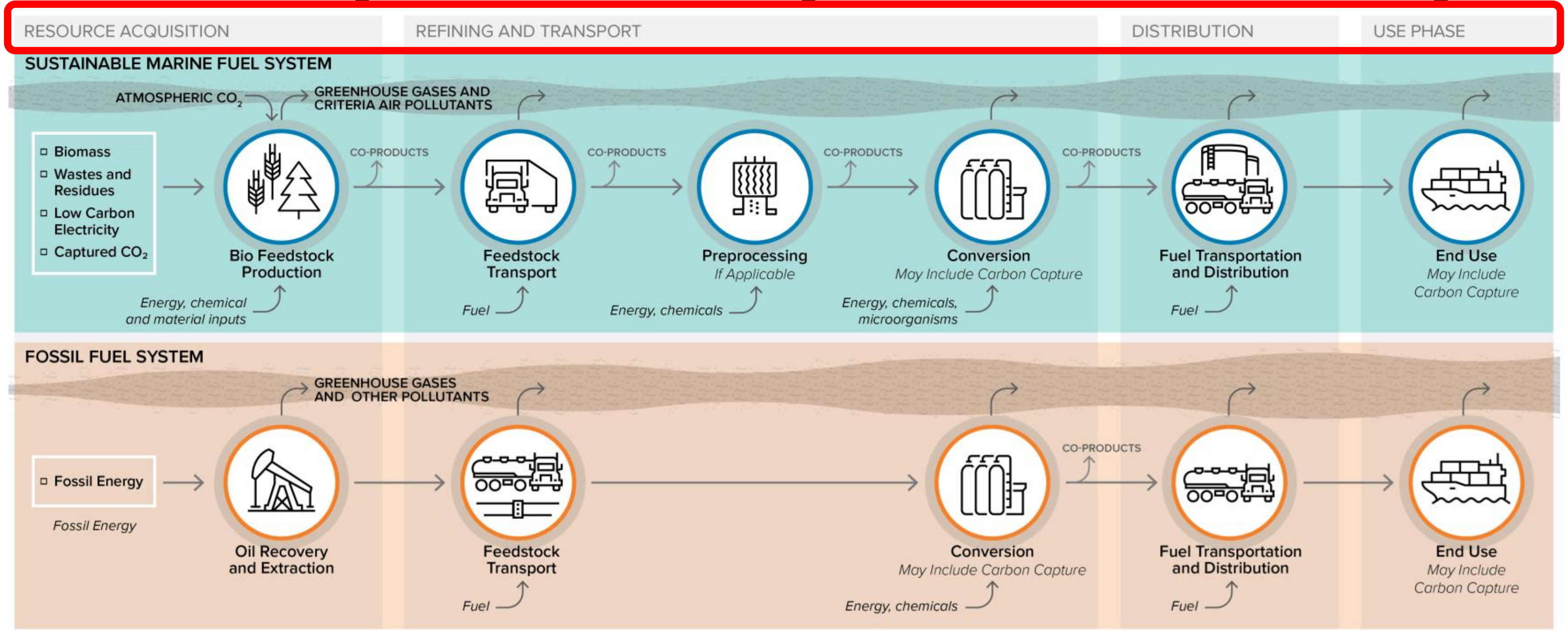
Life Cycle Result, Total: 5.16 g GHGs / MJ Fuel



Life Cycle Results, by Stage (per MJ)

	Feedstock	Conversion	Fuel Combustion	WTH
Total energy (Btu)	4.0E+02	-4.6E+02	9.5E+02	8.9E+02
Fossil fuels (Btu)	3.7E+02	-3.2E+02	-	4.8E+01
Coal (Btu)	3.4E+01	-1.6E+02	-	-1.2E+02
Natural gas (Btu)	2.5E+02	-1.9E+02	-	5.4E+01
Petroleum (Btu)	8.8E+01	3.1E+01	-	1.2E+02
Water consumption (L)	5.4E-02	-1.7E-01	-	-1.1E-01
VOC (g)	2.7E-02	-5.2E-04	5.7E-02	8.4E-02
CO (g)	1.4E-01	-5.6E-03	1.3E-01	2.6E-01

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

R&D GREET Marine Fuel Pathways

Fossil

- **HFO**: HFO w/Scrubber; HFO (2.7% S); HFO (0.5% S); HFO (0.1% S)
- **MDO**: MDO (1.92 % S); MDO (0.5 % S); MDO (0.1 % S)
- **MGO**: MGO (1.0 % S); MGO (0.5 % S); MGO (0.1 % S)
- **LNG**: Liquefied Natural Gas
- **MeOH**: Methanol (NG); Methanol (Coal)
- **FTD**: FT-Diesel (NG)
- **NH_3**: Ammonia (H2 from SMR-NG)

Dedicated Biomass & Wastes

- **SVO**: Straight Vegetable Oil (Soybean Oil)
- **Bio-Oil**: Pyrolysis Oil (Wood Biomass); HTL Biocrude (Wet Wastes)
- **FTD**: FT-Diesel (Biomass); FT-Diesel (LFG); FT-Diesel (Biomass & Coal); FT-Diesel (Biomass & NG)
- **BD**: Biodiesel (Soybean Oil)
- **RD**: Renewable Diesel (Yellow Grease); Renewable Diesel (Yellow Grease & HFO)
- **MeOH**: Methanol (RNG); Methanol (Biomass); Methanol (Black Liquor); Methanol (Flare Gas)
- **EtOH**: Ethanol (Corn); Ethanol (Cellulosic Biomass)

Other Renewables

- **eFuels**: eMethanol (Ind. Waste CO2); eFT Fuel (Ind. Waste CO2)
- **NH3**: Ammonia (H_2 From Low Carbon Sources)

HFO: heavy fuel oil
MDO: marine diesel oil
MGO: Marine gasoline oil
FTD: Fischer- Tropsch Diesel

