Environmental Assessment of Alternative Fuels for Maritime Shipping

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Introduction

- **Climate Impacts of International Shipping**
  - Shipping emissions account for ~3.1% of annual global CO2 and approximately 2.8% of annual GHGs (IMO 2014)
  - Smith et al. (2015) estimate that ship CO_2 emissions will **increase** 50% to 250% from 2012 to 2050
- **Pressure to reduce carbon intensity of shipping**
  - IMO framework to reduce carbon intensity (CO2 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 complete decarbonization attained by the end of century
- **Broad support for maritime decarbonization across public and private entities**
  - Maersk, the worlds largest container shipping company, has pledged to achieve net zero carbon emissions by 2050 and is pursuing the deployment of carbon-neutral vessels by 2030
  - A growing number of maritime decarbonization initiatives

MISSION INNOVATION

Denmark, Norway, and the United States to Lead Zero-Emission Shipping Mission

Maersk calls on carbon tax for fossil fuel bunkers to bridge transition gap

HIGHLIGHTS

Maersk calls for a $450 per ton fuel carbon tax on fossil fuel-based fuels

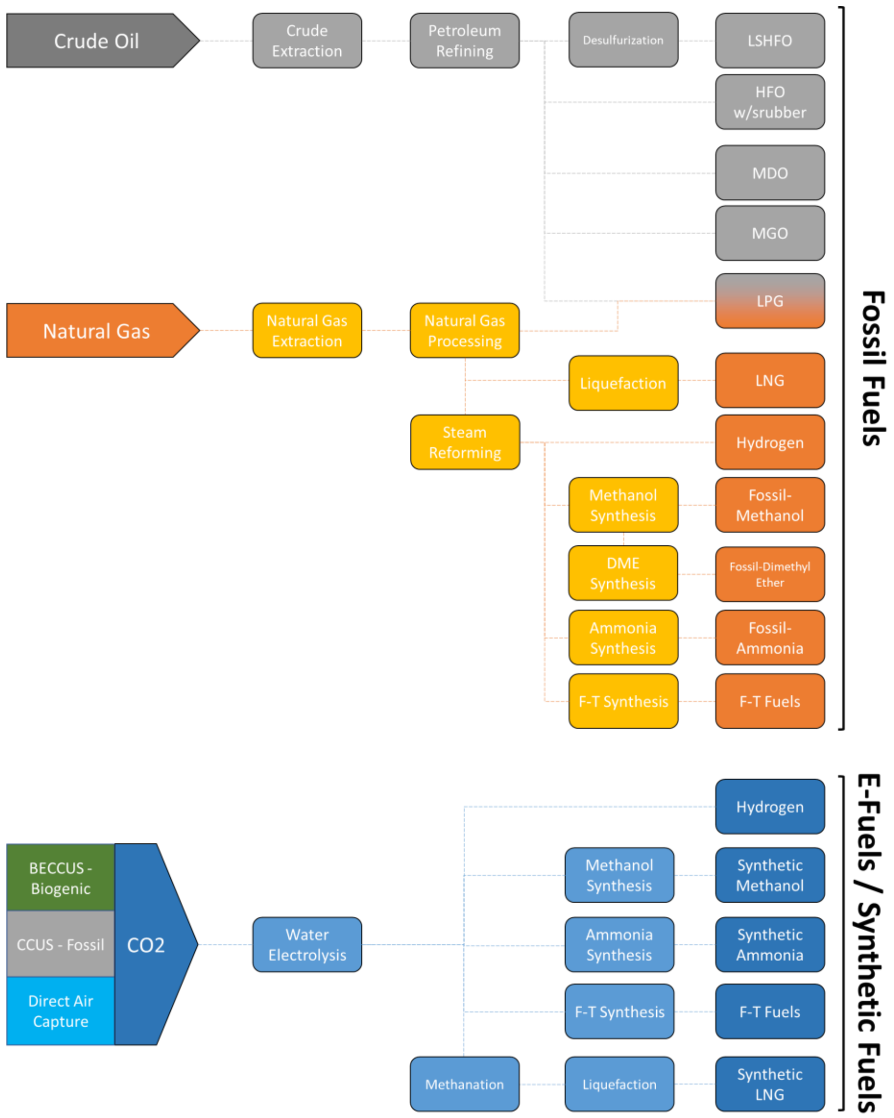
Plans to power carbon-neutral methanol vessel by 2023

Cost, supply concerns remain key for methanol bunker uptake

1. https://www.energy.gov/eere/articles/denmark-norway-and-united-states-lead-zero-emission-shipping-mission
2. https://www.spglobal.com/platts/en/market-insights/latest-news/agriculture/060221-maersk-calls-on-carbon-tax-for-fossil-fuel-bunkers-to-bridge-transition-gap

Alternative Fuels For Marine Shipping

- **Situation complicated by many competing options and constraints**
  - Extremely slim operating margins
  - Alternatives include expanded use of distillates, LNG, LPG, DME, methanol, ammonia, hydrogen, e-Fuels, biofuels, and employing air pollution control technologies
- **Biofuels could offer emissions reductions, improved energy security, and reductions in the carbon intensity of marine shipping**
  - Biofuels are distinct amongst competing liquid fuels in their potential to significantly reduce GHG emissions
  - Biofuels could provide near-term benefits for meeting recently promulgated IMO fuel sulfur regulations
  - Biofuel are potentially fungible with existing marine engines and infrastructure



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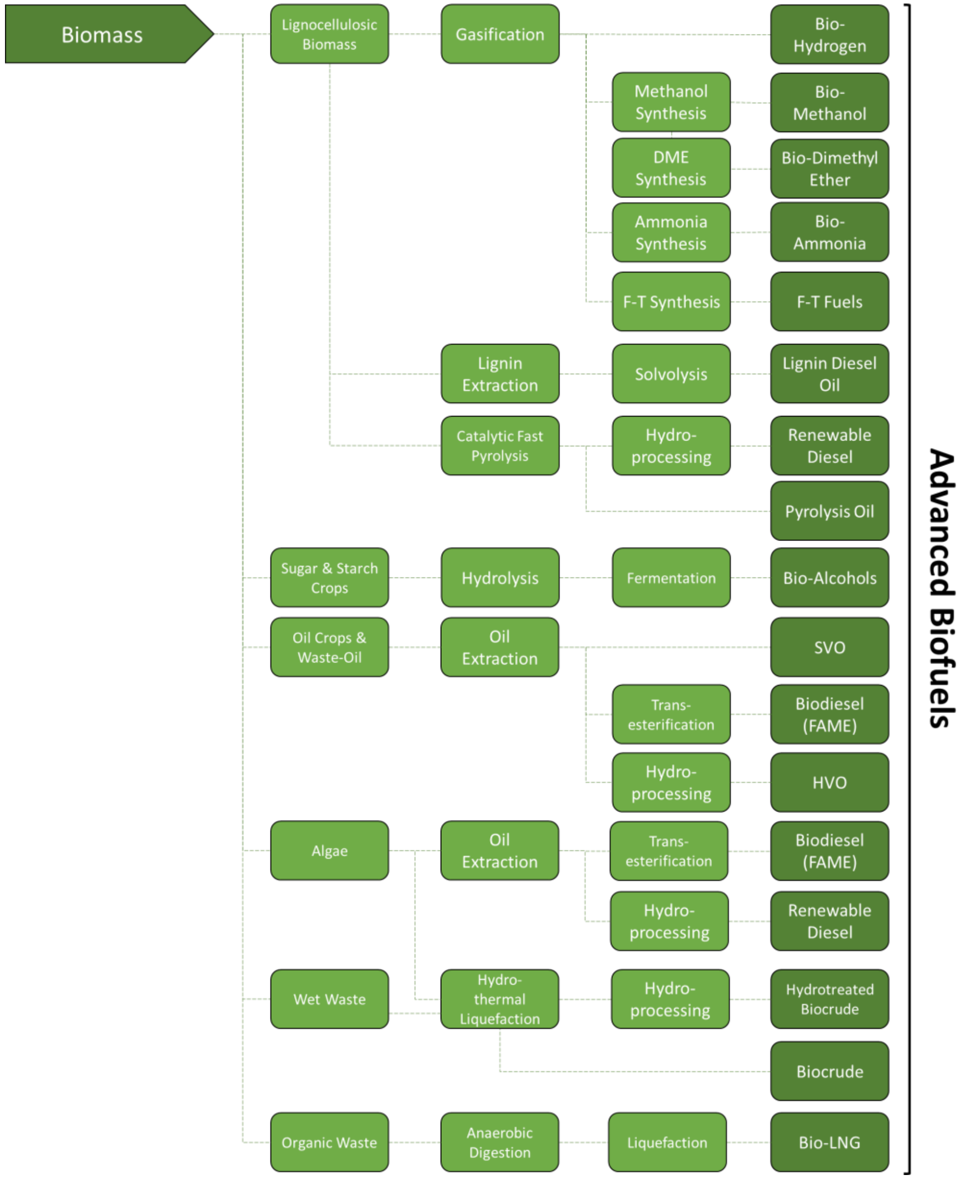
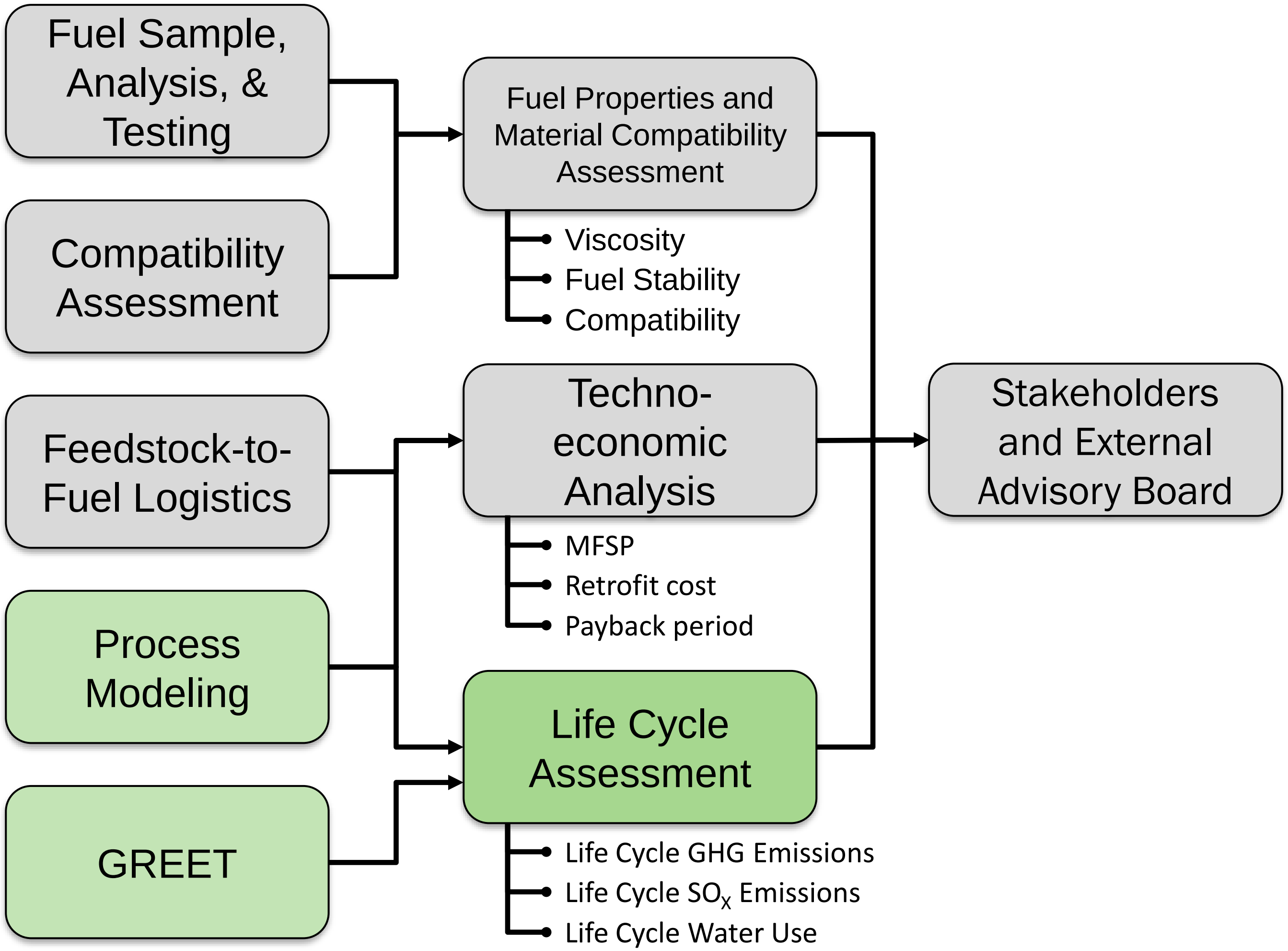


