BIOFUELS FOR MARINE SHIPPING: A LIFE-CYCLE AND SECTORAL LEVEL ANALYSIS

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MARINE SHIPPING SECTOR: ENVIRONMENTAL CHALLENGES AND OPPORTUNITIES

MARINE SHIPPING SECTOR:

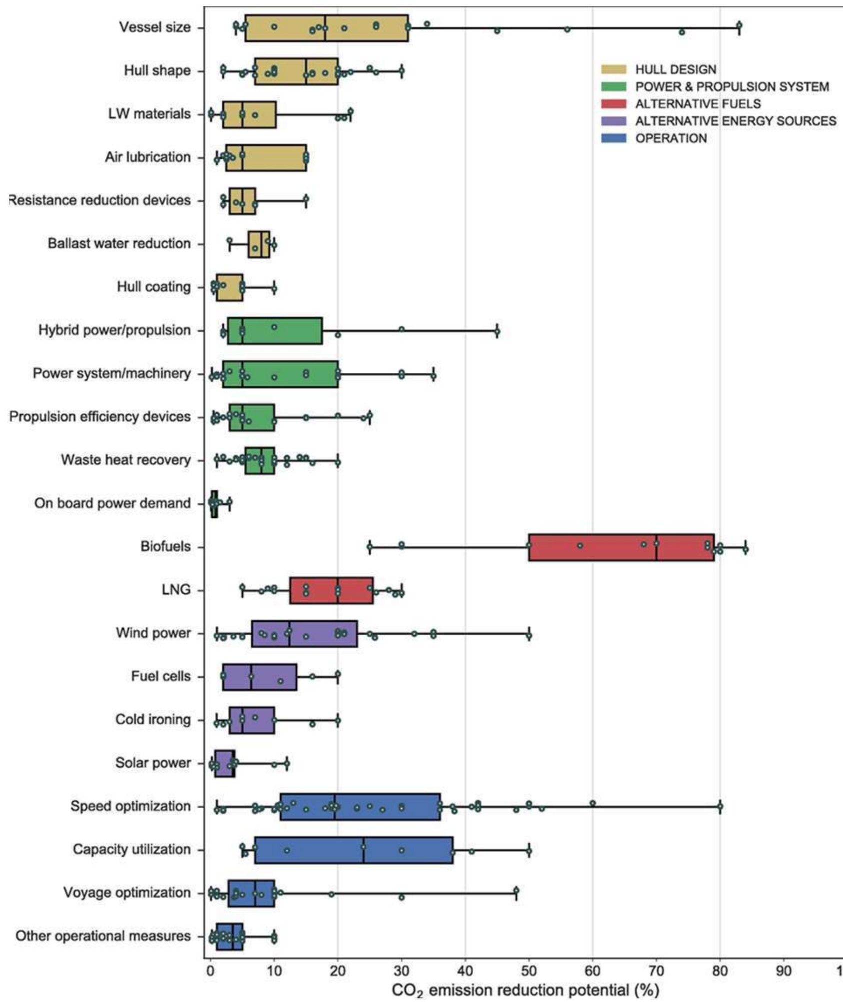
Environmental Impacts and Emissions Reductions Targets

- Marine shipping accounts for over 2% of worldwide GHG emissions (> 900 tons CO_2 per year)
  - Increasing regulatory focus on Maritime decarbonization
  - IMO has set target for 50% reduction in GHG emissions from International Shipping by 2050 relative to 2008
- Marine Shipping one of single largest producers of anthropogenic SOx
  - In 2020, IMO put into place restrictions on Marine Fuel to 0.5% Sulfur by weight
  - Carriage ban on non-compliant fuel

BIOFUELS VS. ALTERNATIVES:

Potential for CO_2 Emission Reduction

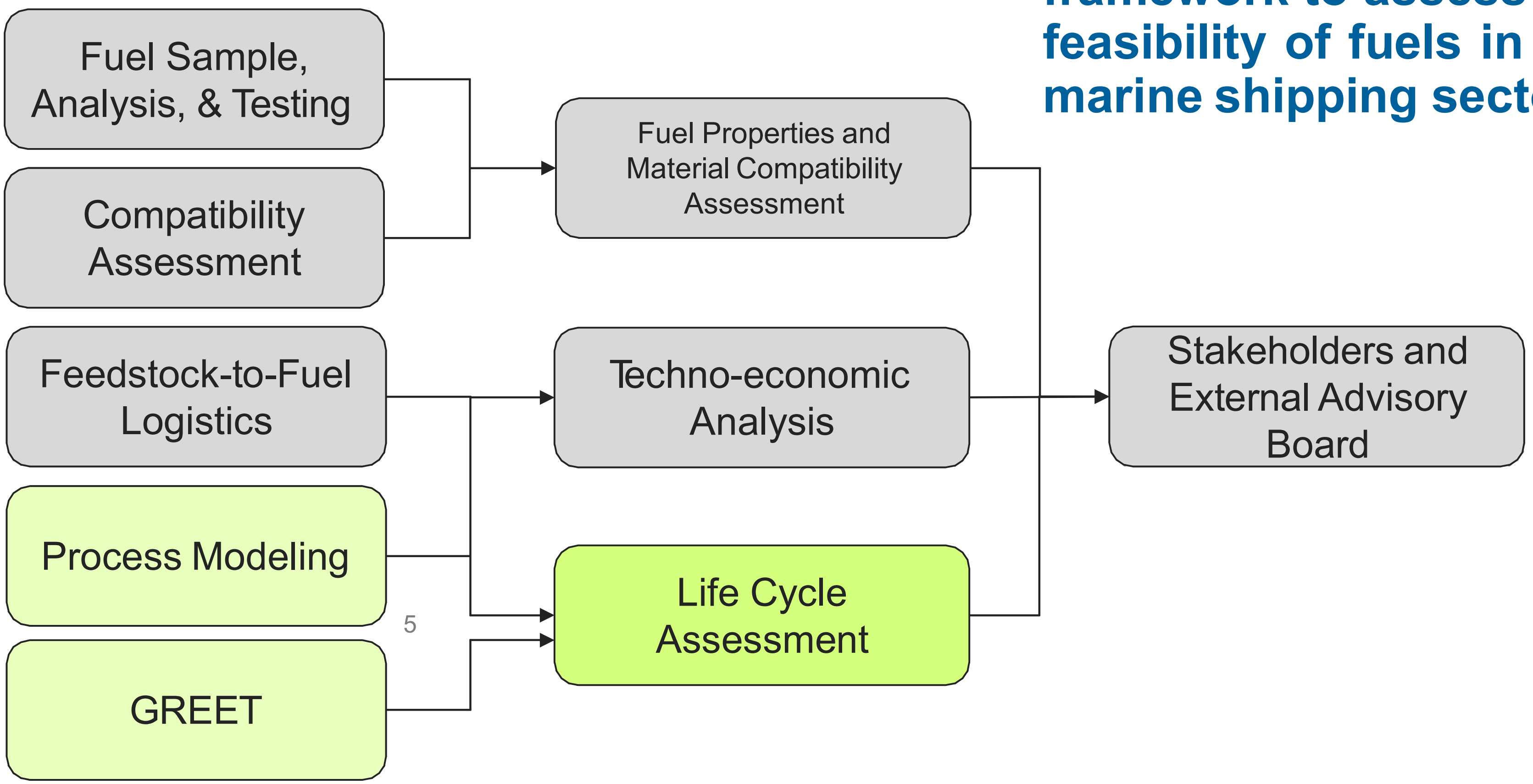
- In 2017, Bouman et al. assessed the potential of difference technologies and efficiency improvements for CO_2 emission reduction
- Biofuels demonstrated the highest potential for reducing CO_2 emissions across all considered measures