https://greet.es.anl.gov/

Fuels in the Marine Sector

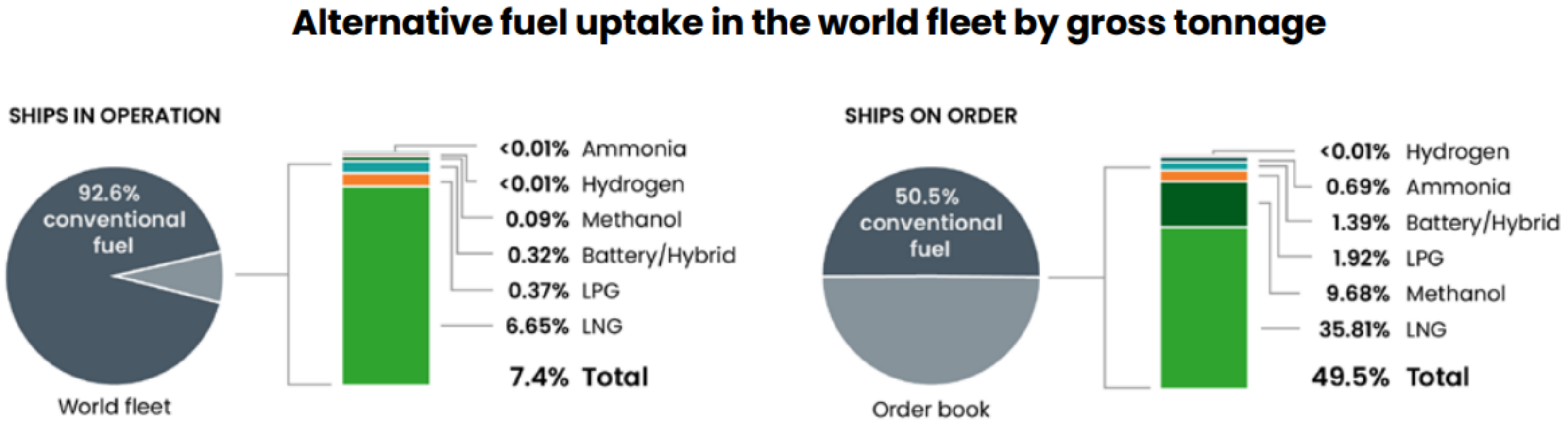
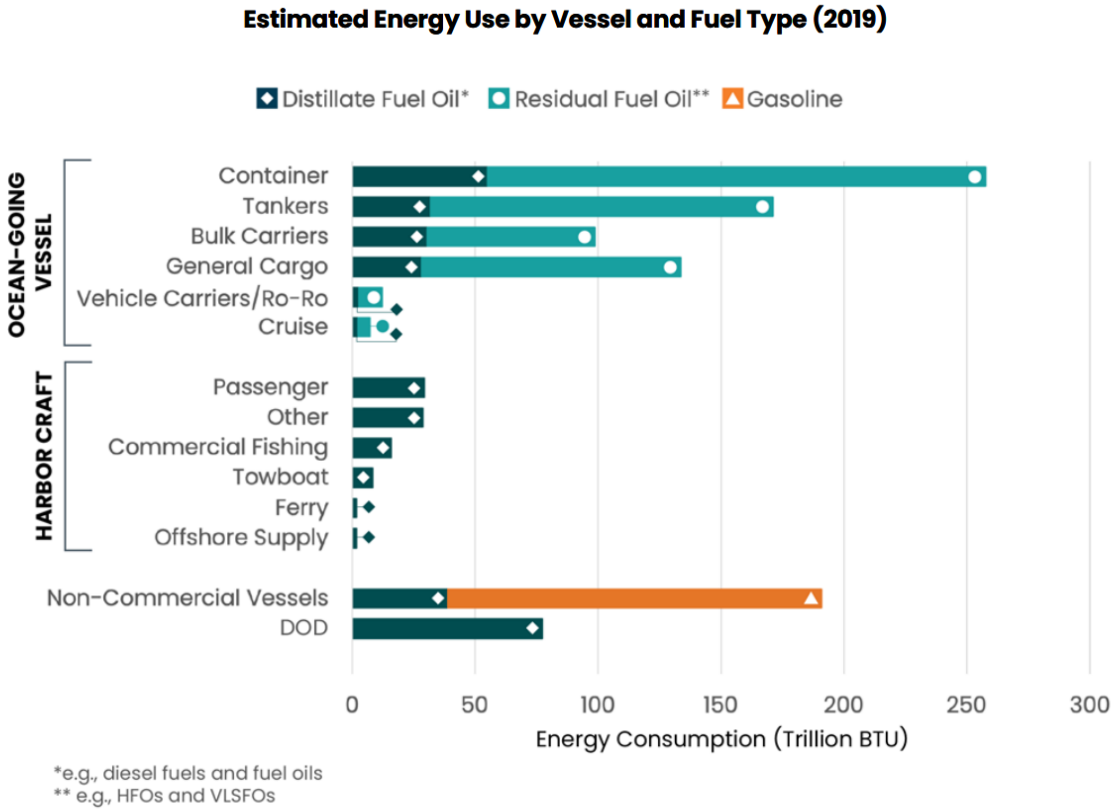


Figure 15: Alternative fuel-capable vessels in the world fleet in gross tonnage, as of October 2024, reported by IHS Markit (ihsmarkit.com) and DNV's Alternative Fuels Insights for the shipping industry—AFI platform (afi.dnv.com). Note that these figures indicate vessels that are "capable" of operating on alternative fuels but are not necessarily doing so. These vessels may also need further major refits (tankage, fuel management systems, etc.). However, these numbers are indicative of the potential use for alternative fuels in the future fleet that is already, or will soon be, operational.

Source: An Action Plan for Maritime Energy and Emissions Innovation (Photo), IHS Markit and AFI (Data)

Fuels in the Marine Sector

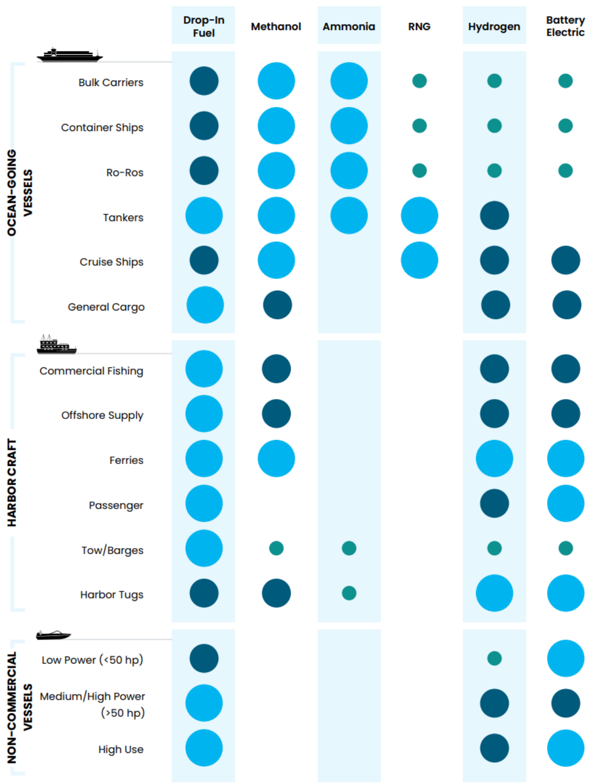


Source: *An Action Plan for Maritime Energy and Emissions Innovation*

Fuels in the Marine Sector

Figure 18: Conceptualization of the predominant, supporting, and niche fuels and powertrain technologies of the U.S. maritime sector in 2050 by vessel type. (Note: Hybridization and partial electrification will be important to improving vessel operational efficiency and decarbonization.)