Multi-Laboratory Effort

- **Interdisciplinary Framework**
  - Conduct TEA, LCA, and technical feasibility analyses to determine the viability of biofuels for the maritime sector
- **Supported by the U.S. Department of Energy's (DOE) Bioenergy Technology Office (BETO)**

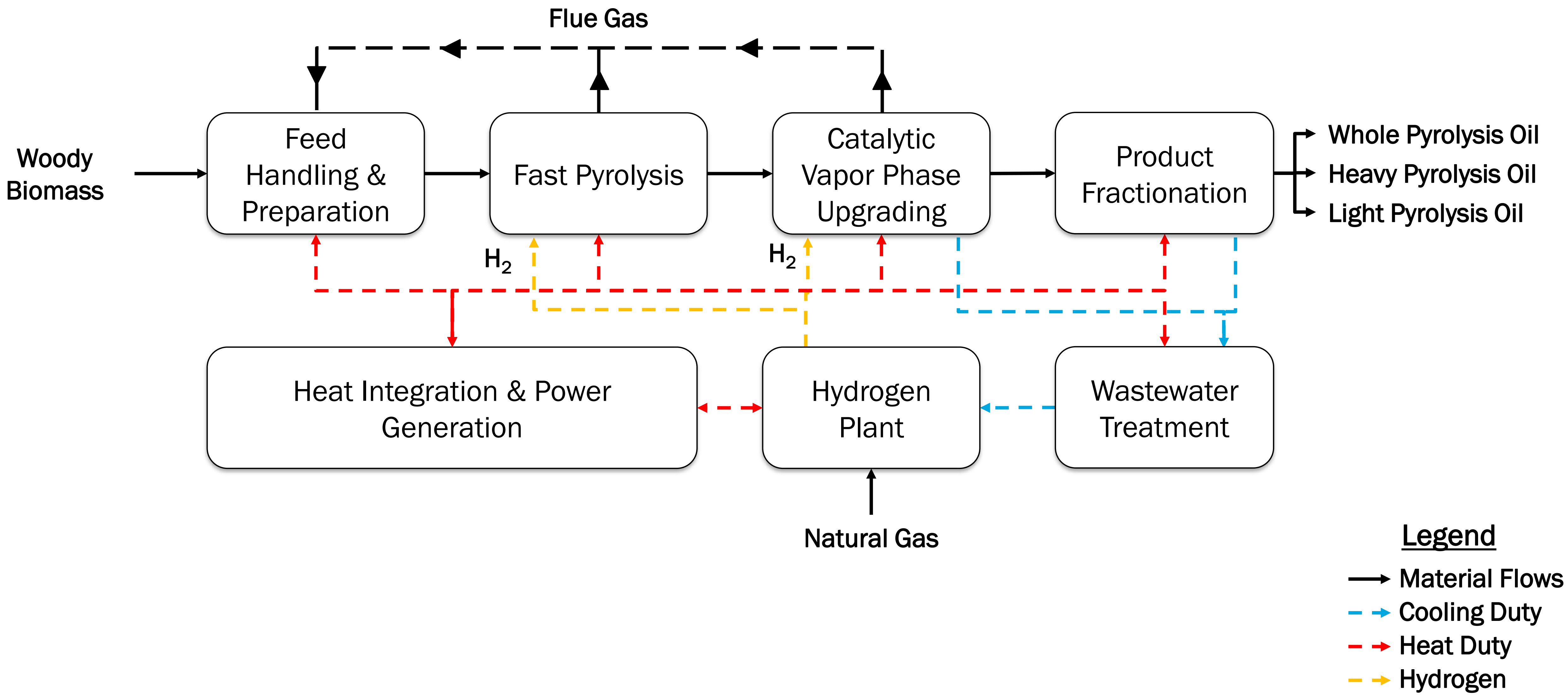


Research Objectives

- **Evaluate the life cycle environmental impacts of novel biofuels pathways for marine shipping using Argonne's GREET Model**
  - Catalytic Fast Pyrolysis: Woody Blend
  - Fischer-Tropsch Synthesis: Landfill Gas
  - Hydrothermal Liquefaction: Waste Streams

- **Forecast the global environmental impacts of international shipping across the 2020 to 2050 time horizon**
  - IEA's Sustainable Development Scenarios
  - Time-series analysis based on projected fuel demand, and environmental characterization using Argonne's GREET model

Catalytic Fast Pyrolysis (CFP)



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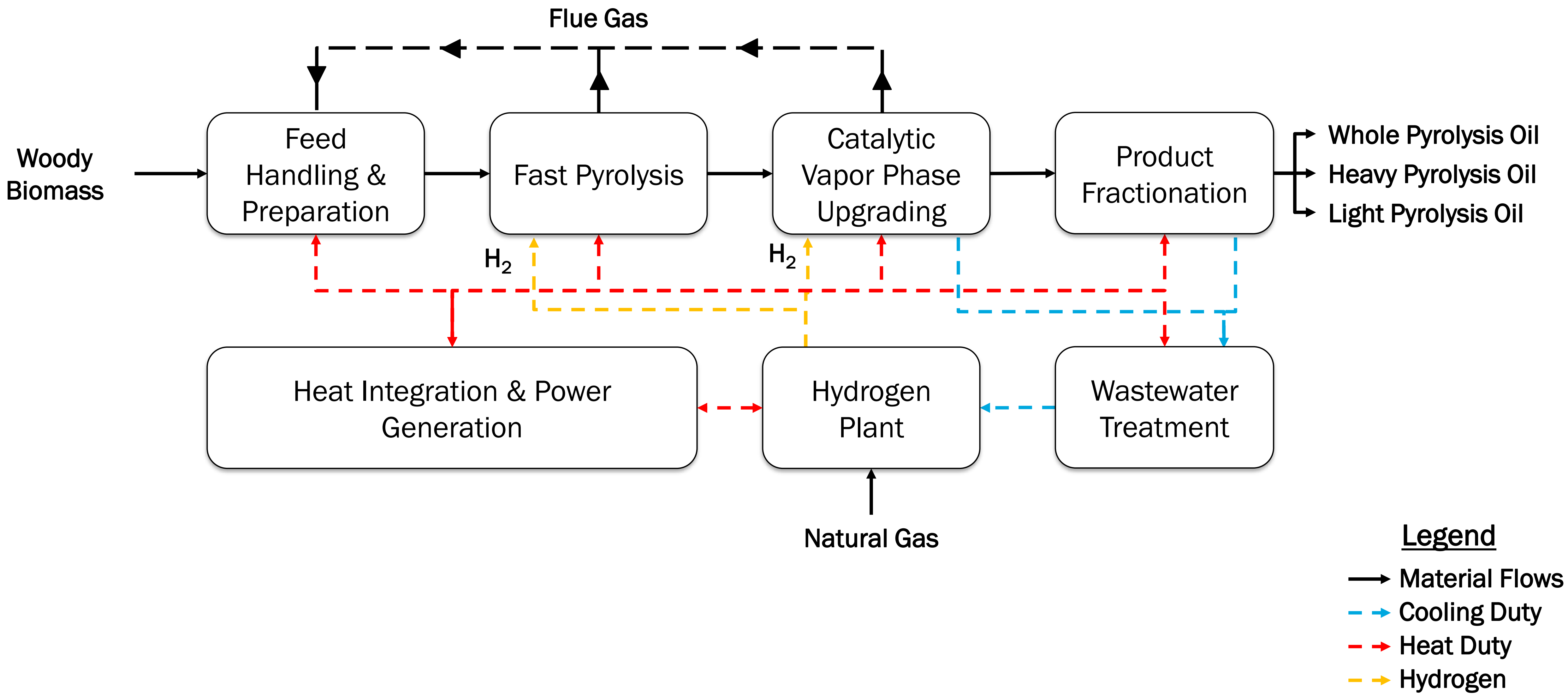
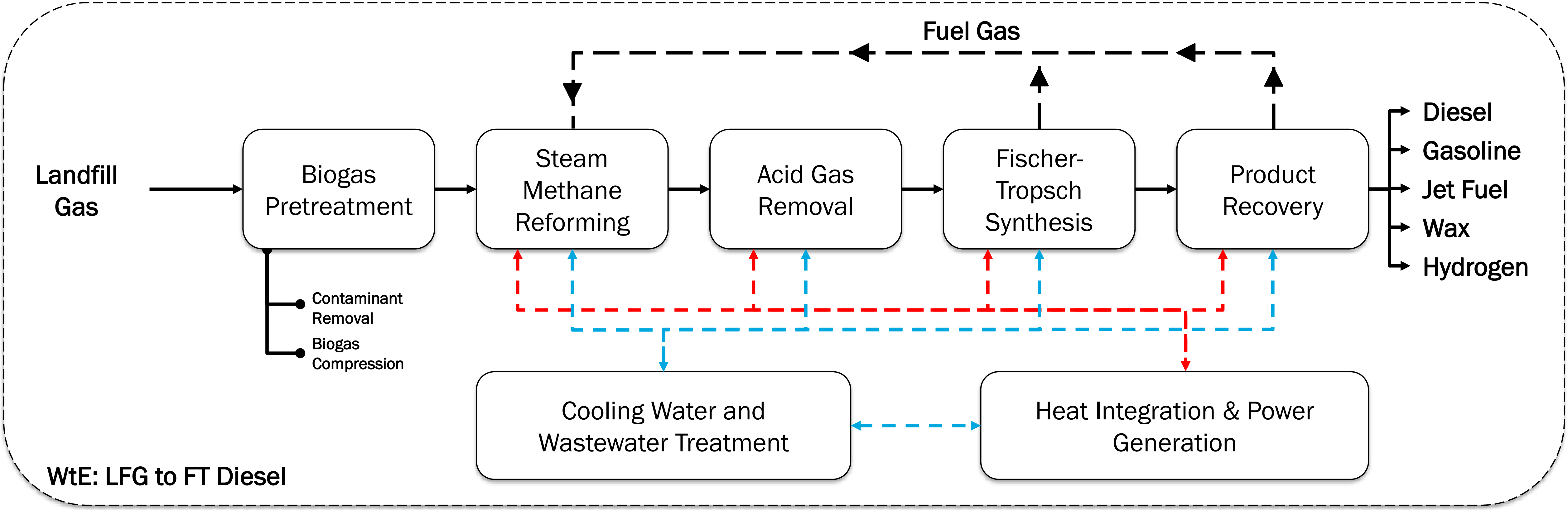
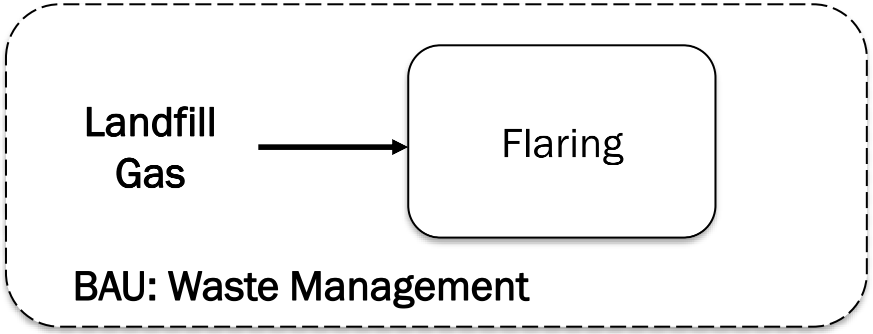
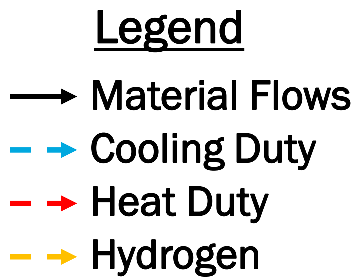