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

MARINE BIOFUELS ANALYSIS

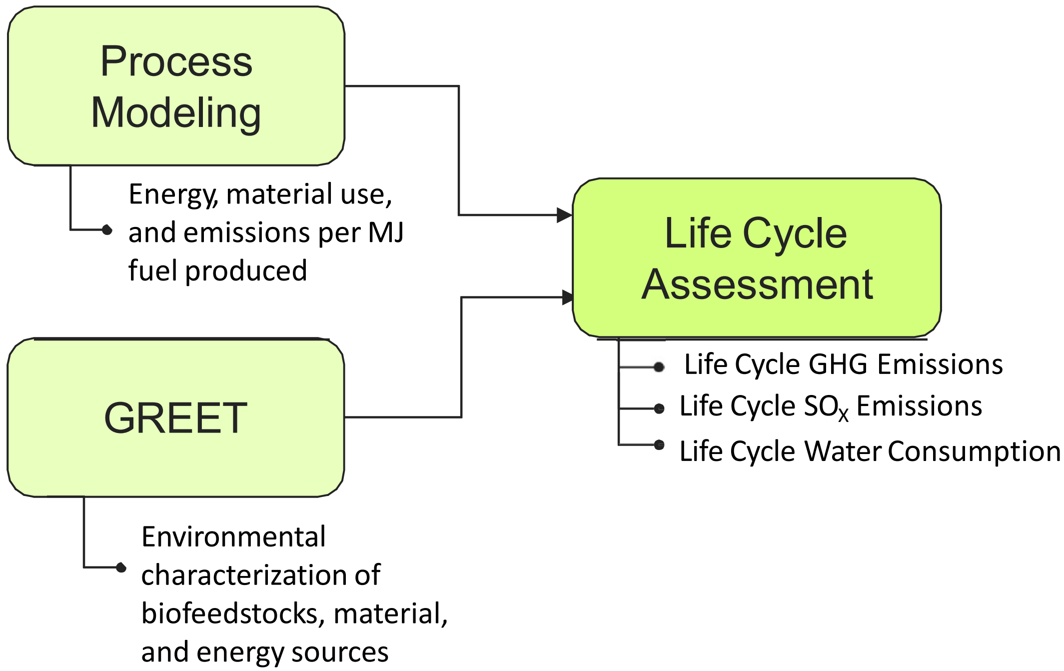
An integrated modelling framework to assess the feasibility of fuels in the marine shipping sector



MARINE BIOFUELS ANALYSIS

Life-Cycle Assessment

- Life-Cycle inventories are derived from process model simulation provided by PNNL and NREL
- Process models estimate material/energy balances, and utility requirements for biofuel conversion and upgrading
- LCA conducted using Argonne's GREET model



RESEARCH OBJECTIVES

- Evaluate Life-Cycle impacts of novel biofuel pathways using Argonne's GREET model and process simulation from partners at NREL, PNNL
  - Catalytic Fast Pyrolysis: Woody Blend
  - Hydrothermal Liquefaction: Waste Streams
  - Fischer-Tropsch Synthesis: Landfill Gas
- Forecast the global environmental impacts of international shipping across the 2020 to 2050 time horizon
  - IEA international shipping projections
  - Time-series GREET analysis of fuel impacts
    - Methanol
    - Pyrolysis Oil

LIFE-CYCLE ANALYSIS OF 18 NOVEL MARINE BIOFUEL PATHWAYS

Pathway ID	Feedstock	Process	SOT/Target	Final Fuel Product	Co-Products
1	Landfill Gas	Fischer-Tropsch (FT) Synthesis	-	FT - Diesel	Jet Fuel, Gasoline, Wax, Hydrogen, Electricity
2	Woody Blend	CFP w/ Pi/TiO2	SOT	Whole Oil	MEK, Acetone, Electricity
3	Woody Blend	CFP w/ Pi/TiO2	SOT	Heavy Oil	'Light Cut', MEK, Acetone, Electricity
4	Woody Blend	CFP w/ ZSM5	SOT	Whole Oil	MEK, Acetone, Electricity
5	Woody Blend	CFP w/ ZSM5	SOT	Heavy Oil	'Light Cut', MEK, Acetone, Electricity
6	Woody Blend	CFP w/ Pi/TiO2	Target	Whole Oil	MEK, Acetone, Electricity
7	20% FOG	HTL	Target	HTL - Biocrude	No Coproducts
8	Swine Manure	HTL	-	HTL - Biocrude	No Coproducts
9	Wet Waste Sludge	HTL	Target	HTL - Biocrude	No Coproducts
10	Food Waste	HTL	-	HTL - Biocrude	No Coproducts
11	Manure-Food-Sludge-FOG Blend	HTL	-	HTL - Biocrude	No Coproducts
12	Food-Sludge-FOG Blend	HTL	-	HTL - Biocrude	No Coproducts
13	20% FOG	HTL/Catalytic Hydro-treating	Target	HTL - Diesel	Naphtha, Residue
14	Swine Manure	HTL/Catalytic Hydro-treating	-	HTL - Diesel	Naphtha, Residue
15	Wet Waste Sludge	HTL/Catalytic Hydro-treating	Target	HTL - Diesel	Naphtha, Residue
16	Food Waste	HTL/Catalytic Hydro-treating	-	HTL - Diesel	Naphtha, Residue
17	Manure-Food-Sludge-FOG Blend	HTL/Catalytic Hydro-treating	-	HTL - Diesel	Naphtha, Residue
18	Food-Sludge-FOG	HTL/Catalytic Hydro-treating	-	HTL - Diesel	Naphtha, Residue