Predominant Supporting Niche



Source: An Action Plan for Maritime Energy and Emissions Innovation

Biodiesel, Renewable Diesel, Biooil as Marine Fuels

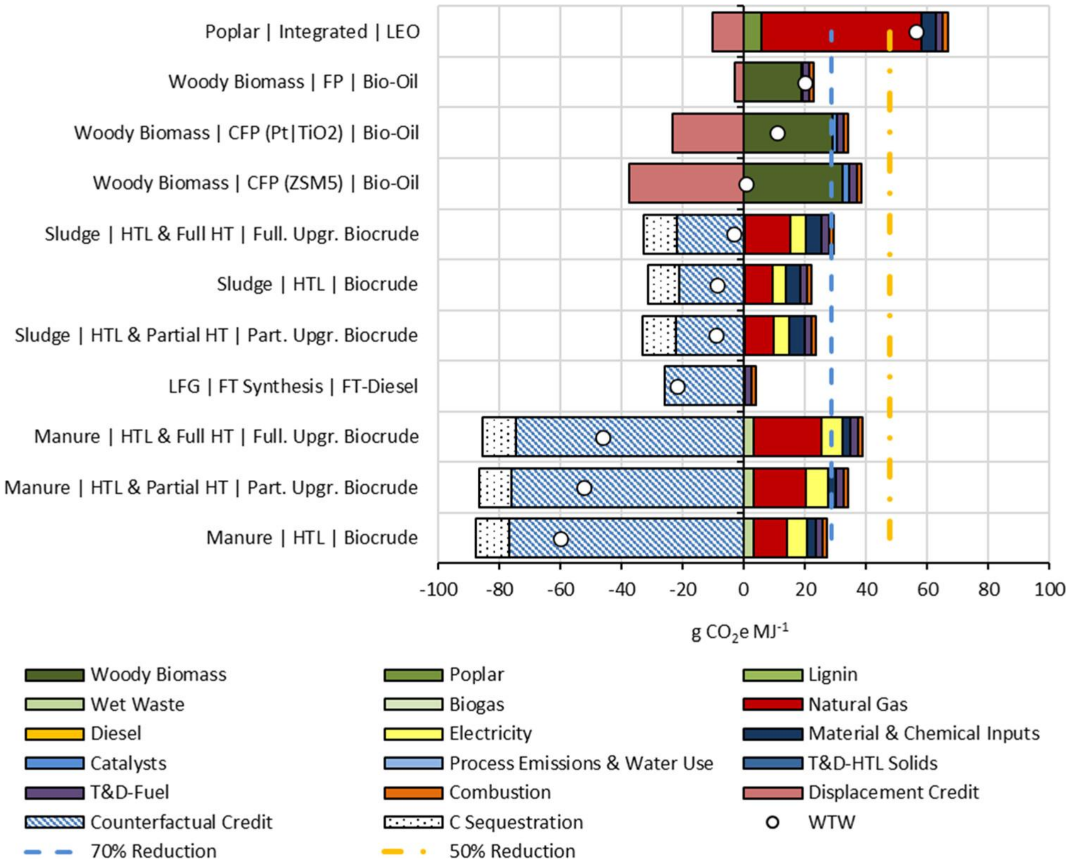
SCOPE

- Can be a near drop-in petroleum fuel replacement, blendable, and can use much of today's infrastructure
- High energy density
- Pathways for low to negative carbon intensity on full life cycle basis

LIMITATION

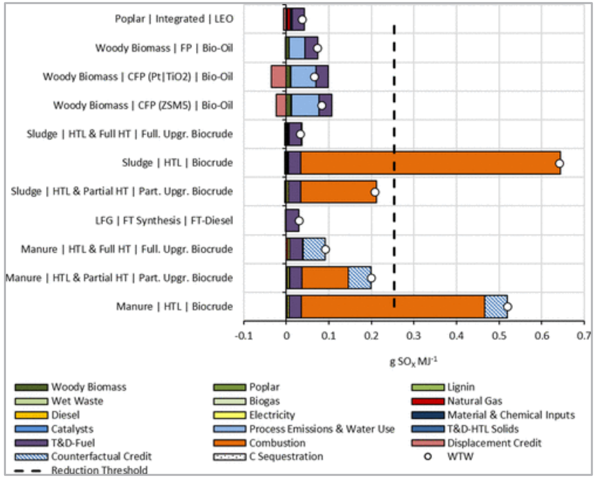
- Criteria air pollutants remain
- Wide variation in life cycle GHG emissions; some biofuels are more GHG-intensive than traditional fuels on a WTW basis
- Feedstock resource limitations exist and will need significant increase in feedstock production to the full U.S. potential
- End-use competition (aviation, offroad, rail, etc.)

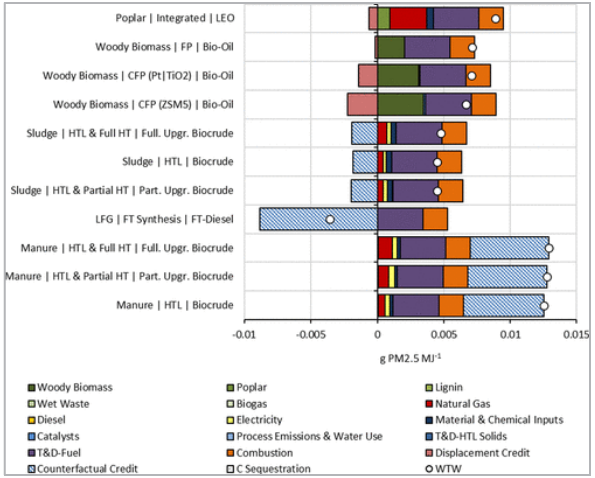
Comparative Emissions of Marine Bio-oils