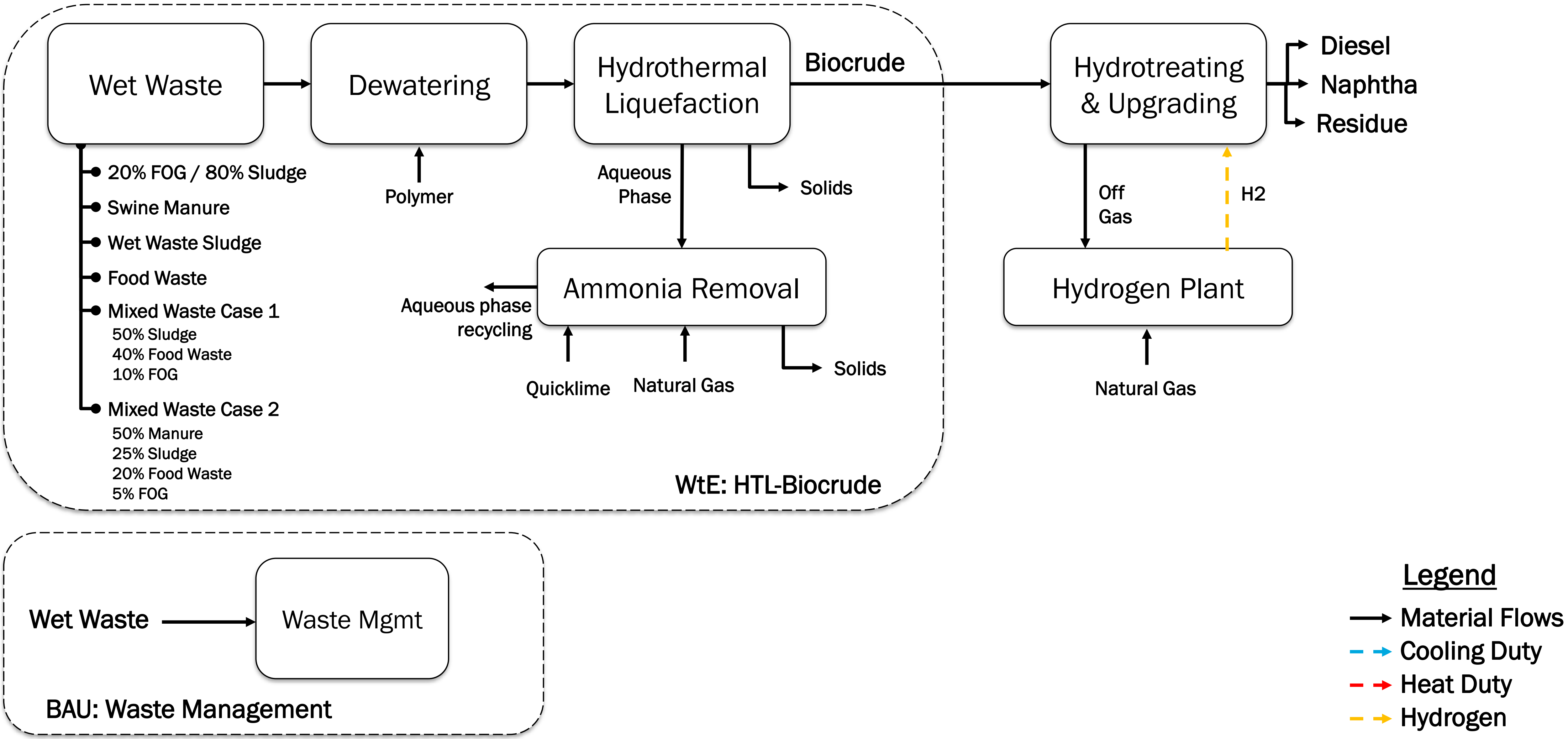
Landfill Gas to Fischer Tropsch Diesel







Hydrothermal Liquefaction (HTL)



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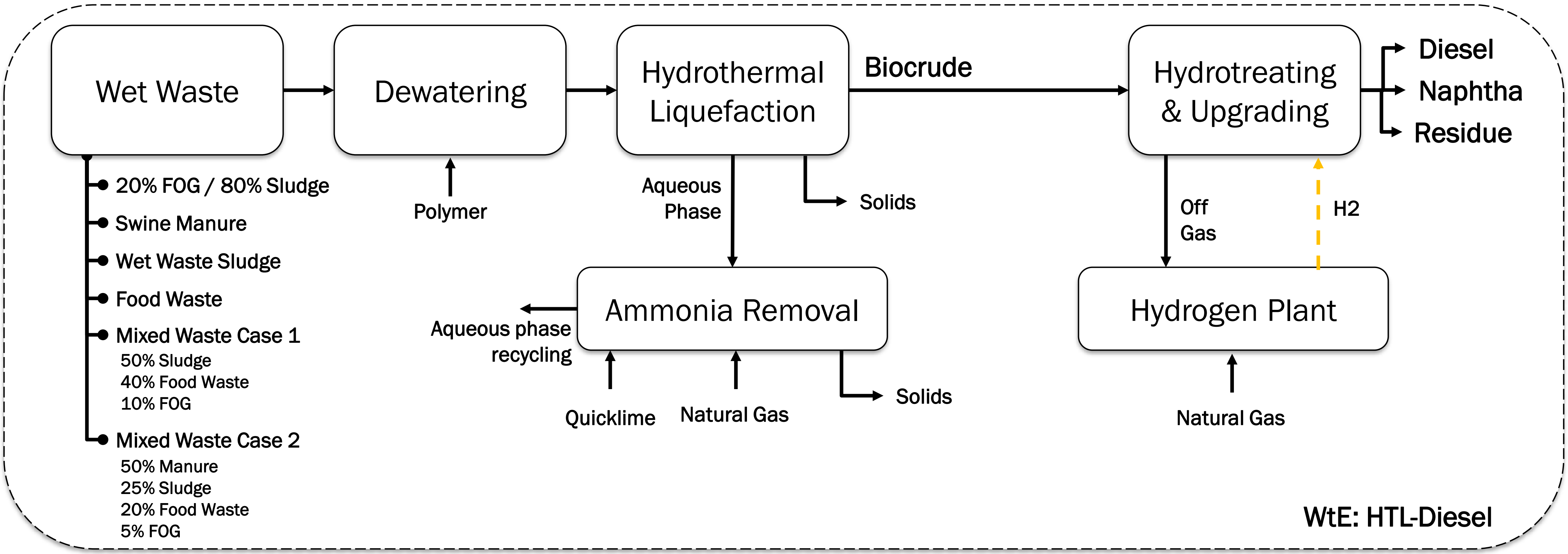
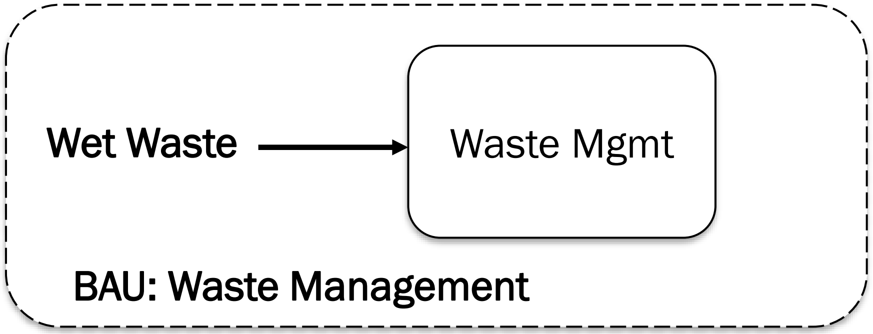
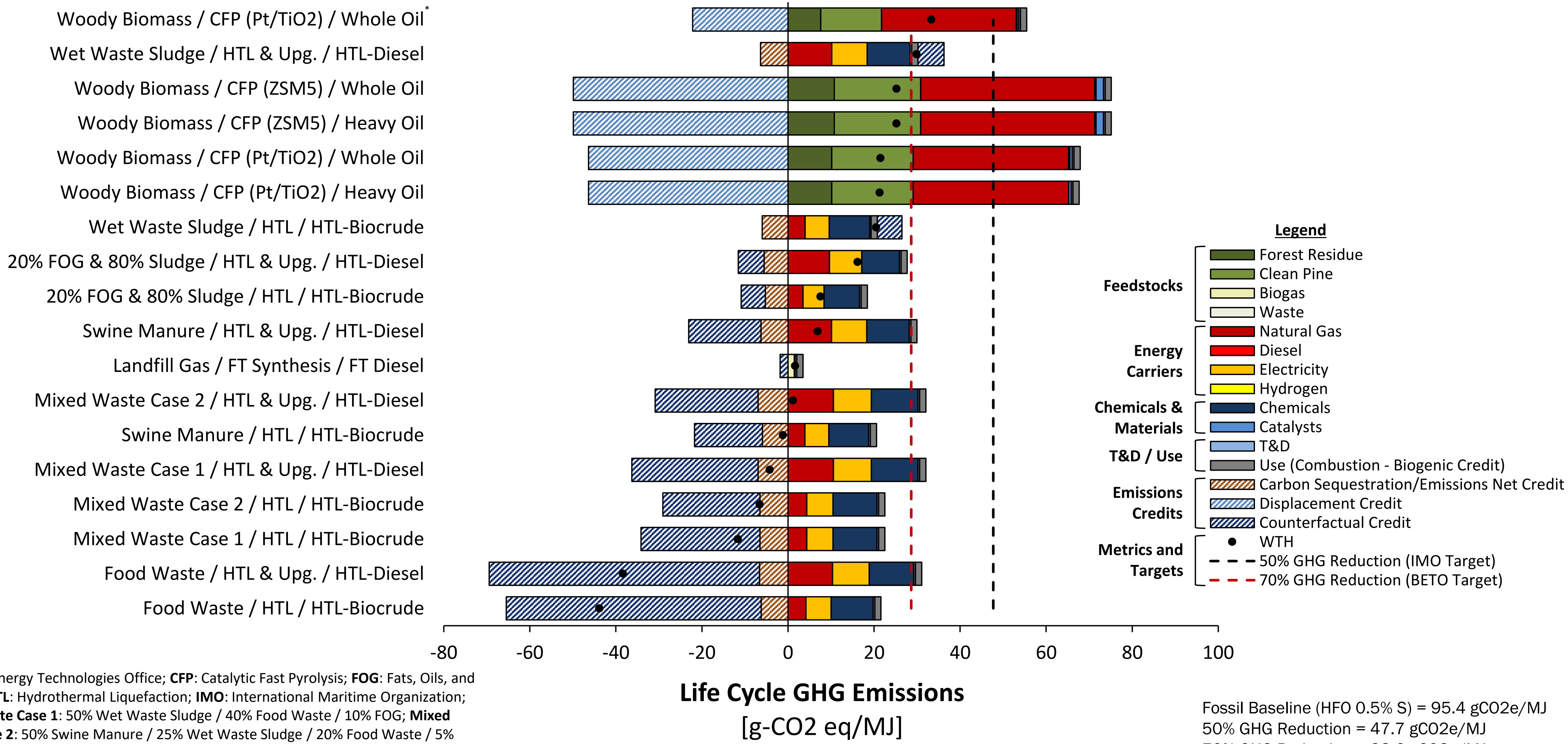