LANDFILL GAS FISCHER-TROPSCH SYNTHESIS

Block flow diagram

- Landfill Gas is modelled assuming a composition of 60% CH4 and 40% CO2 by mass

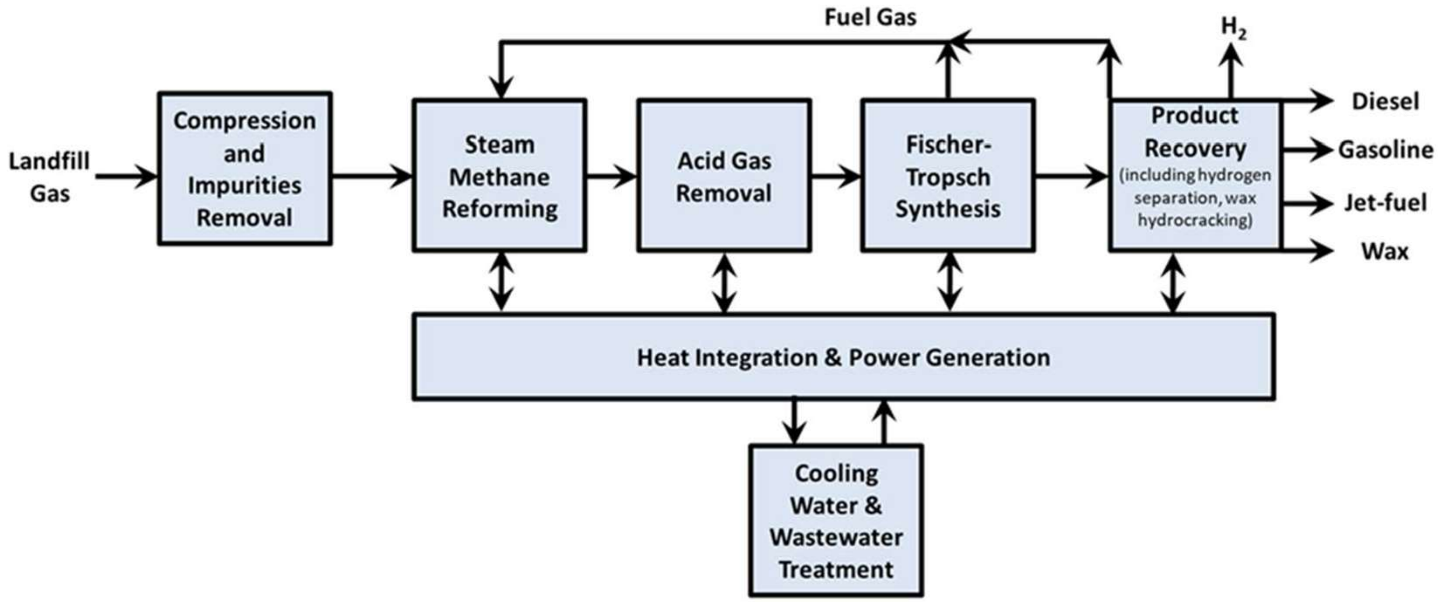


Figure provided by Eric Tan, NREL

CATALYTIC FAST PYROLYSIS (CFP)

Block flow diagram

- Woody biomass is 50/50 blend of clean pine, forest residues
- Projected feedstock rate is 2,000 ton/day

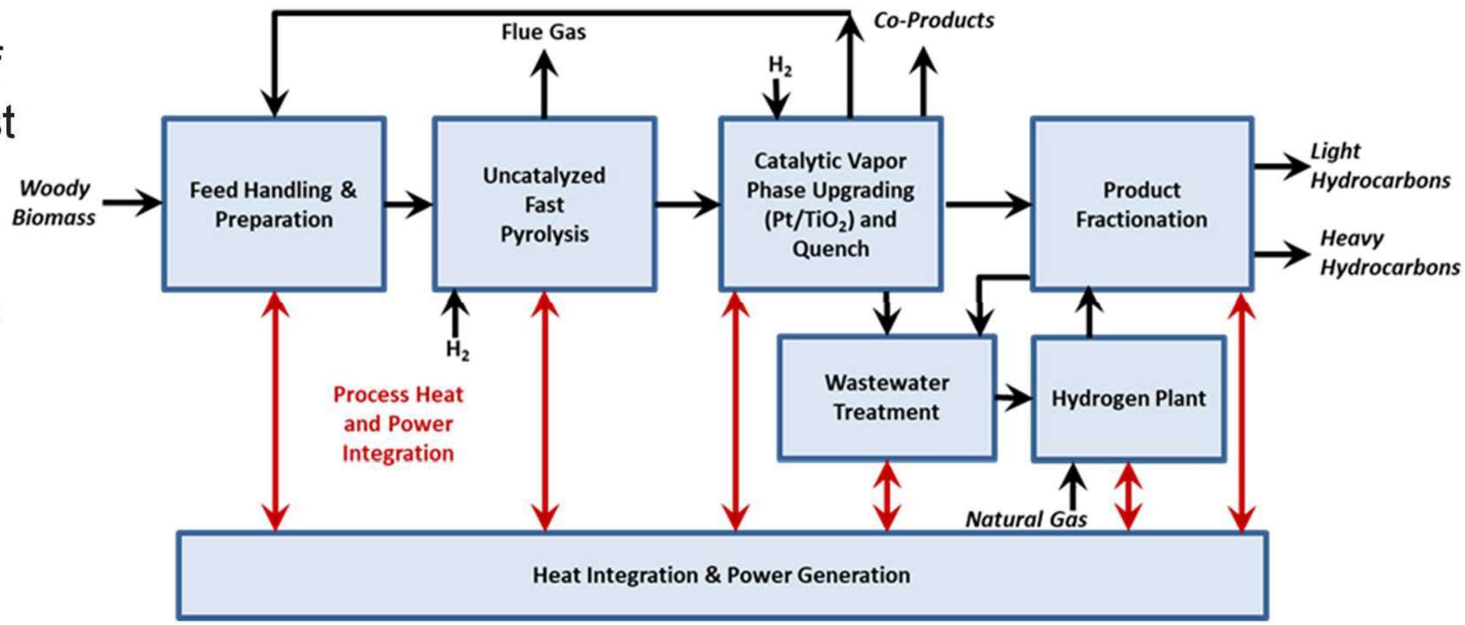


Figure provided by Eric Tan, NREL

HYDROTHERMAL LIQUEFACTION (HTL)