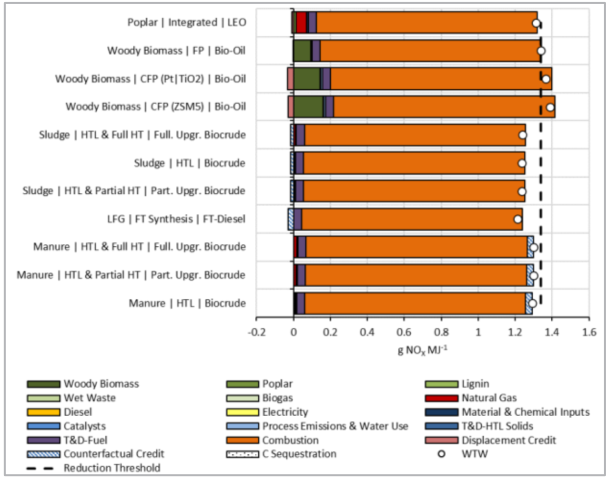


Source: Masum et al. 2023, https://pubs.acs.org/doi/full/10.1021/acs.est.3c00388

Comparative CAP Emissions of Marine Bio-oils







Source: Masum et al. 2023, https://pubs.acs.org/doi/full/10.1021/acs.est.3c00388

Technoeconomic Assessment of Marine Bio-oils

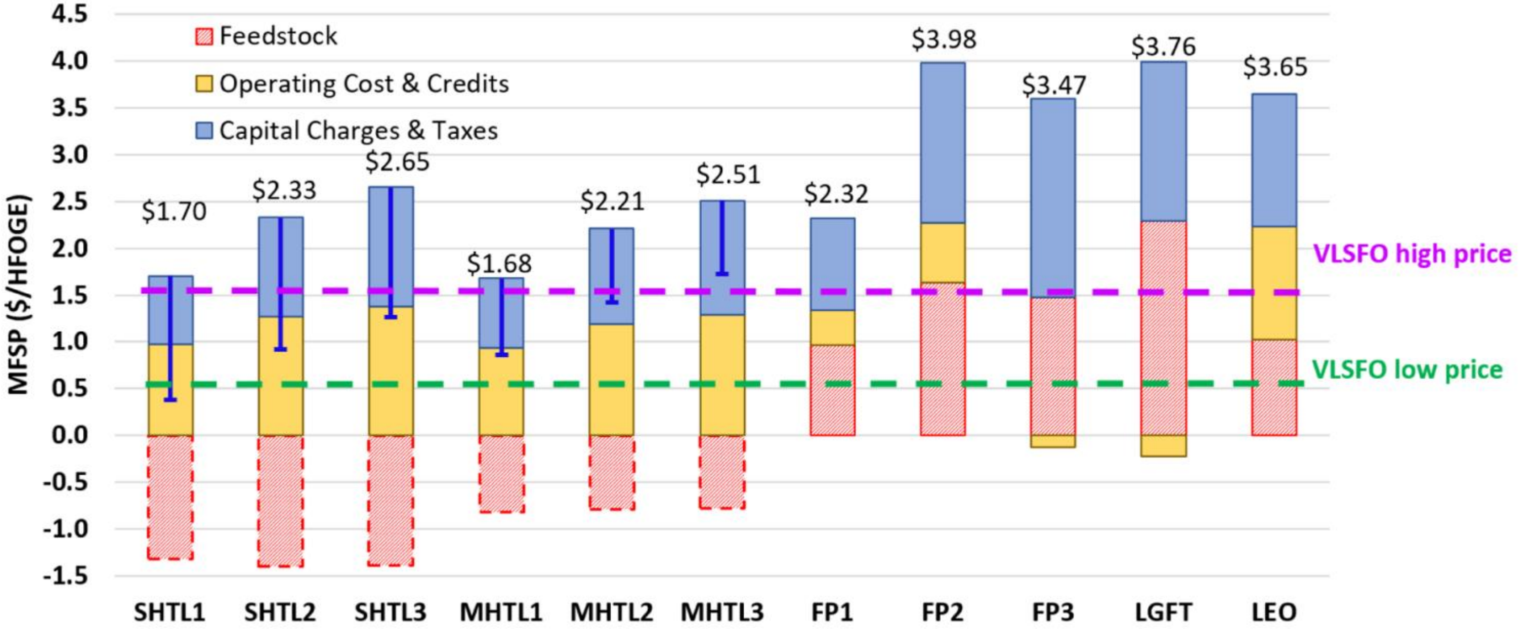


Figure 1. Comparative TEA result summary (the dash feedstock costs for HTL cases represent the sensitivity cases with the potential wet waste-avoided disposal fee, while the blue error bars indicate the potential decrease of MFSP for HTL pathways; high and low VLSFO prices are the last 2 years' historical price range from the main ports of North America;[35] see Table S10 in Supporting Information for biofuel prices from the literature).

Methanol as a Marine Fuel

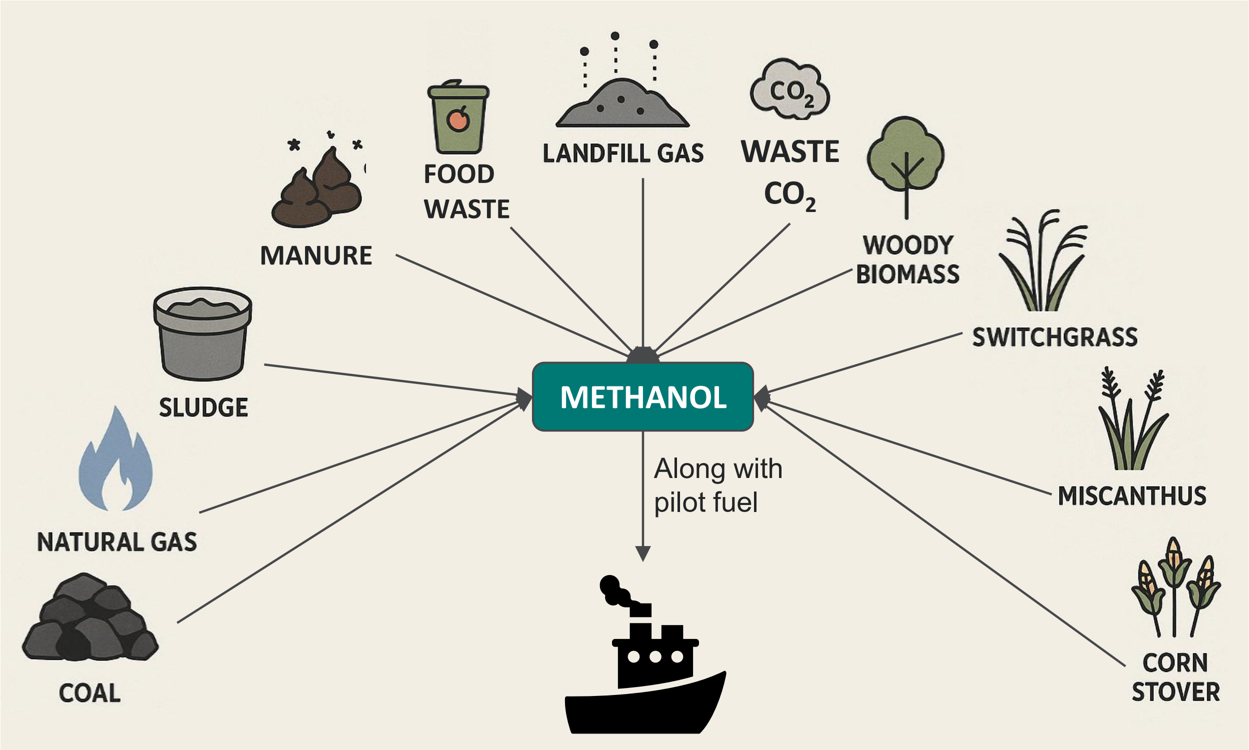
SCOPE

- Multiple sustainable production pathways (bio and electro) for low lifecycle GHG production
- Large criteria air pollutant reduction
- Methanol-using vessels are starting to come online

LIMITATION

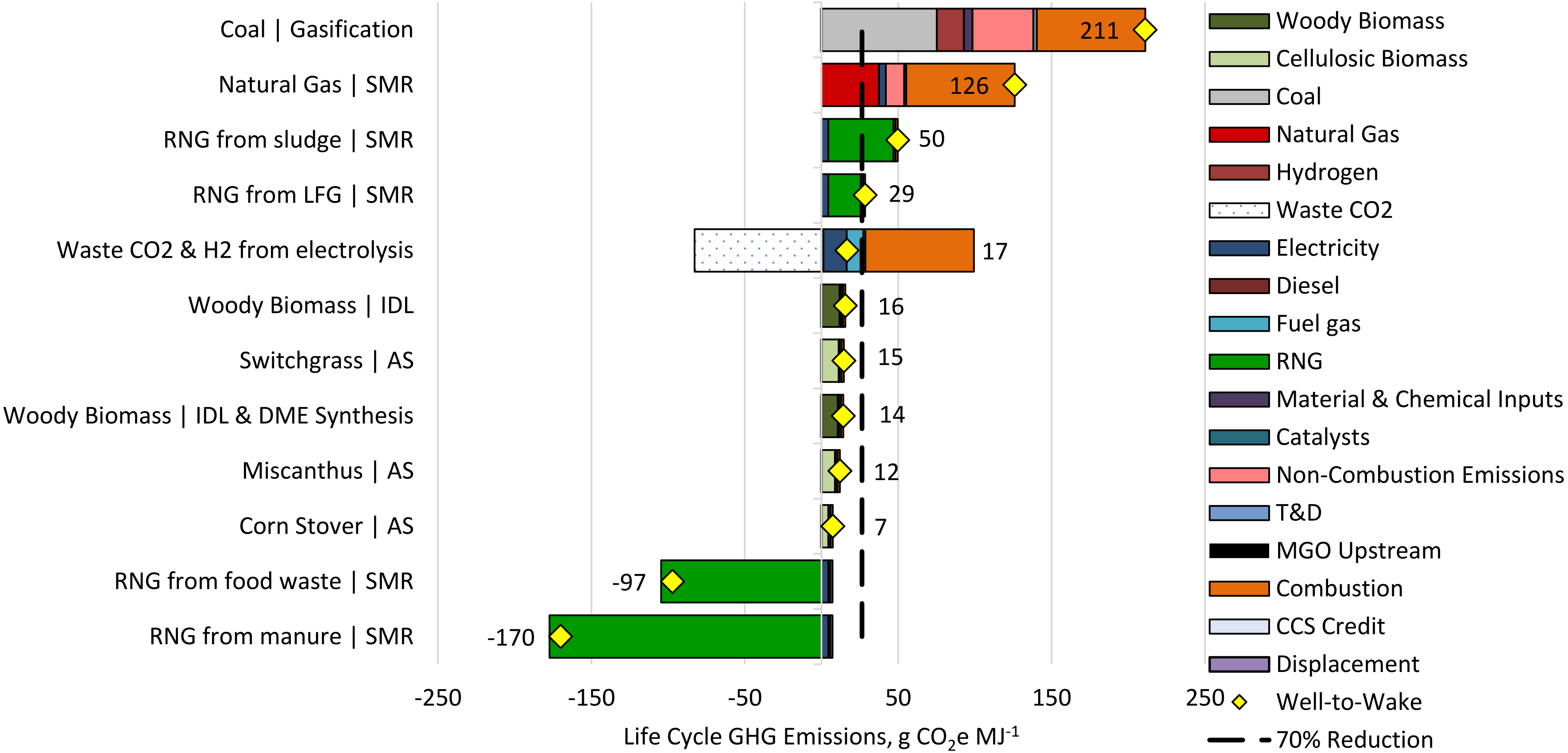
- Lower energy density
- Requires larger tank
- Limited feedstock resource
- Large clean electricity requirement for production
- Safety considerations
- Potential for traditional methanol enabler
- End-use competition (chemical industry)