Legend

- Material Flows
- Cooling Duty
- Heat Duty
- Hydrogen

Life Cycle GHG Contribution



BETO: Bioenergy Technologies Office; **CFP**: Catalytic Fast Pyrolysis; **FOG**: Fats, Oils, and Greases; **HTL**: Hydrothermal Liquefaction; **IMO**: International Maritime Organization; **Mixed Waste Case 1**: 50% Wet Waste Sludge / 40% Food Waste / 10% FOG; **Mixed Waste Case 2**: 50% Swine Manure / 25% Wet Waste Sludge / 20% Food Waste / 5% FOG; **WTH**: Well-to-Hull; *Target Case

Fossil Baseline (HFO 0.5% S) = 95.4 gCO2e/MJ
50% GHG Reduction = 47.7 gCO2e/MJ
70% GHG Reduction = 28.6 gCO2e/MJ

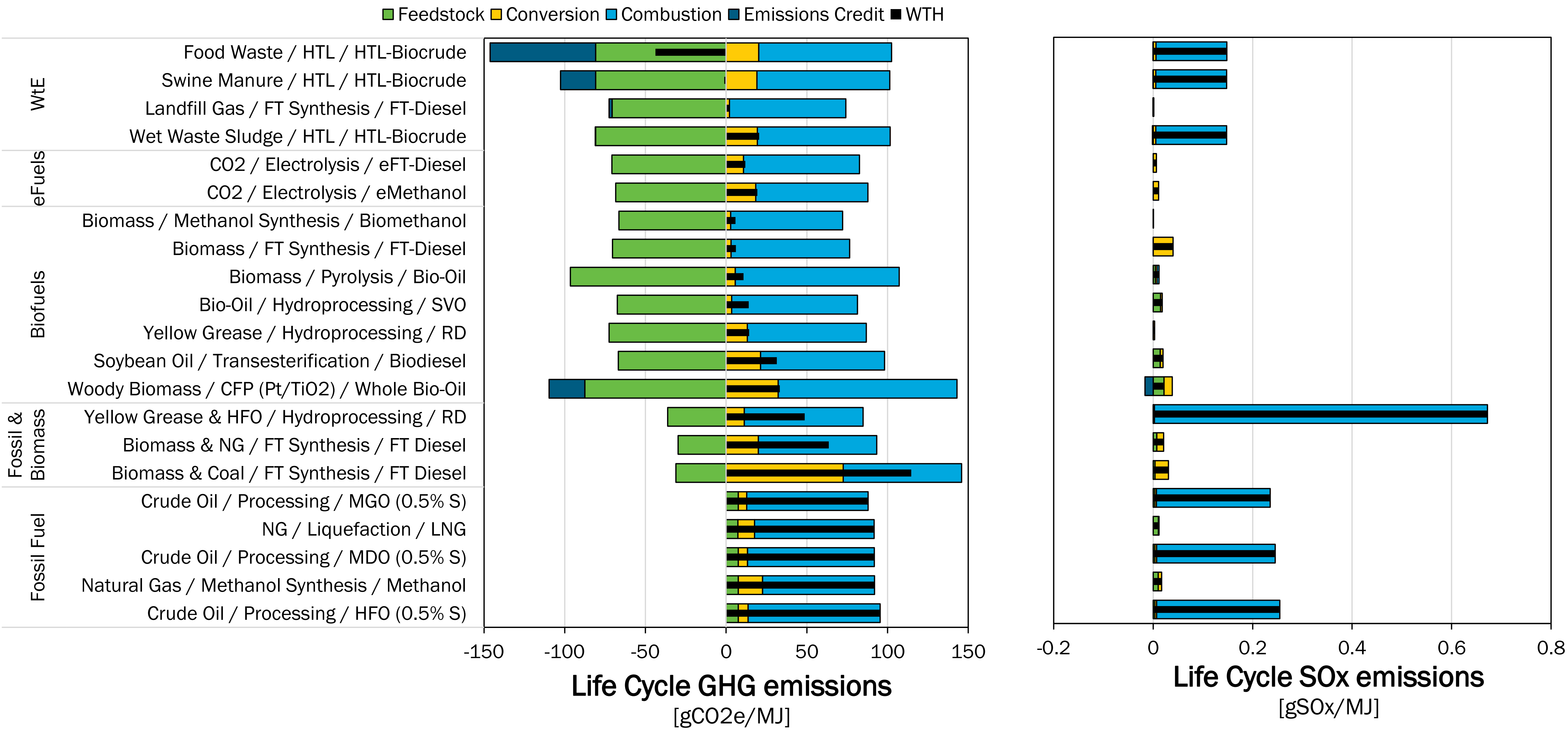
Environmental Heat Map

- **Life Cycle Impacts Relative to HFO (0.5 %S)**
  - Marine Biofuel pathways demonstrate >50% reduction in life cycle GHG emissions relative to HFO
  - Biofuels exhibit low GHG, SO_X, and PM emissions, but in select cases may demonstrate higher water-use relative to HFO