Block flow diagram

- Pathways consider both Biocrude and Diesel end-products
- 1000 Tons-Per-Day Throughput

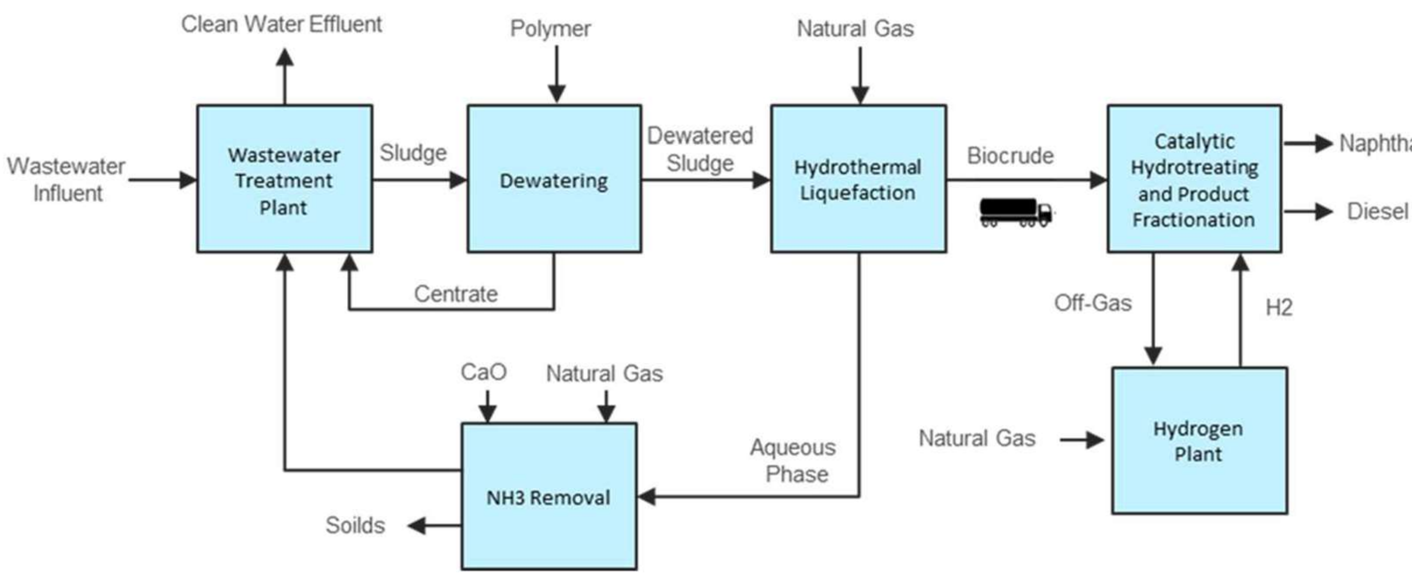
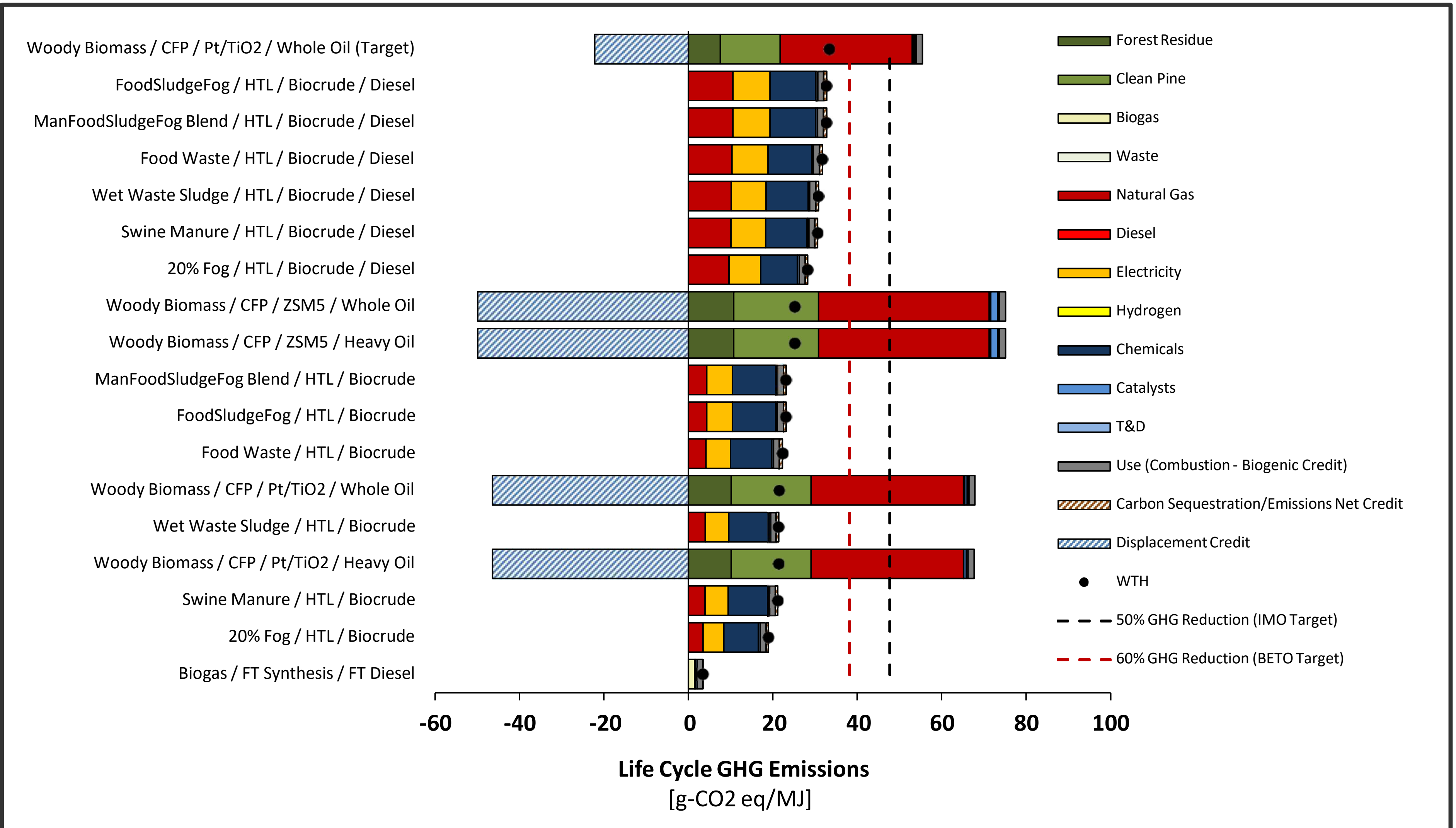
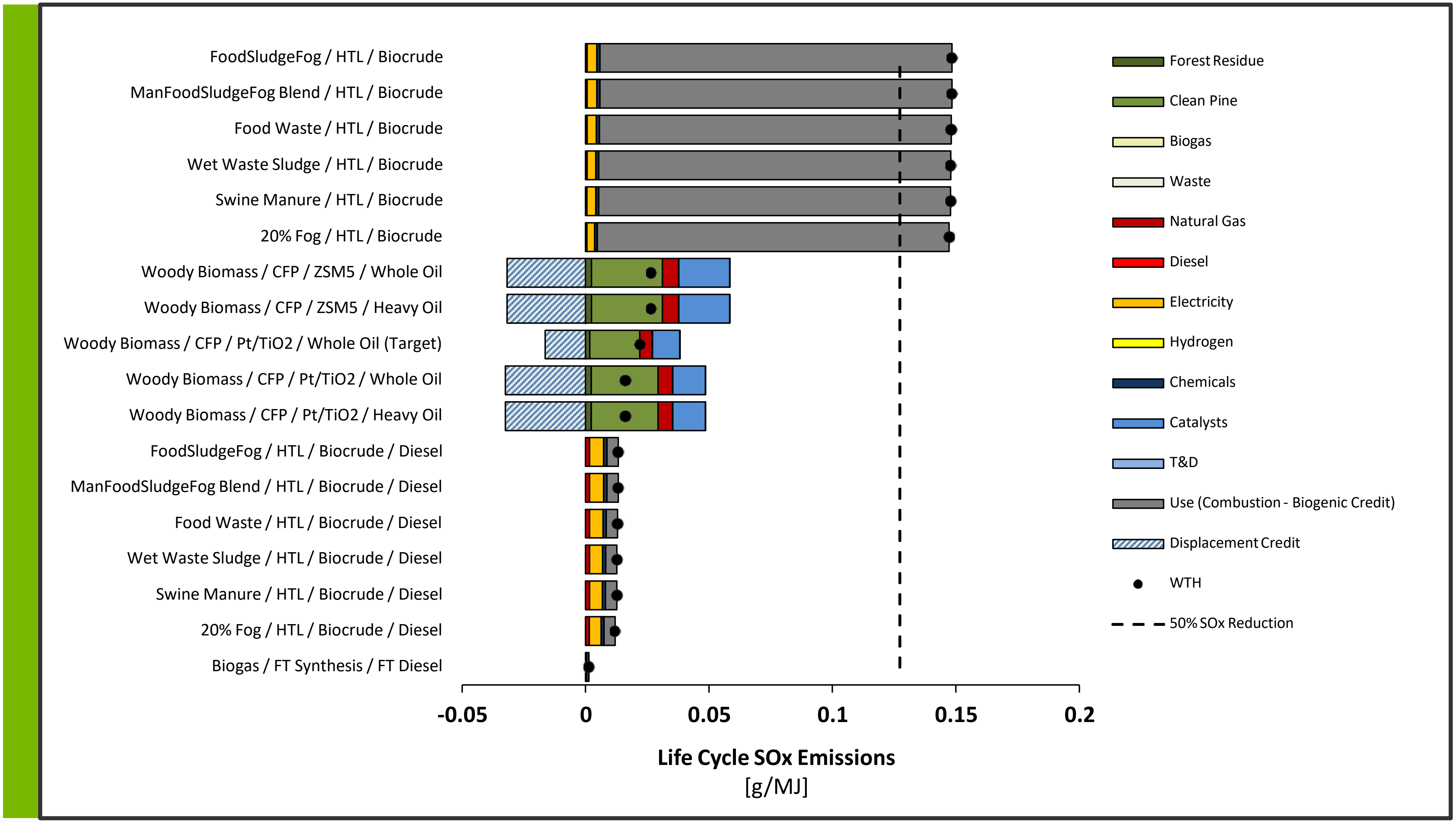