Comparative LCA of Methanol as a Marine Fuel



Masum et al. 2025, https://pubs.acs.org/doi/10.1021/acs.est.5c08873

Comparative LCA of Methanol as a Marine Fuel



Masum et al. 2025, https://pubs.acs.org/doi/10.1021/acs.est.5c08873

Ethanol as a Marine Fuel

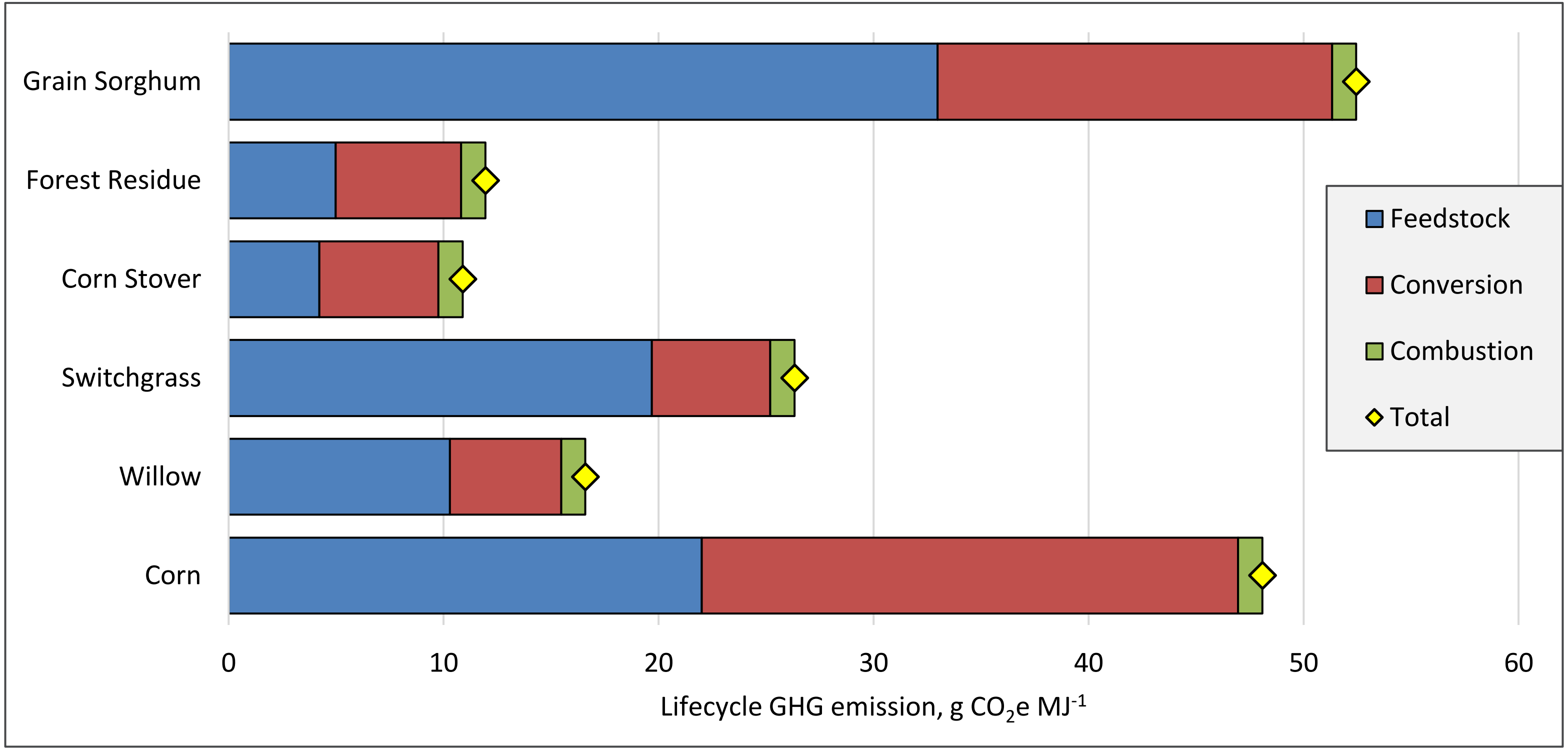
SCOPE

- Already in production
- High Octane rating
- Potentially compatibility with some existing engines

LIMITATION

- Lower energy density
- Requires larger tank
- Cold start and vapor lock
- Feedstock competition