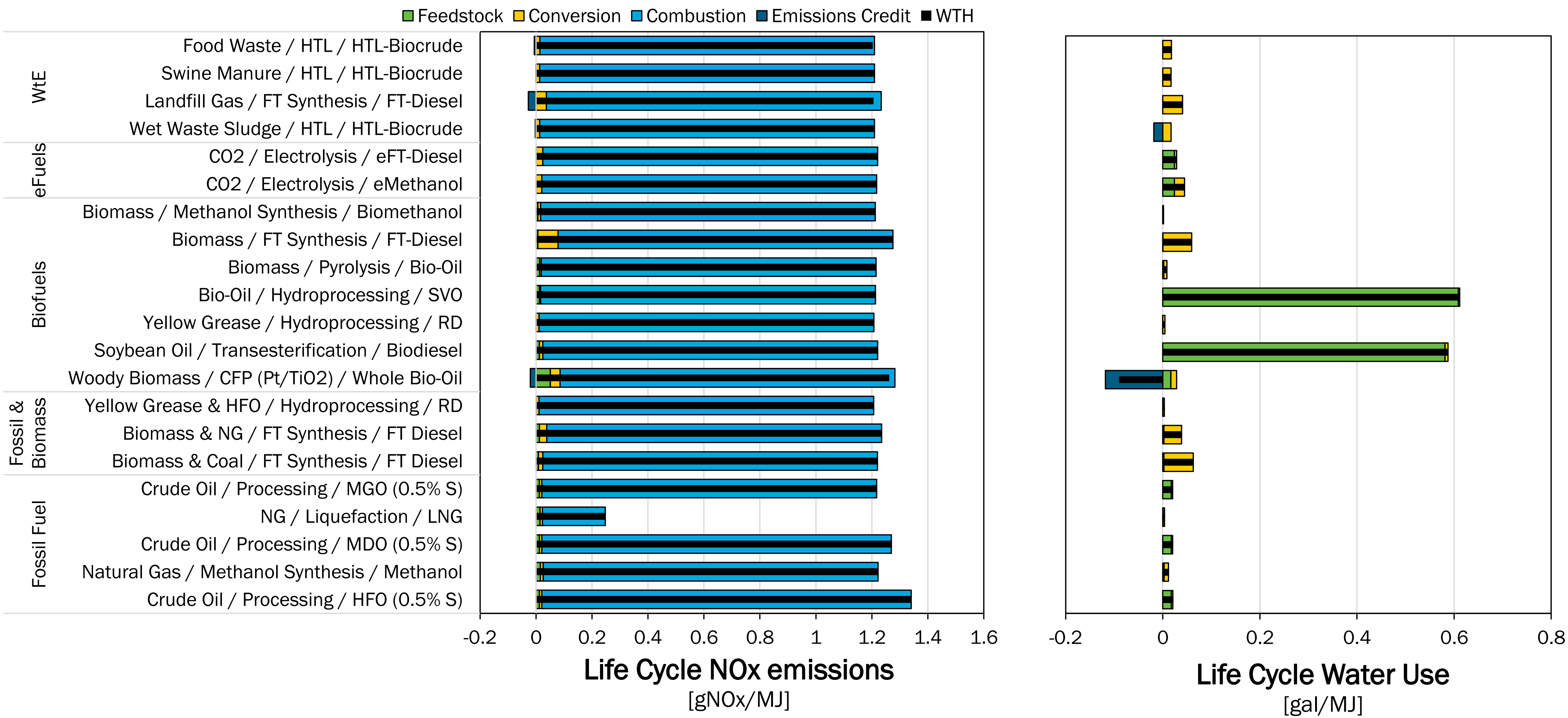
		GHG	SOX	NOX	PM2.5	PM10	Water Use
Marine Biofuel	Food Waste / HTL / HTL-Biocrude	-146%	-42%	-10%	-68%	-68%	-13%
	Food Waste / HTL & Upg. / HTL-Diesel	-140%	-95%	-10%	-80%	-79%	37%
	Mixed Waste Case 1 / HTL / HTL-Biocrude	-112%	-42%	-10%	-67%	-67%	-58%
	Mixed Waste Case 2 / HTL / HTL-Biocrude	-107%	-42%	-10%	-66%	-66%	-33%
	Mixed Waste Case 1 / HTL & Upg. / HTL-Diesel	-104%	-95%	-9%	-79%	-78%	-11%
	Swine Manure / HTL / HTL-Biocrude	-101%	-42%	-10%	-66%	-66%	-17%
	Mixed Waste Case 2 / HTL & Upg. / HTL-Diesel	-99%	-95%	-9%	-78%	-78%	15%
	Landfill Gas / FT Synthesis / FT Diesel	-98%	-100%	-10%	-73%	-74%	99%
	Swine Manure / HTL & Upg. / HTL-Diesel	-93%	-95%	-9%	-78%	-77%	32%
	20% FOG & 80% Sludge / HTL / HTL-Biocrude	-92%	-43%	-10%	-67%	-66%	-90%
	20% FOG & 80% Sludge / HTL & Upg. / HTL-Diesel	-83%	-96%	-9%	-78%	-78%	-45%
	Wet Waste Sludge / HTL / HTL-Biocrude	-79%	-42%	-10%	-66%	-66%	-106%
	Woody Biomass / CFP (Pt/TiO2) / Heavy Oil	-78%	-94%	-6%	-76%	-77%	-799%
	Woody Biomass / CFP (Pt/TiO2) / Whole Oil	-77%	-94%	-6%	-76%	-77%	-799%
	Woody Biomass / CFP (ZSM5) / Heavy Oil	-74%	-90%	-5%	-75%	-77%	-278%
	Woody Biomass / CFP (ZSM5) / Whole Oil	-74%	-90%	-5%	-75%	-77%	-278%
	Wet Waste Sludge / HTL & Upg. / HTL-Diesel	-69%	-96%	-9%	-78%	-78%	-63%
	Woody Biomass / CFP (Pt/TiO2) / Whole Oil*	-65%	-91%	-6%	-76%	-76%	-539%
Marine Fossil Fuels	Marine Gasoil (1.0% sulfur)	-8%	82%	-9%	-38%	-37%	-2%
	Marine Gasoil (0.5 % sulfur)	-8%	-8%	-9%	-58%	-58%	-1%
	Marine Gasoil (0.1 % sulfur)	-7%	-79%	-9%	-75%	-75%	-1%
	Marine Distillate Oil (1.92% sulfur)	-5%	263%	-5%	5%	5%	-2%
	Liquefied Natural Gas (LNG)	-4%	-95%	-82%	-93%	-93%	-82%
	Marine Distillate Oil (0.5% sulfur)	-4%	-4%	-5%	-56%	-56%	-1%
	Marine Distillate Oil (0.1% sulfur)	-3%	-79%	-5%	-74%	-73%	0%
	HFO (2.7% sulfur)	-1%	428%	0%	98%	98%	-2%
	HFO (0.5% sulfur)	0%	0%	0%	0%	0%	0%
	HFO (0.1% sulfur)	0%	-78%	0%	-18%	-18%	0%
	NG / Fischer-Tropsch / Diesel	3%	-94%	-9%	-80%	-80%	44%

*Target Case

Life Cycle GHG and SOx



Life Cycle NOx and Water-Use



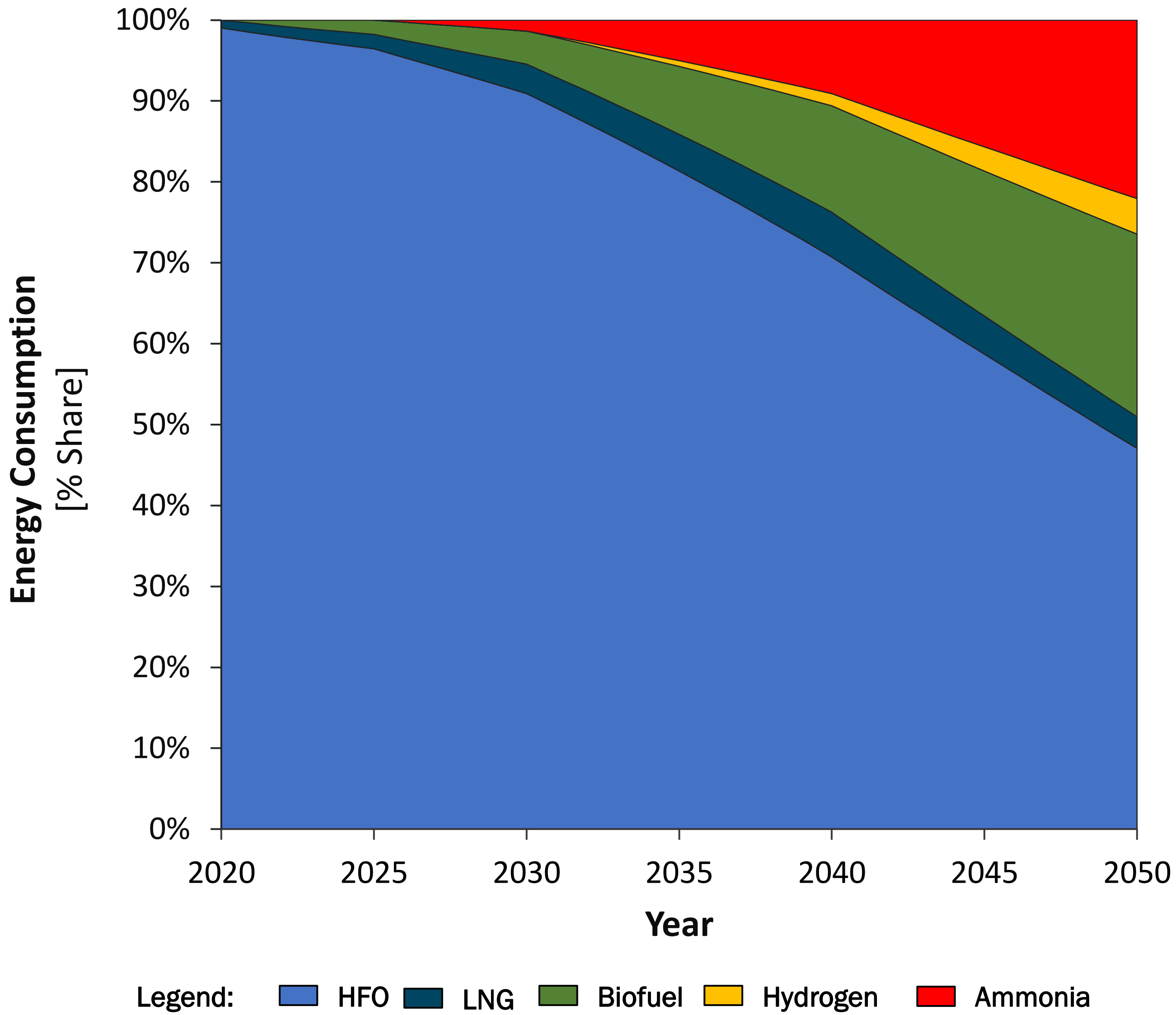
IEA Global energy consumption from international shipping: Sustainable Development Scenario (SDS) 2020-2050

Forecast the environmental impacts of global international shipping

- IEA international shipping SDS projections over the 2020-to-2050 time horizon
- GREET Time-series EF's

