DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Marine Alternative Fuel Pricing, Supply, and Demand

April 5, 2023

Data Modeling and Analysis

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NREL Transforming ENERGY

U.S. Department of Transportation Volpe Center

Marine Alternative Fuel Pricing, Supply, and Demand (MPSD): Project Purpose

What are you trying to do?

- Deliver context on marine biofuels for decision makers
- Provide analytical support for strategic facility and supply chain design to meet International Maritime Organization (IMO) standards
- Encourage expansion of domestic bioenergy industry
- Establish standard for regional biofuel scenario exploration through system dynamics and geospatial modeling approaches

Why is it important?

- Establishment of marine bioeconomy decreases emissions.
- Decision makers can better evaluate strategic benefits of low sulfur fuels.
- Decision makers can assess options for meeting IMO goals.

How is it done today and what are the limits?

- National biofuels scenarios are explored through system dynamics modeling.
- Limiting factor is real-world data: advanced biofuel supply chains are not commercial.
- Existing analyses are primarily at aggregate level and historical; there is a gap for exploring regional and scenario-based marine fuel demand.

Approach

Risk Identification and Mitigation Strategies

- Enhance understanding of how very low-sulfur fuel, low-carbon fuel requirements, and promising biofuel processes will affect the marine fuel supply chain
- Explore how these effects interact and impact indicators such as pricing, number of trips, and demand behavior, along with the potential to meet low sulfur and carbon fuel demand with biofuel supply chains

Risk Identification

- **Modeling Risks:** overfitting of the model to the data, excessive complexity, and lack of institutional knowledge
- **Project Risks:** scope creep, answering questions appropriate to methodologies
- **Data Risks:** difficulty calibrating the model to regional and scenario-based marine fuel demand, since existing marine fuel burn analyses primarily at aggregate level and historical

Mitigation Strategies

- **Modeling:** Ensure modeling represents best available information and is vetted by domain experts and mathematics is appropriate to represent the system
- **Methodologies and Uses:** Clearly state appropriate uses for modeling and seek out other methodologies/models when needed
- **Collaboration and Data:** Establish collaboration with meaningful information exchange to acquire best available data

Specific analysis teams meet weekly. BETO briefing is held quarterly.

MPSD Project Team

Emily Newes
15+ years of experience in economics, energy data, modeling, and analysis

Erika Sudderth
Ph.D. in biology with 15+ years of experience in data analysis, climate science, sustainability, and resilience

Kevin Zhang
Data scientist with experience in operations research, software development, and transportation modeling

Nicholas Carlson
Chemical engineer and applied mathematician with 5+ years of refinery operations and modeling experience

Kelcie Kraft
M.S. in climate science with background in organics, carbon accounting, and data analysis

Kristin Lewis
Ph.D. in biology with 15+ years of experience in alternative fuels, climate change resilience, and transportation analysis

Swaroop Atnoorkar
Trained in energy systems engineering, with a focus on transportation systems and environmental analysis

Michael Talmadge
20+ years of experience in process modeling and engineering for fuels and chemicals production with 10+ years in petroleum industry

Daniel Flynn
Ph.D. environmental scientist with 15+ years of experience in data science and sustainability

Modeling Suite

What is the fuel burn around a specific port? How does it relate to fuel demand?

Fuel Burn Model

Could biofuels be economically blended into marine fuels?

Refinery Optimization Model

What is the optimal routing of feedstocks and fuels, and what is the optimal biorefinery location?

Freight/Fuel Transportation Optimization Tool (FTOT)

Aligning assumptions

Regional BioEconomy Model (RBEM)

Can potential demand for ultra-low-sulfur fuels at Port of Seattle be met with locally derived bio-based fuels?

What is the potential impact of policy and investment on each marine biofuel conversion strategy?