Ethanol as a Marine Fuel



Source: GREET Database, Argonne National Lab

LNG as a Marine Fuel

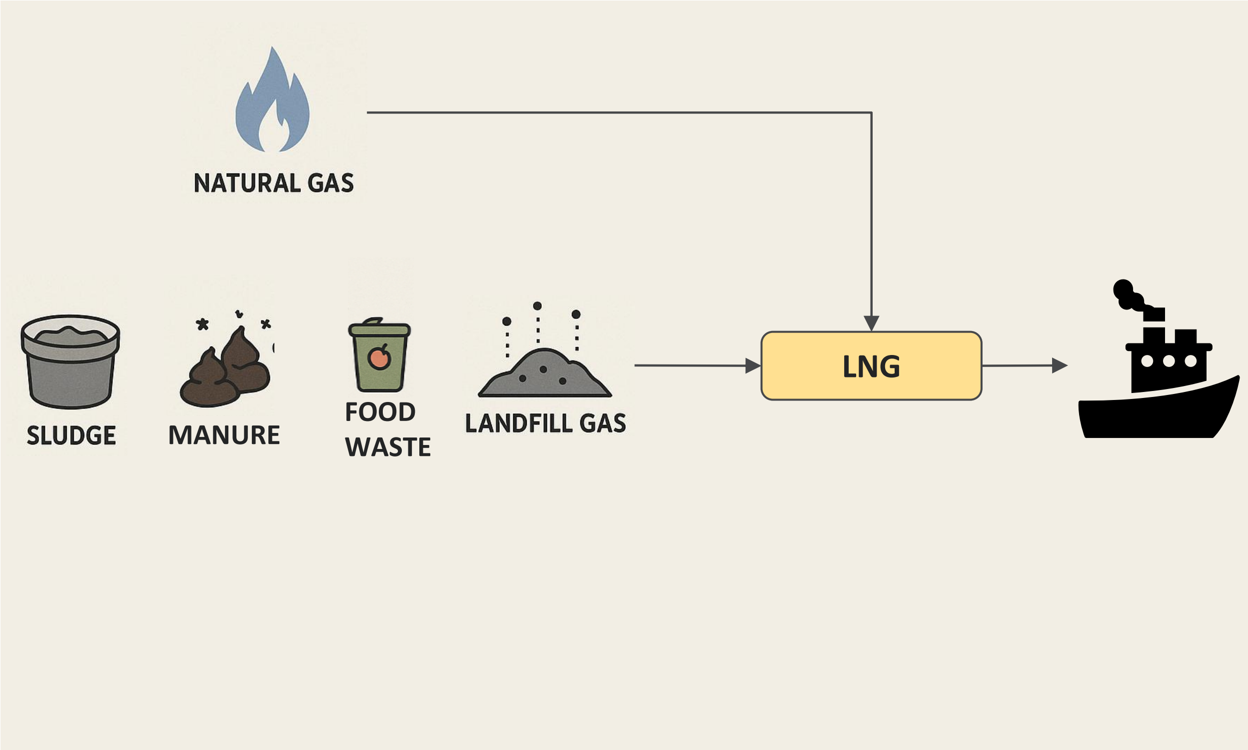
SCOPE

- Reduced criteria air pollutants
- Current supply-side infrastructure in place

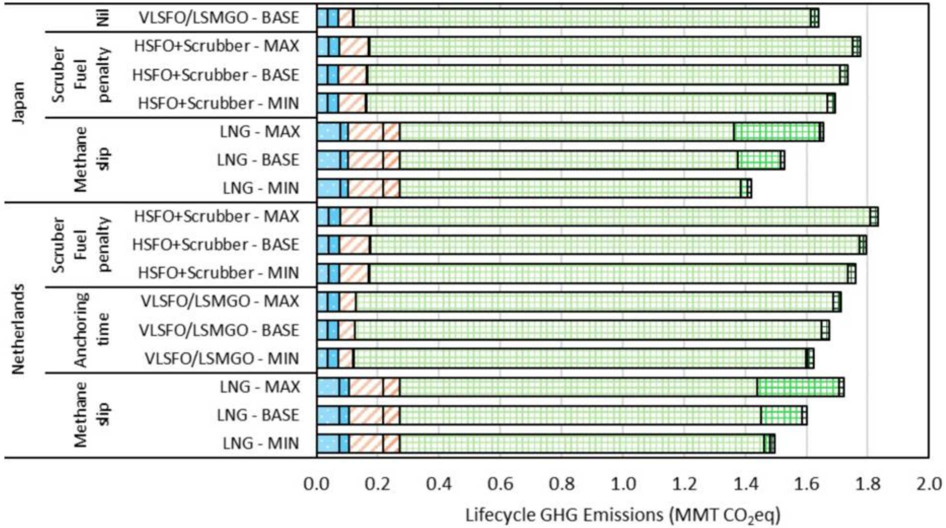
LIMITATION

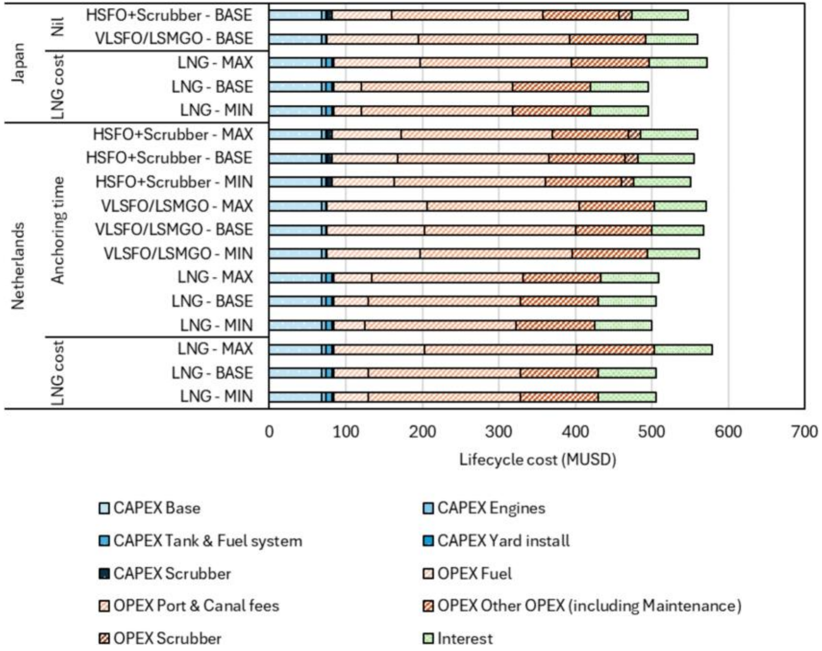
- Fugitive CH_4 emissions during combustion (CH_4 slip) and across supply chain
- Potential reliance on fossil CH_4
- RNG feedstock resource limitations exist