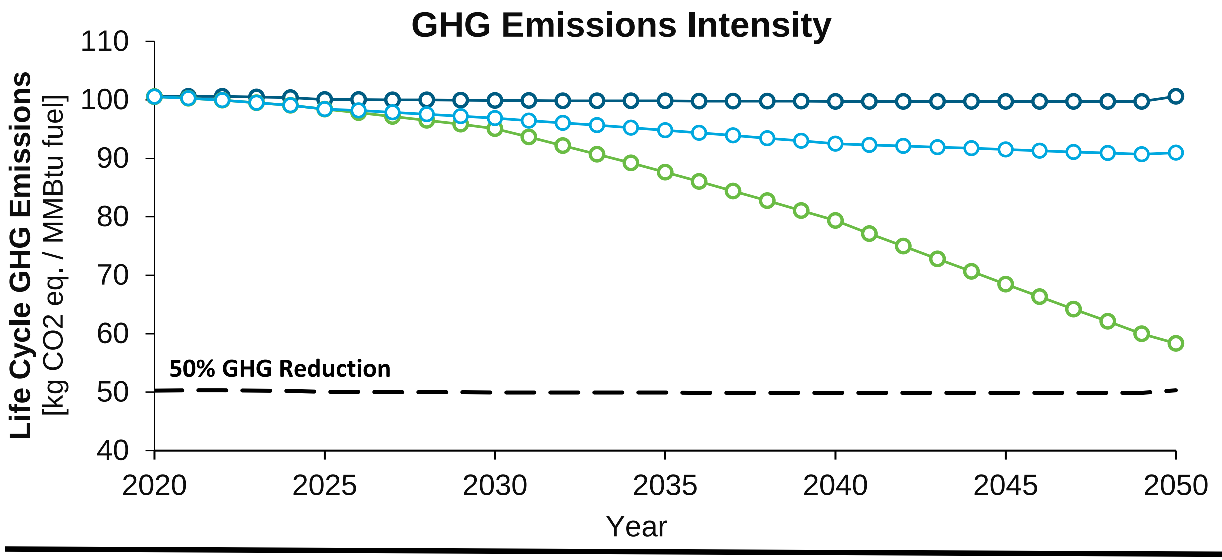
Maritime AGE

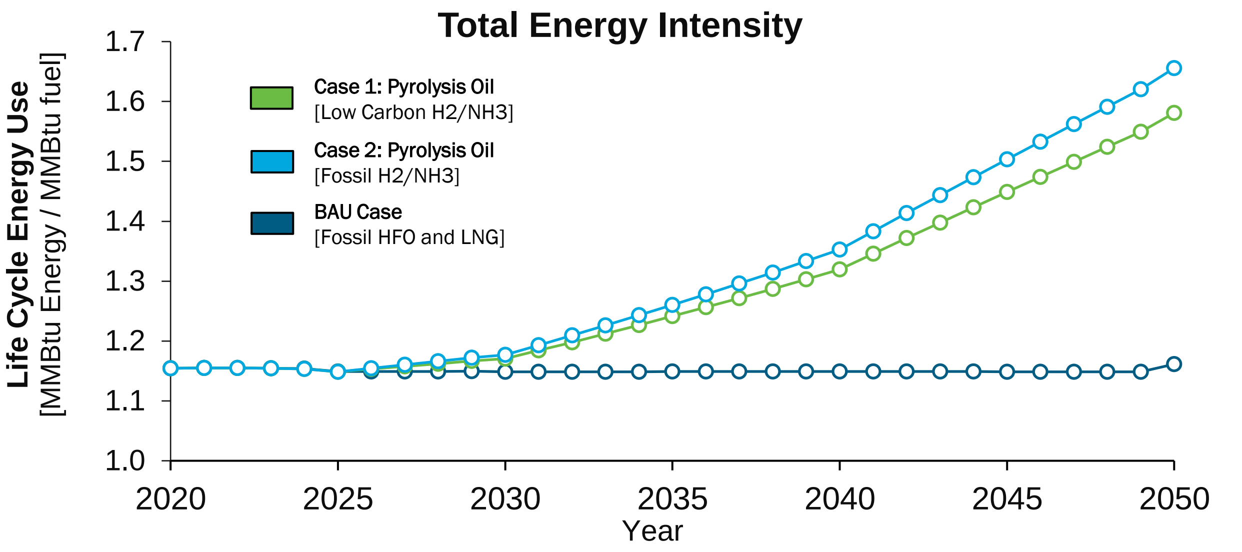
- Characterize the environmental impact of maritime biotechnology at scale
- Case Study: Pyrolysis-Oil as a marine biofuel
  - Case 1: Low Carbon H2 & Ammonia
  - Case 2: Fossil H2 & Ammonia
  - Comparison with Hypothetical BAU case (HFO/LNG)

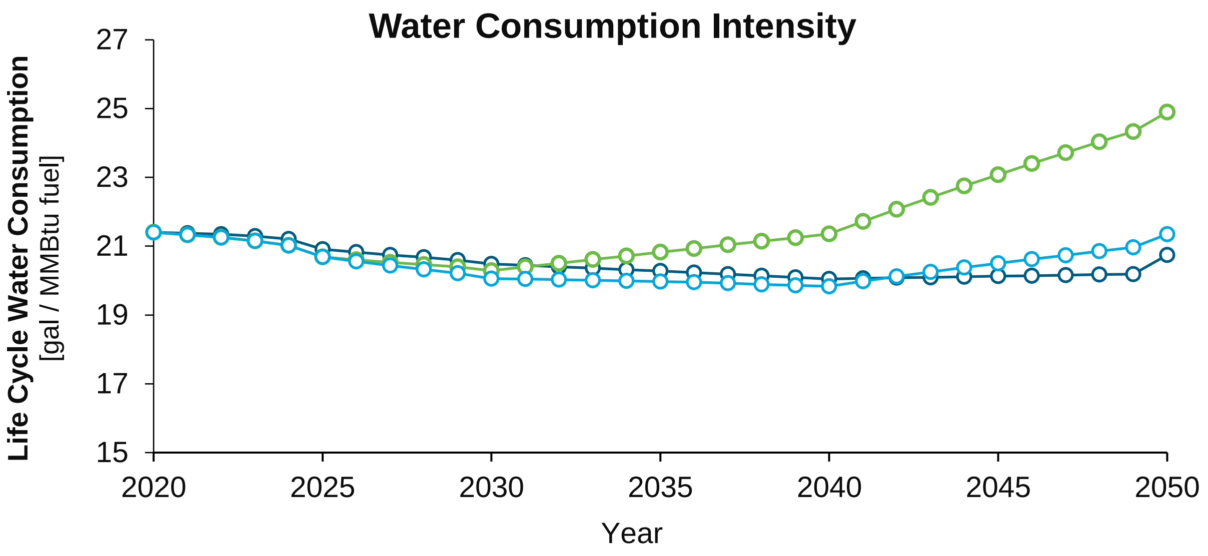


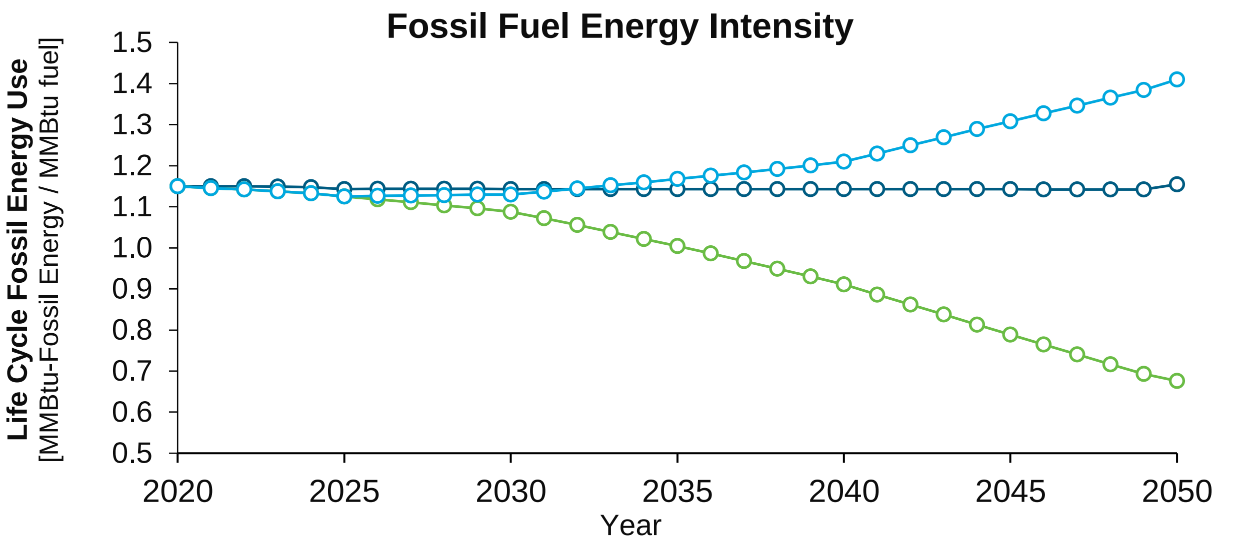
Source: IEA, Global energy consumption and CO2 emissions in international shipping in the Sustainable Development Scenario, 2019-2070, IEA, Paris

Time-Series GHG Emissions, Energy, and Water Intensity of International Shipping: Comparison of SDS and BAU Case