Figure adapted from Cai et al 2020

Cai, Hao, Ou, Longwen, Wang, Michael, Tan, Eric, Davis, Ryan, Dutta, Abhijit, Tao, Ling, Hartley, Damon, Roni, Mohammad, Thompson, David N., Snowden-Swan, Lesley, and Zhu, Yunhua. *Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Ex Situ Catalytic Fast Pyrolysis, Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2019 State-of-Technology Cases*. United States: N. p., 2020. Web. doi:10.2172/1616516.


Woody Biomass / CFP / Pt/TiO2 / Whole Oil (Target)
FoodSludgeFog / HTL / Biocrude / Diesel
ManFoodSludgeFog Blend / HTL / Biocrude / Diesel
Food Waste / HTL / Biocrude / Diesel
Wet Waste Sludge / HTL / Biocrude / Diesel
Swine Manure / HTL / Biocrude / Diesel
20% Fog / HTL / Biocrude / Diesel
Woody Biomass / CFP / ZSM5 / Whole Oil
Woody Biomass / CFP / ZSM5 / Heavy Oil
ManFoodSludgeFog Blend / HTL / Biocrude
FoodSludgeFog / HTL / Biocrude
Food Waste / HTL / Biocrude
Woody Biomass / CFP / Pt/TiO2 / Whole Oil
Wet Waste Sludge / HTL / Biocrude
Woody Biomass / CFP / Pt/TiO2 / Heavy Oil
Swine Manure / HTL / Biocrude
20% Fog / HTL / Biocrude
Biogas / FT Synthesis / FT Diesel
-60
-40
-20
0
20
40
60
80
100
Life Cycle GHG Emissions
[g-CO2 eq/MJ]
Forest Residue
Clean Pine
Biogas
Waste
Natural Gas
Diesel
Electricity
Hydrogen
Chemicals
Catalysts
T&D
Use (Combustion - Biogenic Credit)
Carbon Sequestration/Emissions Net Credit
Displacement Credit
WTH
50% GHG Reduction (IMO Target)
60% GHG Reduction (BETO Target)



FoodSludgeFog / HTL / Biocrude
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Swine Manure / HTL / Biocrude
20% Fog / HTL / Biocrude
Woody Biomass / CFP / ZSM5 / Whole Oil
Woody Biomass / CFP / ZSM5 / Heavy Oil
Woody Biomass / CFP / Pt/TiO2 / Whole Oil (Target)
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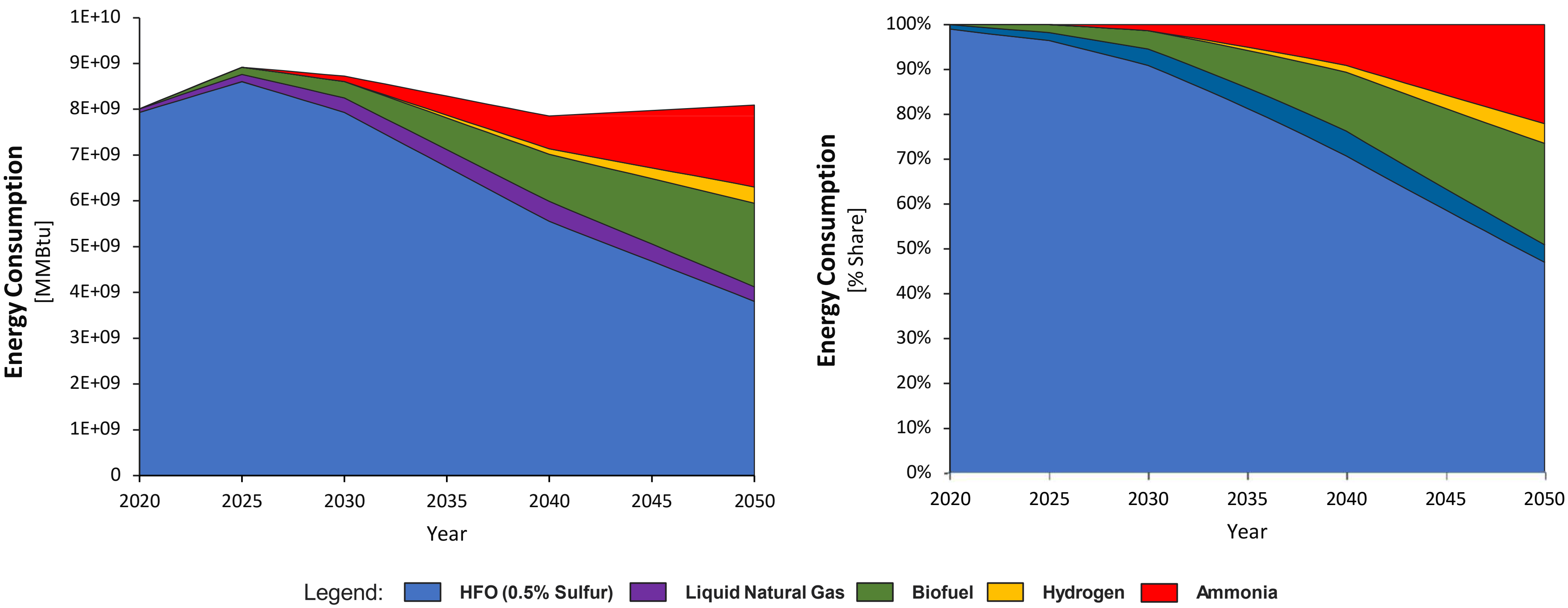
Food Waste / HTL / Biocrude / Diesel
Wet Waste Sludge / HTL / Biocrude / Diesel
Swine Manure / HTL / Biocrude / Diesel
20% Fog / HTL / Biocrude / Diesel
Biogas / FT Synthesis / FT Diesel
-0.05
0
0.05
0.1
0.15
0.2
Life Cycle SOx Emissions
[g/MJ]
Forest Residue
Clean Pine
Biogas
Waste
Natural Gas
Diesel
Electricity
Hydrogen
Chemicals
Catalysts
T&D
Use (Combustion - Biogenic Credit)
Displacement Credit
WTH
50% SOx Reduction