Approach

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Automatic Information System (AIS)-Based Fuel Burn Model

1. Ship Location (AIS)

MSSIS[a] data (e.g., latitude/longitude and speed over ground)

- Data validation
- Trip identification
- Trace interpolation

2. Vessel Characteristics

- Match specific vessel for design speed, installed power, and engine type
- Create lookup tables by vessel type

3. Ship-Specific Power Propulsion Model

- Calculate main engine power demand as function of speed and vessel characteristics

$$Power_{transient} = \frac{0.8 \times Power_{installed} \times Speed_{transient}{}^{3}}{(Speed_{design} + 0.5)^{3}}$$

- Calculate auxiliary engine power demand

assessing alternative ship-specific power models available in public EPA Ship Power and Emissions Model packages

4. Power to Fuel Burn Ratio and Emissions Calculations

- Match engine-specific fuel oil consumption (SFOC)
- Calculate fuel burn based on vessel and fuel type
- Use emissions factors for emission calculations

5. Spatiotemporal Aggregation

- Perform temporal and spatial aggregation by grid cell and overall

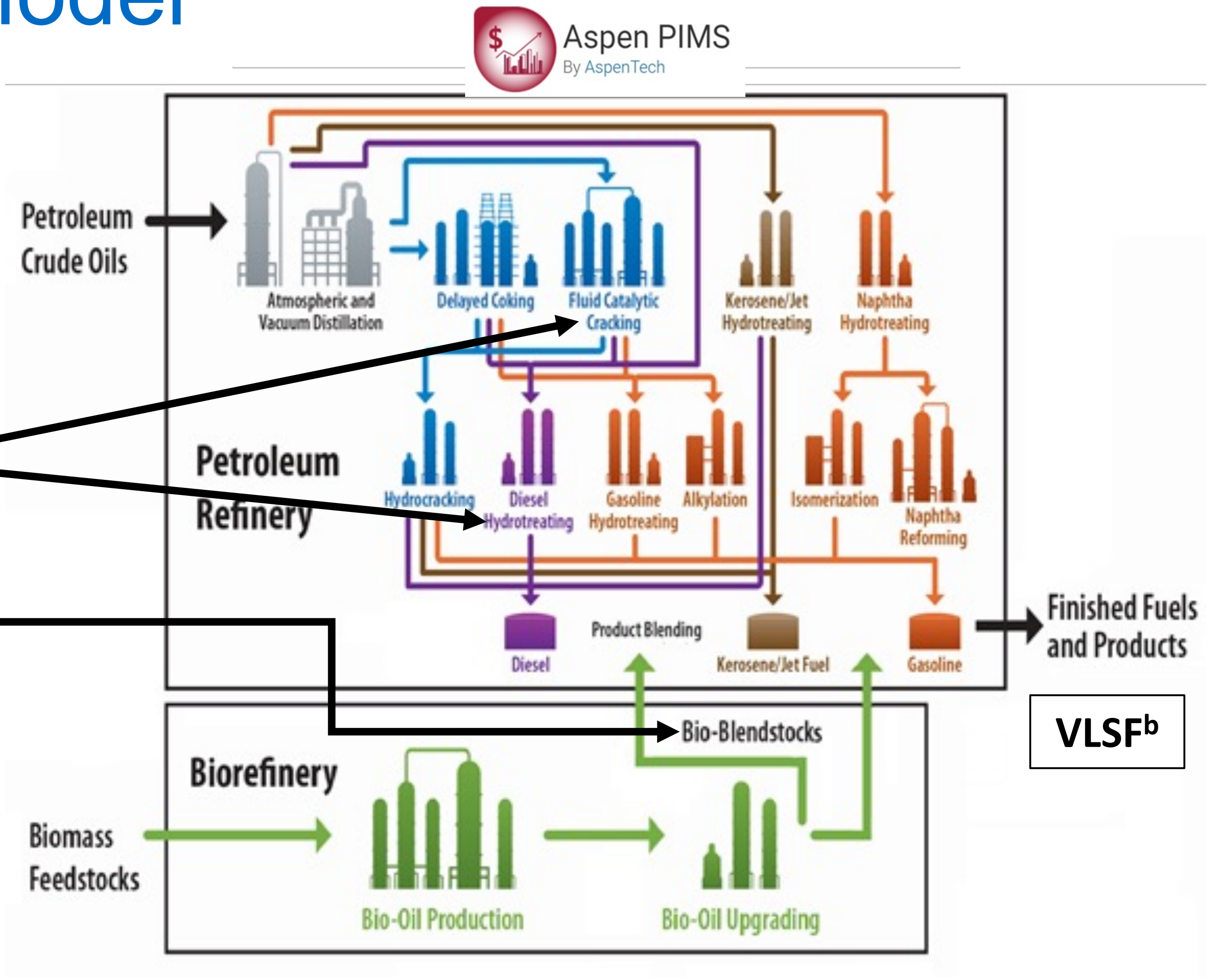
[a] Maritime Safety and Security Information System