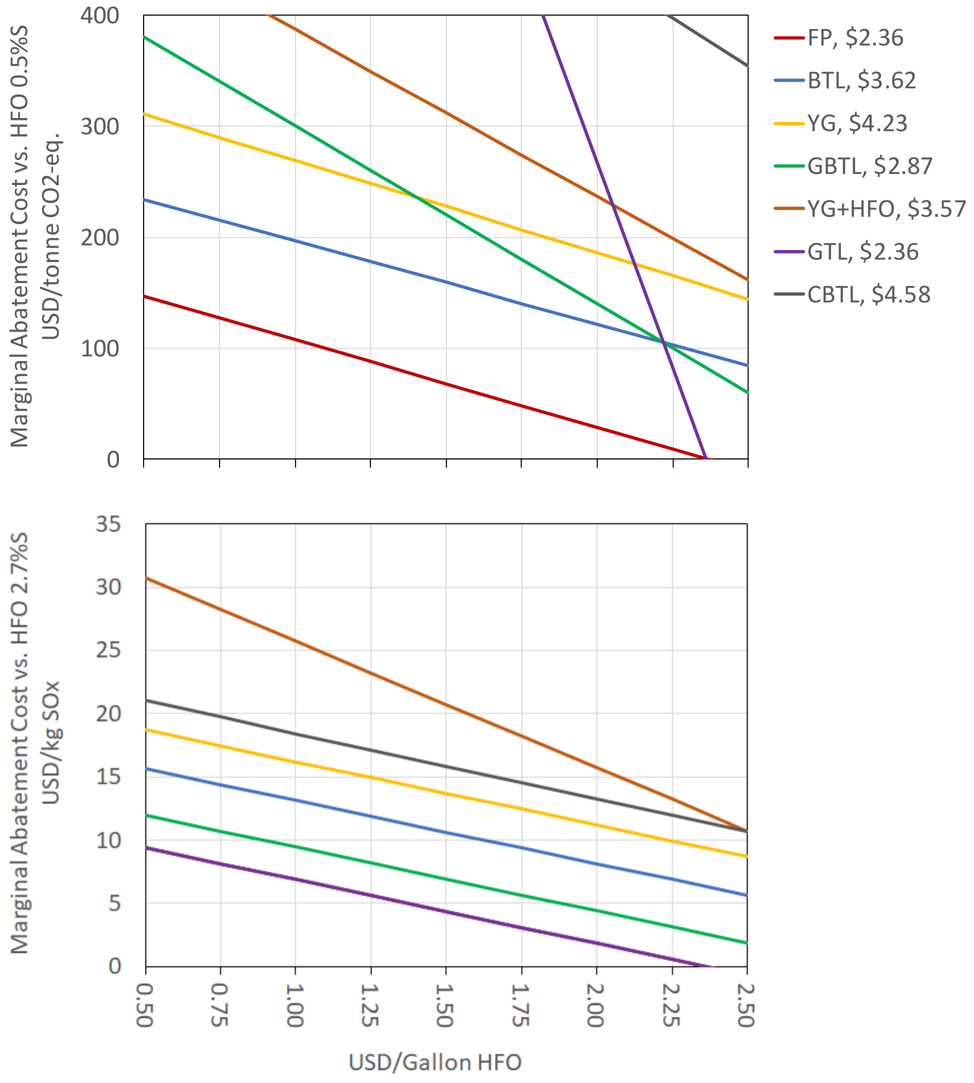




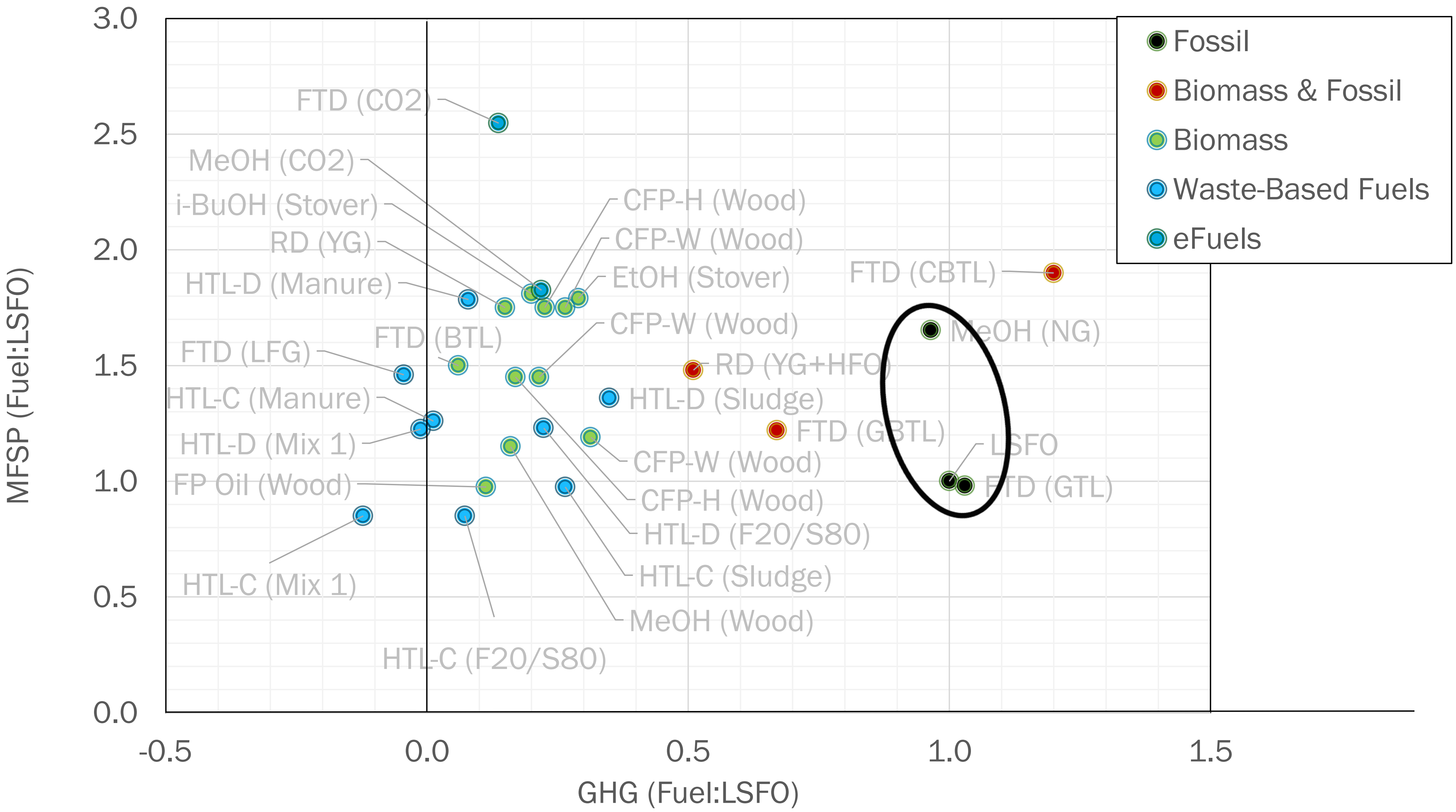


Marginal Abatement Costs for Marine Biofuels

- **Benchmark cost of reducing CO_2 and SO_X emissions**
  - Biofuels compared with avg. HFO, 0.5%S for GHG reduction and HFO, 2.7%S for SO_x reduction.
- **Marginal CO_2 abatement costs can be under \$200/tCO_2-eq. even for low HFO prices.**
  - Pyrolysis oil <\$100/tCO_2-eq. for HFO prices >\$1.09/gallon (\$320/tonne)
  - Biomass-derived fuels outperform those from mixed biomass-fossil feedstocks
- **Marginal SO_x abatement costs follow price for low/no S biomass- and NG-derived fuels**



Examining LCA and TEA results yields multiple promising pathways



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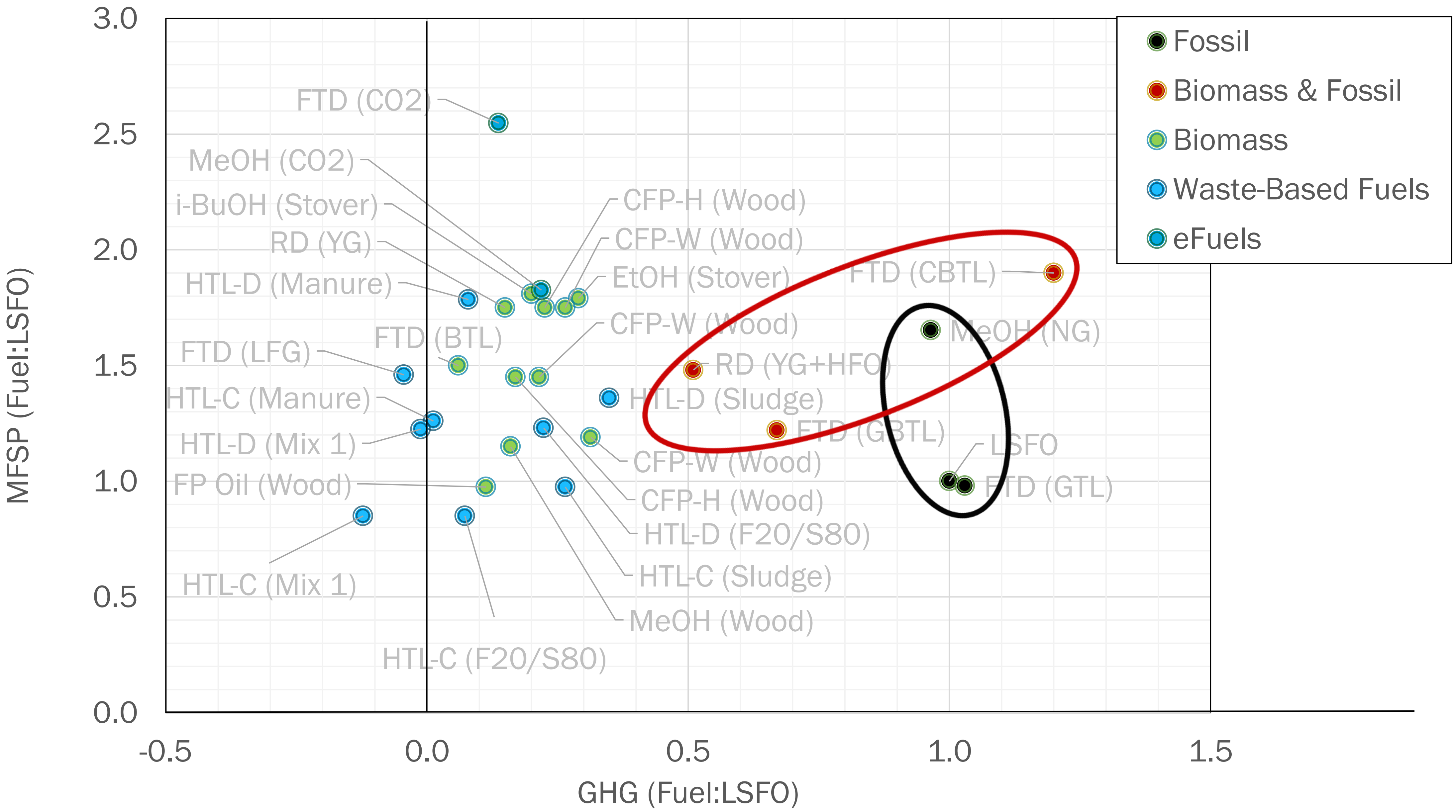

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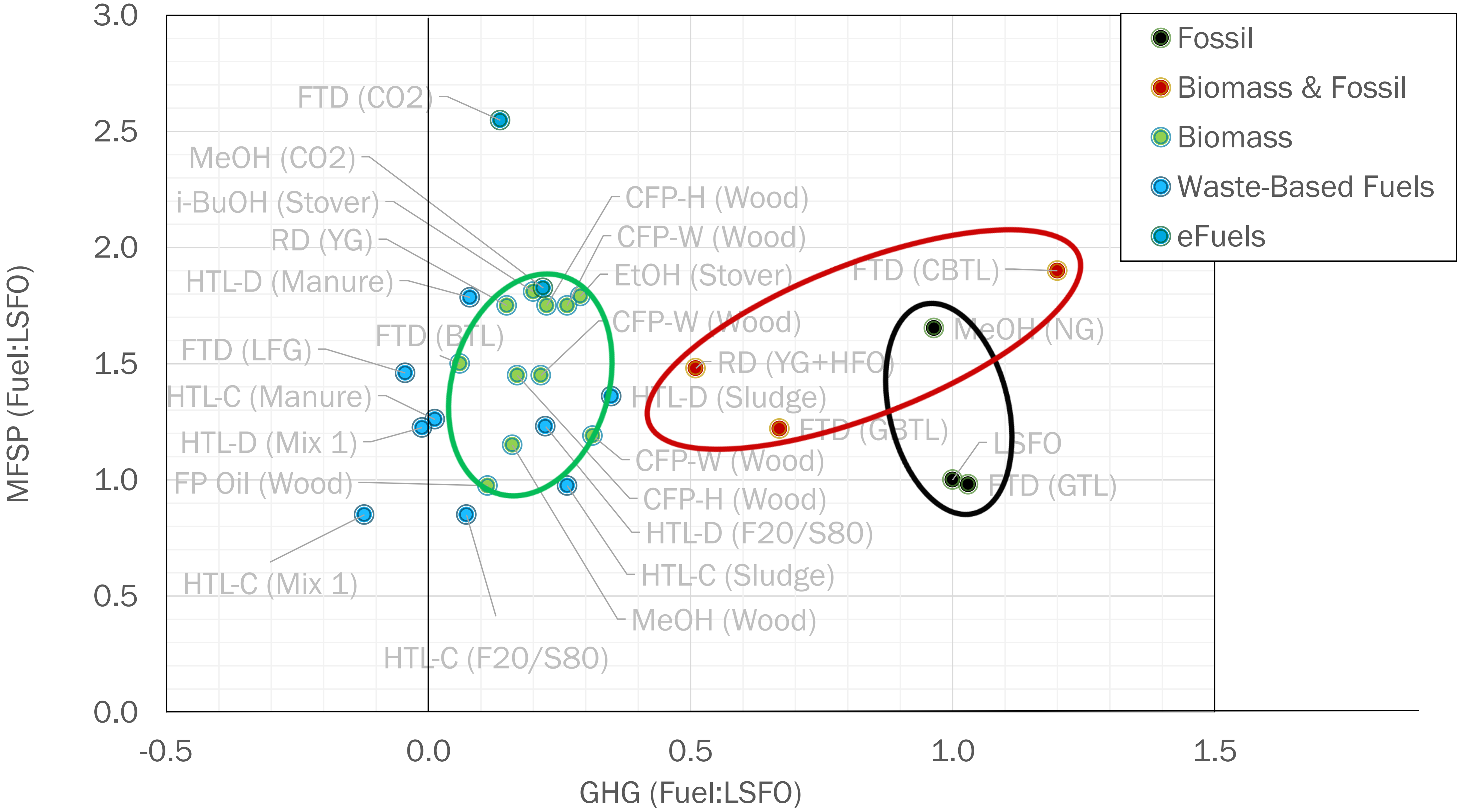