FORECASTED ENVIRONMENTAL IMPACTS OF GLOBAL INTERNATIONAL SHIPPING OVER THE 2020 TO 2050 TIME HORIZON

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

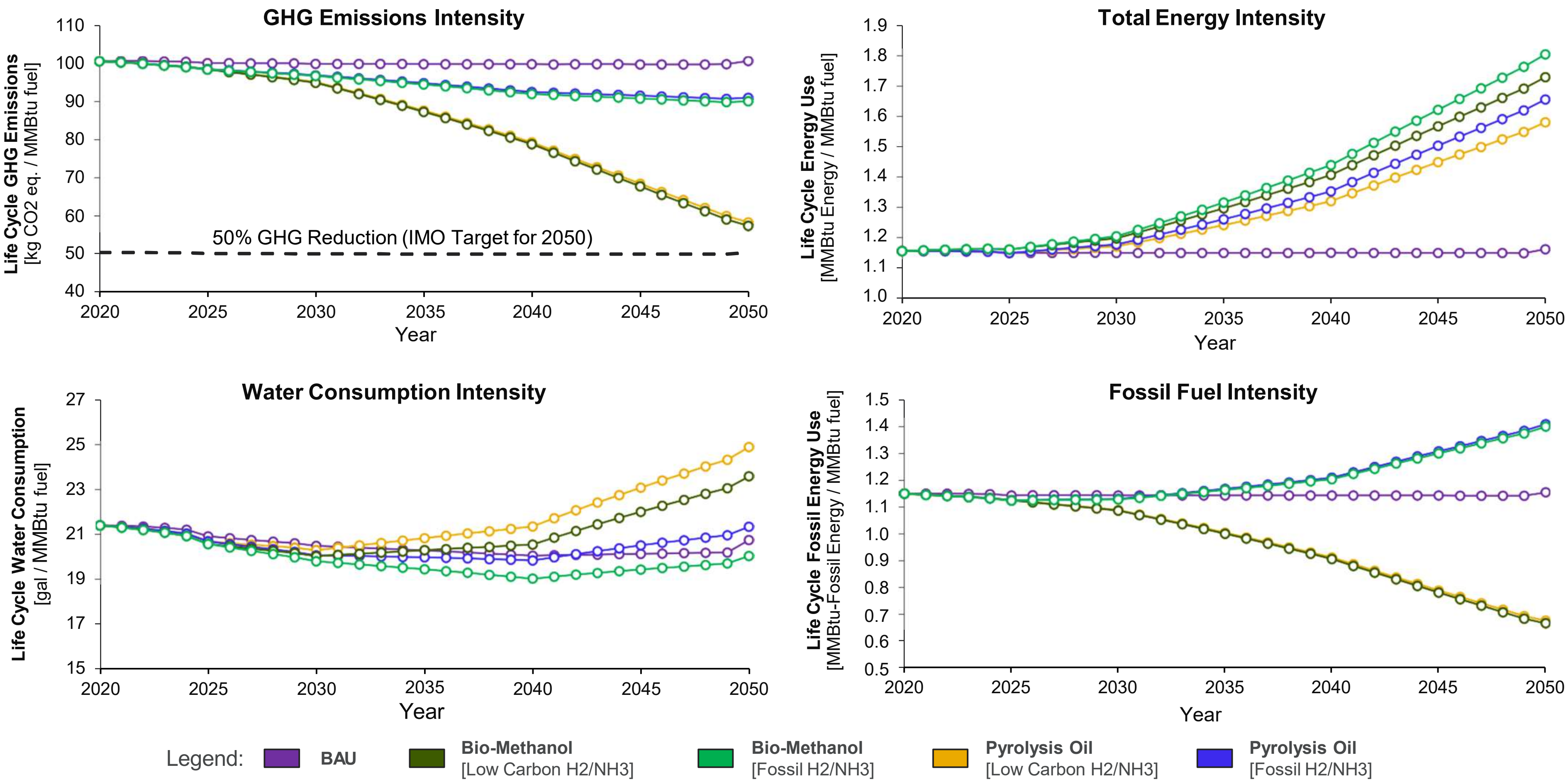


Source: IEA, Global energy consumption and CO2 emissions in international shipping in the Sustainable Development Scenario, 2019-2070, IEA, Paris