Approach

Refinery Optimization Model

Blendstock[a]	Oxygen (Wt%)	Density (kg/m3)	LHV (MJ/kg)	MFSP ($/Gal)	Biofuel Type	
FP 1	50.7	1.22	16.2	1.51	Intermediate	Drop-in
FP 2	33.8	1.07	24.6	2.46		
CFP 1	19.5	0.95	30.2	3.02		
CFP 2	17.7	0.93	30.8	3.05		
CFP 3	14.2	0.90	31.9	3.13		
CFP 4	4.0	0.82	34.6	3.28		
HEFA Diesel	—	0.78	44.0	3.71		
FT-Diesel	—	0.80	43.2	3.20		
FAME/ Biodiesel	—	0.89	37.5	2.99		

[a] FP = fast pyrolysis oil, CFP = catalytic fast pyrolysis oil, HEFA = hydroprocessed esters and fatty acids, FT = Fischer-Tropsch, FAME = fatty acid methyl esters



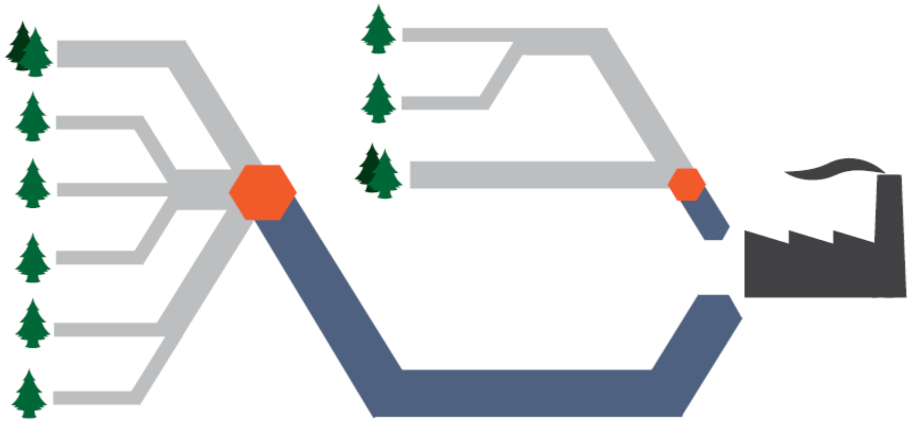
[b] VLSF = very low sulfur fuel

What is FTOT?

volpeusdot.github.io/FTOT-Public

Freight/Fuel Transportation Optimization Tool

- Flexible scenario testing tool
- Created by Volpe Center in support of Federal Aviation Administration, U.S. Department of Energy, and Office of Naval Research (2012–present)



Optimizing flow and routing of raw materials (e.g., wood) to processing locations and then to the destination to fulfill demand
Graphic by Dane Camenzind, Washington State University (used with permission)