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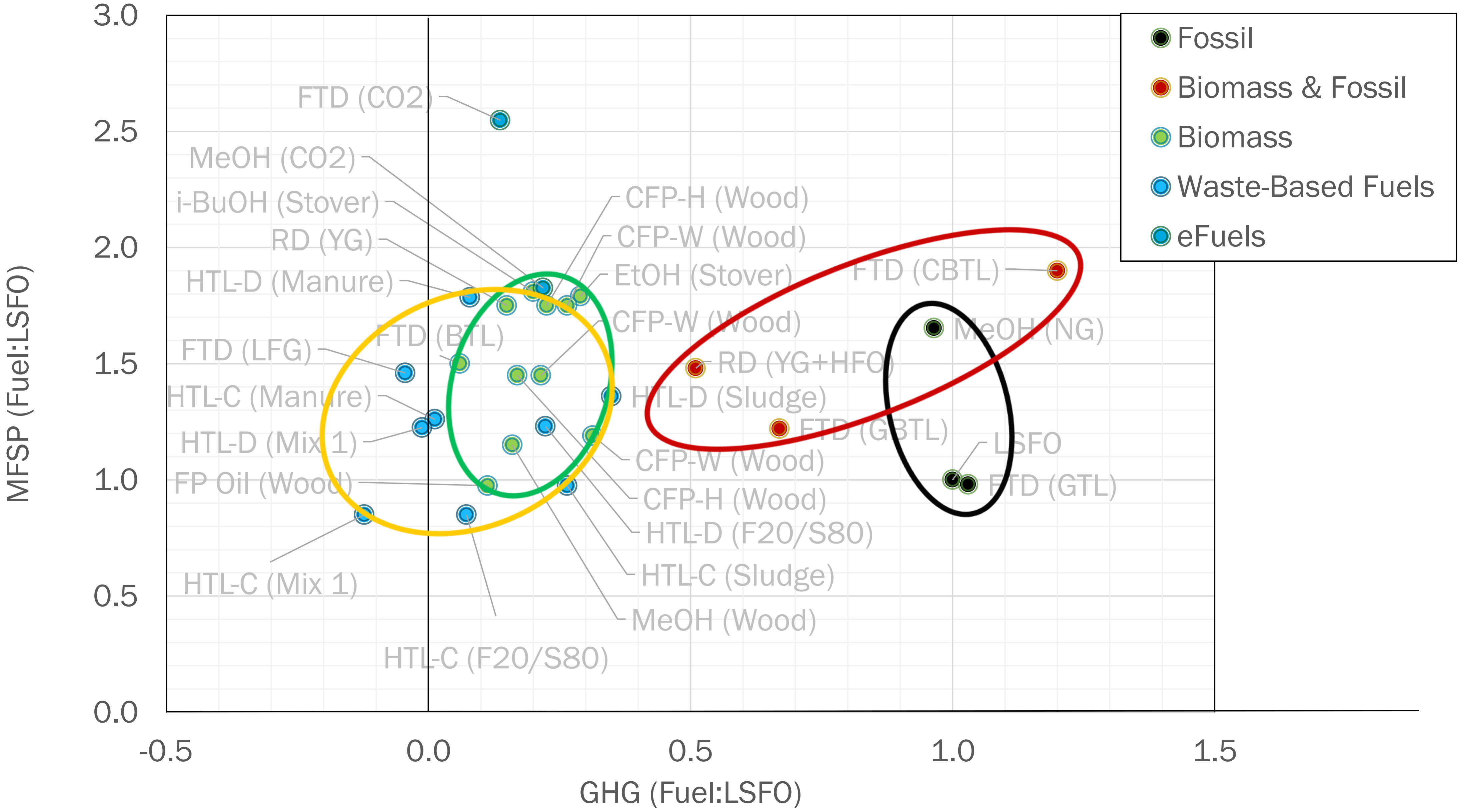

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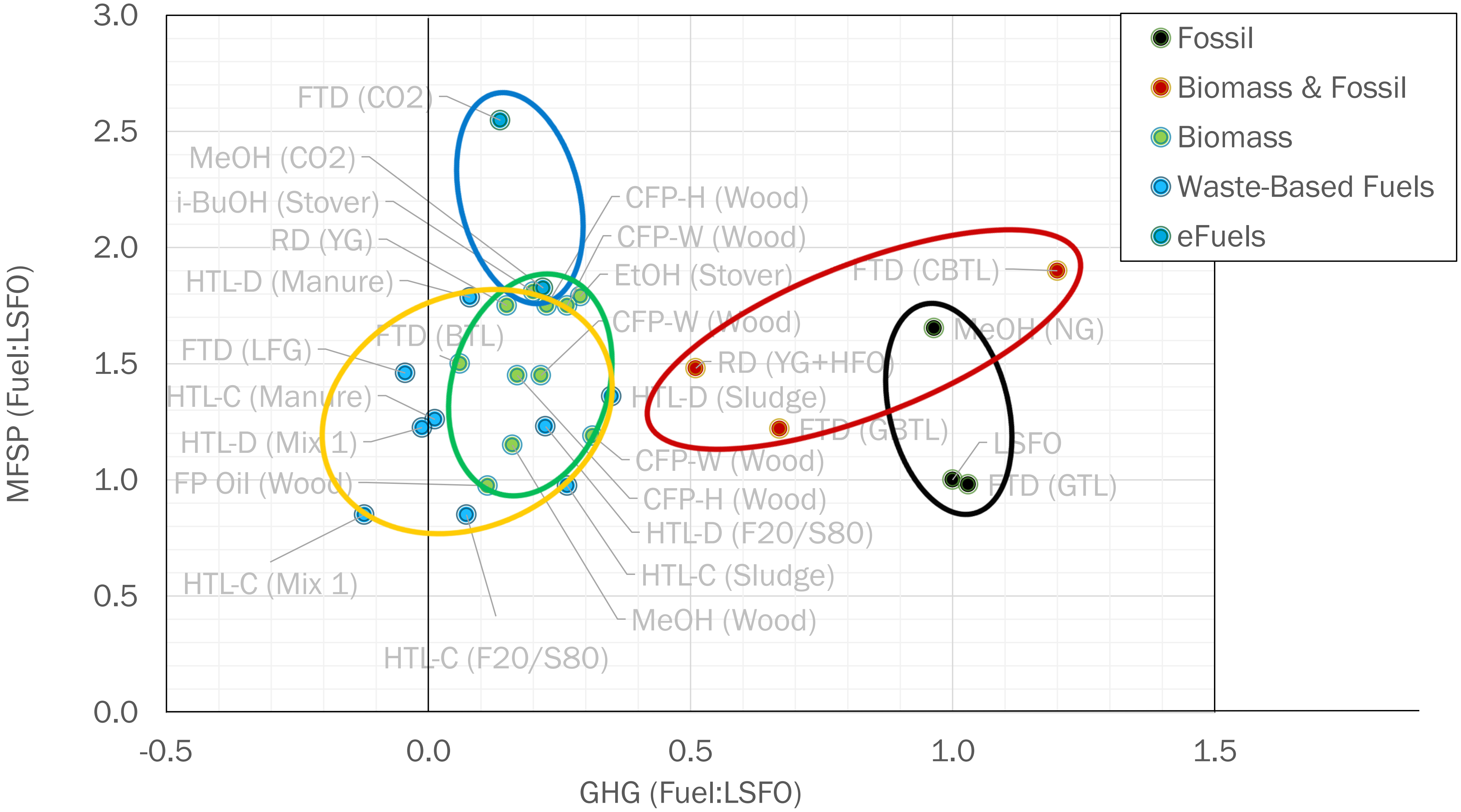

Conclusions & Perspectives

- **Regulations are driving the deployment of low-carbon and low-sulfur fuels**
  - Alternative fuels must meet decarbonization targets and increasingly stringent environmental standards on SOx, NOx, and other environmental pollutant categories
  - The transition to alternative marine fuels is highly complex, requiring a global outlook and coordination across the value-chain including engine manufacturers, fuel suppliers, ship owners and operators

- **LCA is critical for guiding the sustainability of the maritime sector**
  - Analysis should consider impacts across the entire life cycle to avoid shifting environmental burdens across segments of the supply chain or across pollutant categories (e.g., emissions to land, water, and air).
  - Absence of robust accounting protocol can undermine and potentially negate the climate benefit of alternative fuels for marine shipping

- **Biofuels: Challenges & Opportunities**
  - Biofuels from HTL, CFP, and WtE demonstrate >50% reduction in life cycle GHG emissions relative to HFO, and thus are commensurate with IMO's Long-term GHG emissions reductions targets
  - WtE Pathways demonstrate low carbon intensities, and in select cases are carbon negative, but are sensitive to the choice of counterfactual waste management scenario
  - Biofuels used in the marine sector may require minimal processing relative to counterparts for other sectors, and drop-in replacement biofuels and/or bio-blends can leverage existing maritime fuel infrastructure
  - Global availability of biomass and competition for biomass resources across industries (e.g. Aviation, On-Road Transport, etc.)
  - Fuel and engine testing is required to address concerns over fuel stability/compatibility, corrosivity, and storage

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