LNG as a Marine Fuel



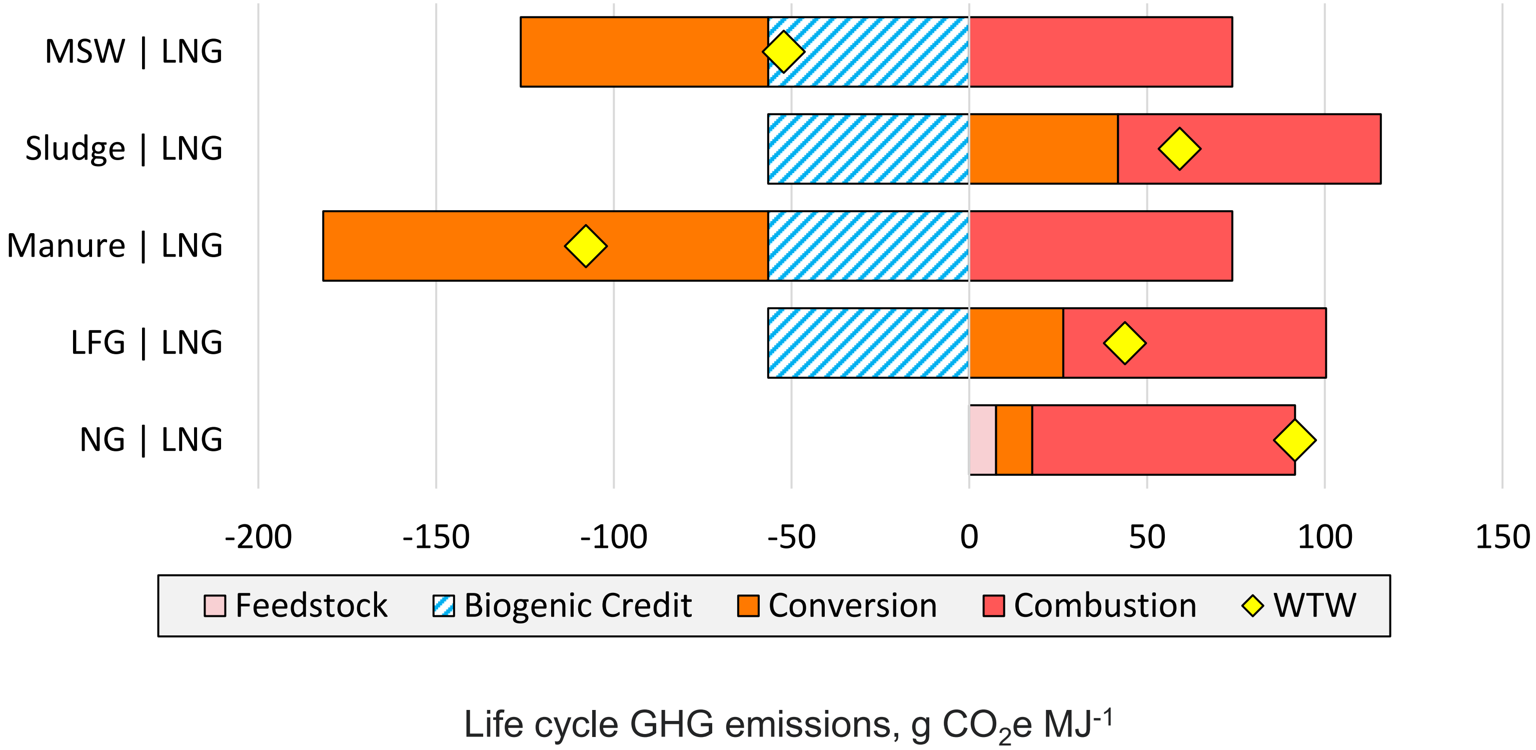
LNG as a Marine Fuel





Source: https://doi.org/10.1016/j.ecmx.2024.100747

Comparative LCA of LNG as a Marine Fuel



Source: GREET Database, Argonne National Lab

Ammonia as a Marine Fuel

SCOPE

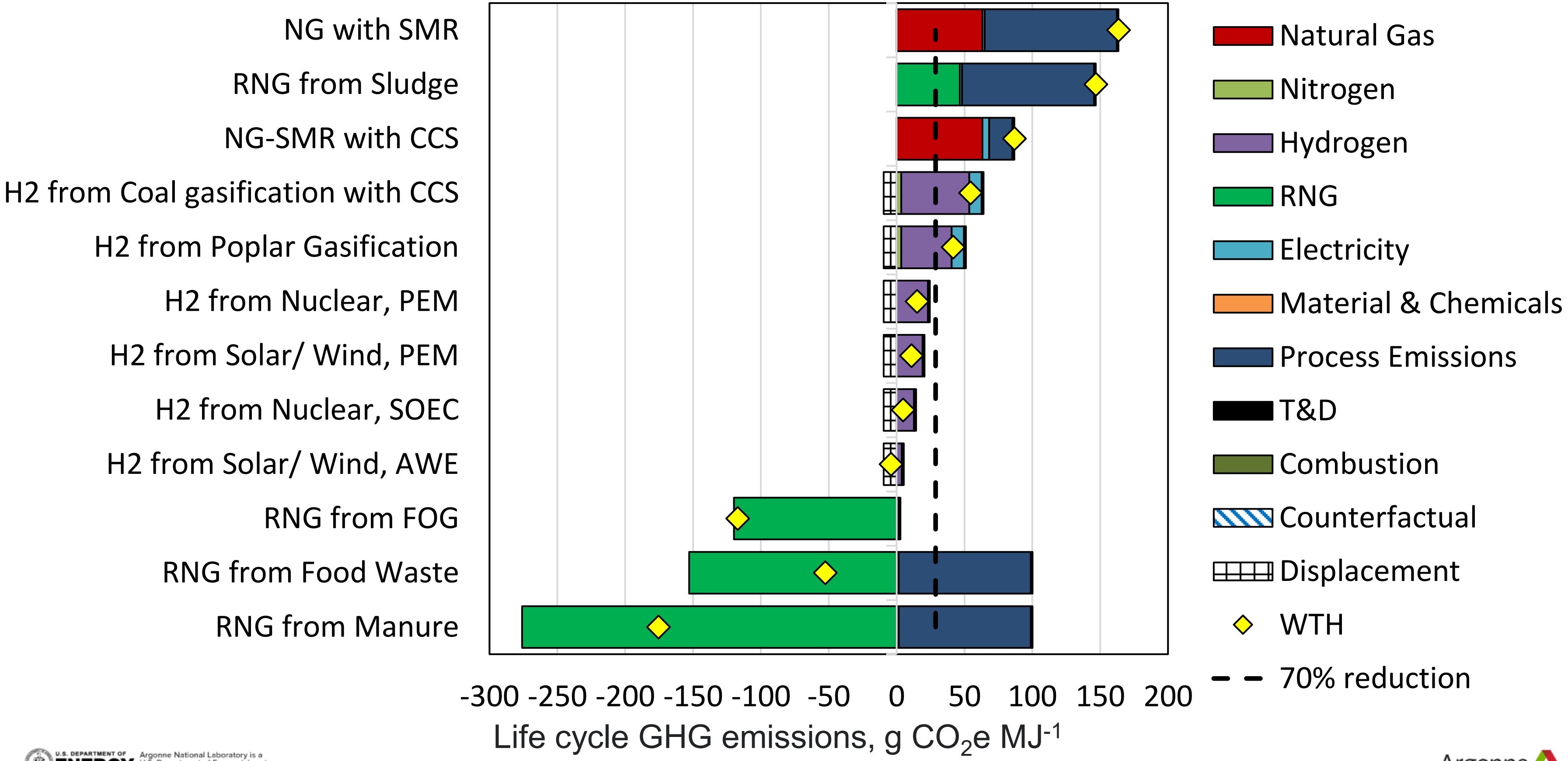
- Large potential GHG reductions
- Limited criteria air pollutants other than nitrogen species
- Abundant nitrogen feedstock (air)

LIMITATION

- Lower energy density
- Requires larger tank
- Large clean electricity requirement for production
- Potential NOX and N2O emission issues
- Safety concerns
- Potential for traditional ammonia enabler
- End-use competition (agricultural industry)