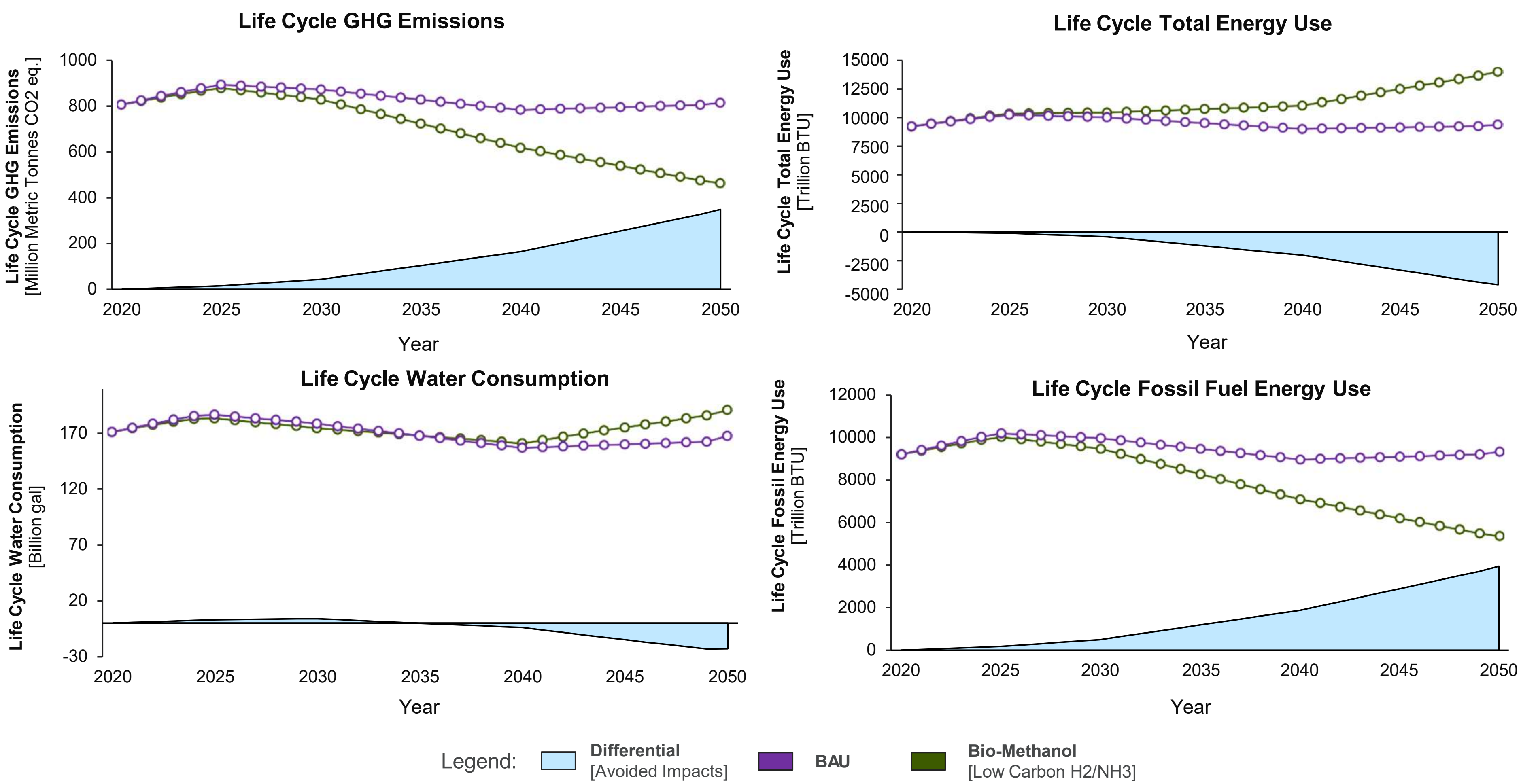
Maritime AGE: Scenario Matrix

Case ID	HFO	LNG	Bio-Methanol	Pyrolysis Oil	Fossil Ammonia	Low Carbon Ammonia	Fossil Hydrogen	Low Carbon Hydrogen
Business As Usual [BAU]	√	√	-	-	-	-	-	-
Bio-Methanol [Low Carbon H2/NH3]	√	√	√	-	-	√	-	√
Bio-Methanol [Fossil H2/NH3]	√	√	√	-	√	-	√	-
Pyrolysis Oil [Low Carbon H2/NH3]	√	√	-	√	-	√	-	√
Pyrolysis Oil [Fossil H2/NH3]	√	√	-	√	√	-	√	-

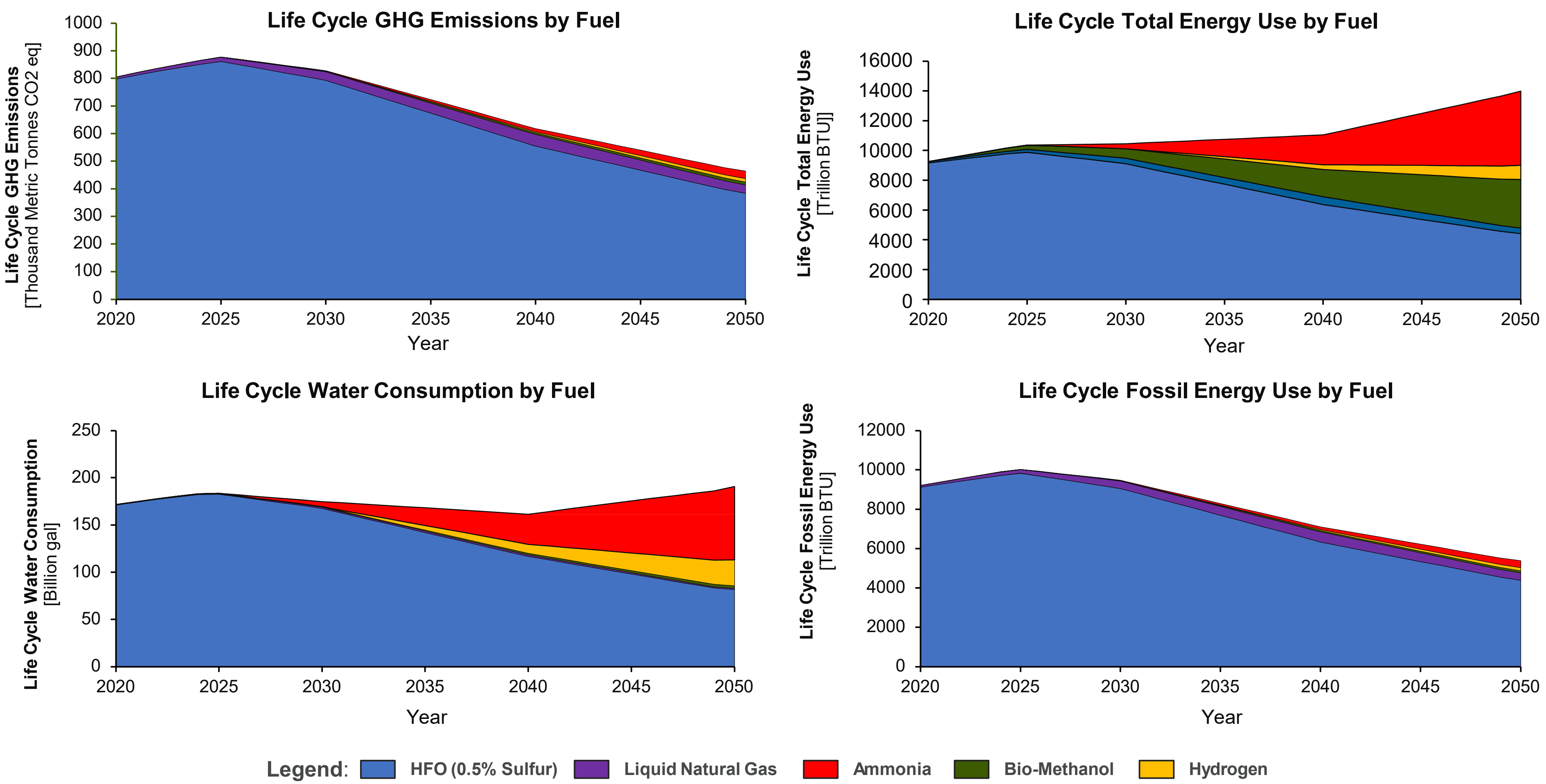
Time-Series Emissions, Energy, and Water Intensity of International Shipping: Comparison of SDS and BAU Cases



Emissions, Energy, and Water Use: Methanol-Low Carbon vs. BAU Case



Methanol [Low Carbon H2/NH3]: Fuel Contribution Analysis



CONCLUSIONS AND TAKEAWAYS

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- Waste-to-fuel biofuel pathways present significant GHG reduction potential with all 18 considered pathways meeting BETO and IMO emissions targets
- SDS with “Low-Carbon” Ammonia and Hydrogen can nearly meet IMO reduction goals by 2050 (42% vs. 50%) but is heavily reliant on fuel supply chains
- Without consideration of fuels’ life-cycles, there is potential for emissions to be shifted from fuel combustion to supply chain (primarily in the cases of Ammonia and Hydrogen)
- Biofuels can play a significant role in decarbonizing marine shipping both as blending fuels and via biomass to liquid fuels, however large emissions reductions come with increased energy demand

FUTURE WORK AND ACKNOWLEDGEMENTS

FUTURE WORK

- For Waste-to-Energy (WtE) systems perform *Consequential LCA* by considering the counterfactual waste management practice and associated avoided emissions and resource consumption
- Analysis resource limitations of biofuel pathways and their potential to constrain sectoral level biofuel adoption
- Synthesis of environmental (LCA), economic (TEA), and technical performance metrics to guide R&D
- Technical recommendations and engagement with maritime stakeholders