FTOT Features

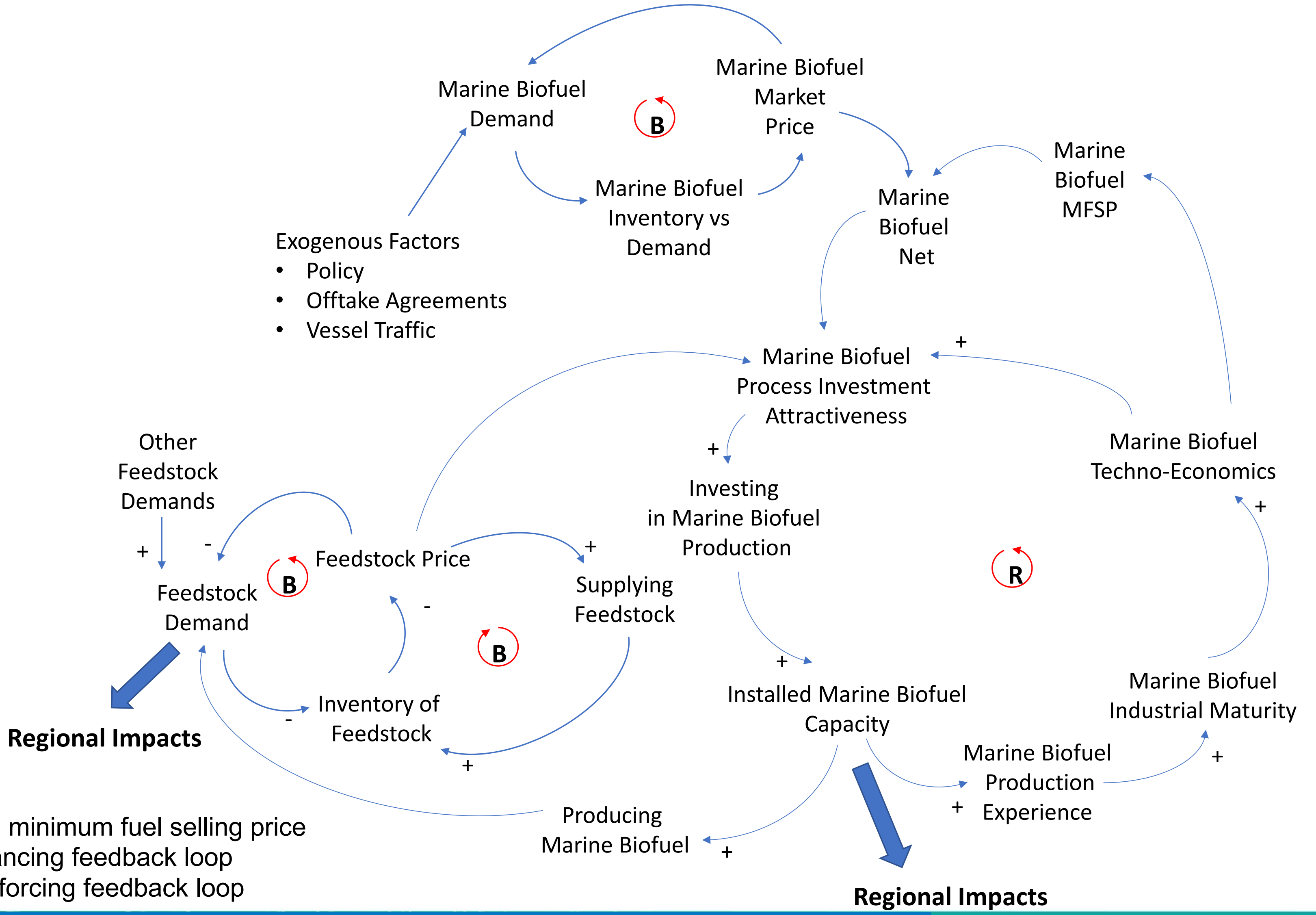
- Optimizes supply chain routing and flows to maximize delivery and minimize cost
- Uses a geographic information system module (GIS), *arcpy*, and Python network and optimization modules, *NetworkX* and *PuLP*
- Multimodal network of road, rail, waterway, pipeline, and multimodal facilities