Comparative LCA of Ammonia as a Marine Fuel

Draft
Do not cite

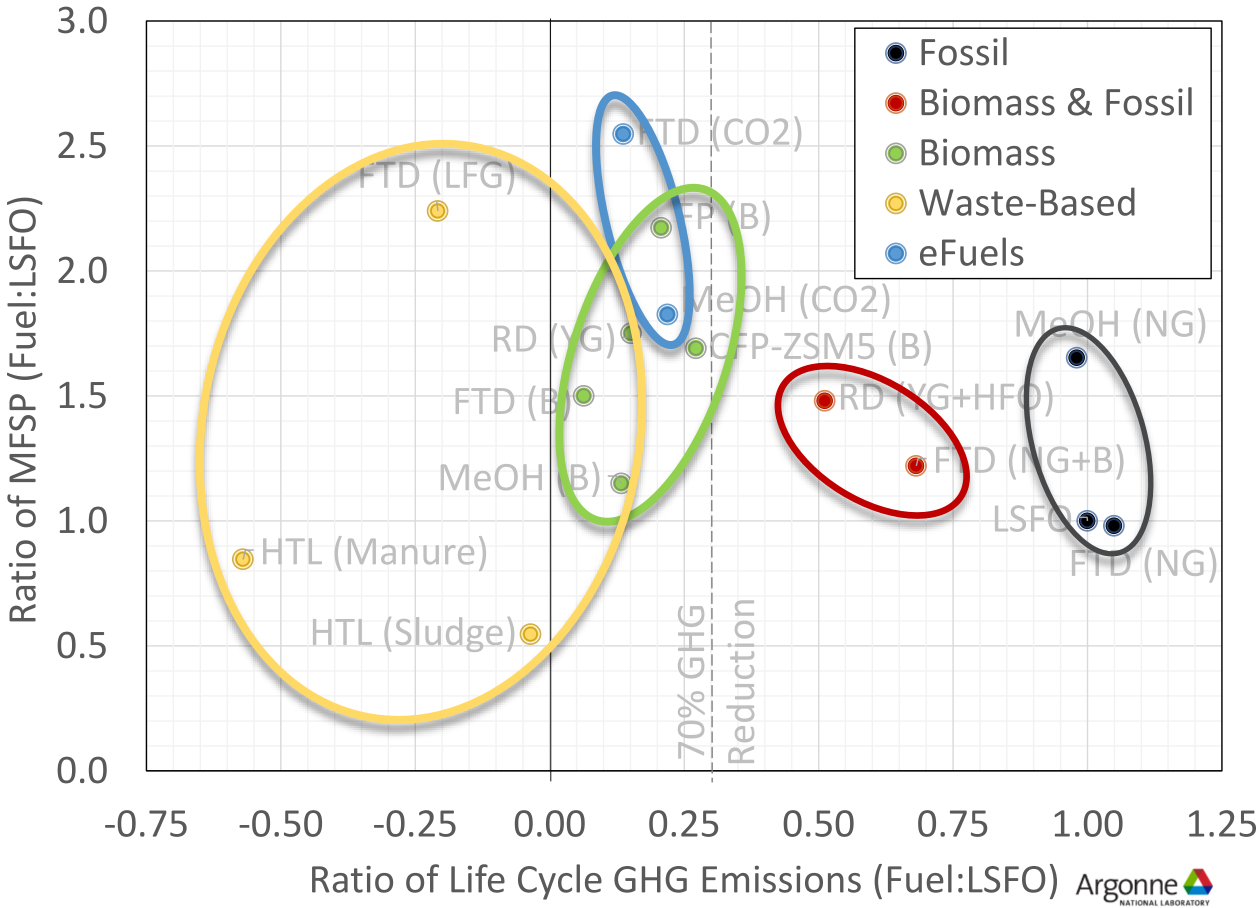


Multiple Promising Pathways: Greenhouse Gas and Cost

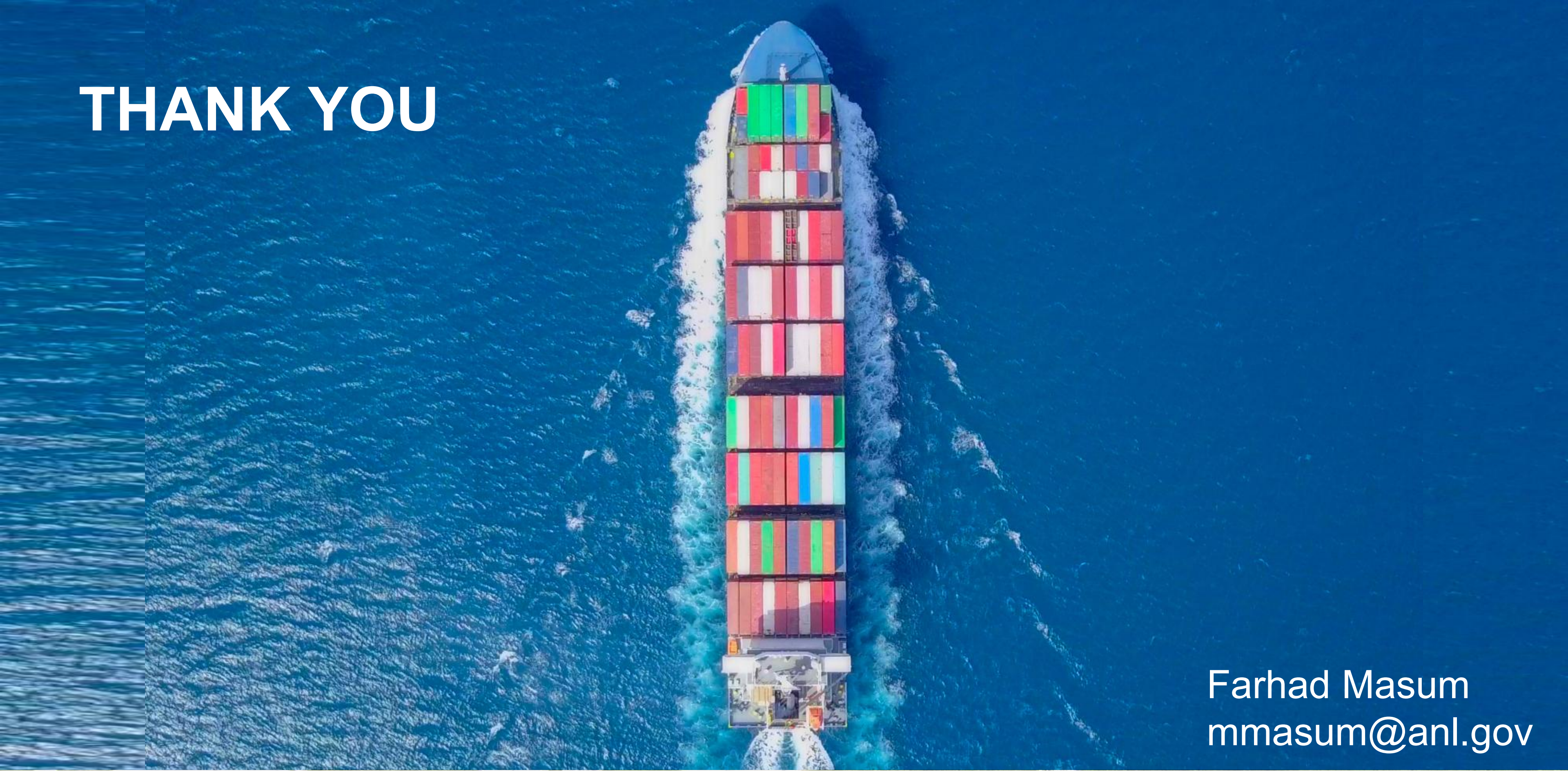
Promising pathways could reduce GHG emissions, relatively modest price increase

Multiple pathways needed to meet demand

Industry experience important to optimize production



THANK YOU



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Argonne's R&D GREET is to inform the life cycle analysis of technical community. Not all pathways and data in R&D GREET are appropriate for use in circumstances where a high level of quantitative certainty or precision is required. GREET is referenced in numerous independent state and federal compliance and incentive programs (including solicitations, rulemakings, and tax incentives), but it is important to note that R&D GREET is not the version used by any of these specific programs. Argonne does not warrant that use of R&D GREET is consistent with the requirements of any particular regulatory or incentive program.