FTOT Outputs (aggregate and by mode/commodity)

- Facility utilization (%)
- Transportation cost ($)
- CO_2 and other pollutant emissions (grams)
- Vehicle miles traveled (vehicle-miles)
- Fuel burn (gallons)

Approach

System Dynamics: Regional BioEconomy Model (RBEM)



MFSP = minimum fuel selling price
B = balancing feedback loop
R = reinforcing feedback loop

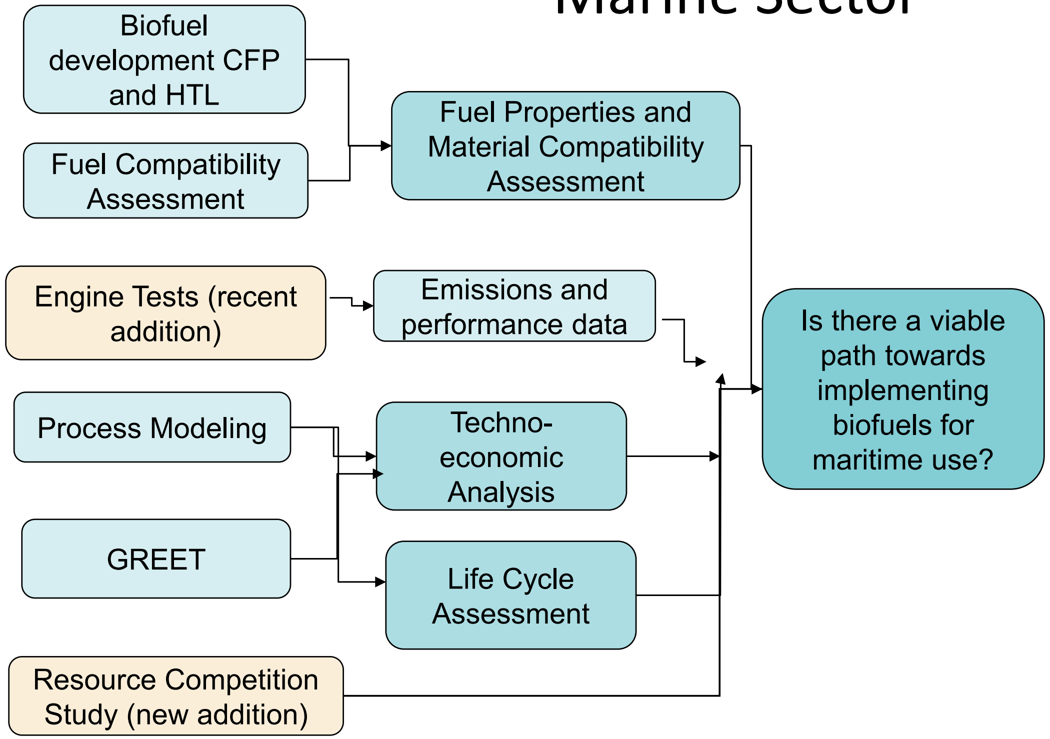
RBEM Analysis

- Can be used to assess scenarios of the marine biofuel industry and associated markets
- Produces insights into the development potential of marine biofuel within a defined region (Which conditions are necessary and sufficient for investment?)
- Creates a better understanding of the implications of existing and potential policies and incentives

Coordination and Outreach

- We coordinate with the BETO Systems Development and Integration marine consortium and benefit from their External Advisory Board.
- RBEM was reviewed by a technical advisory committee in 2022.
- We collaborated with the MSSIS team to leverage processed ship movement data.
- We coordinated with EPA to develop fuel burn model functions consistent with port performance guidance.
- We conducted outreach to U.S. Department of Transportation Maritime Administration to collect feedback on approach.

SDI Project: Advancing the Development of Biofuels for the Marine Sector



Summary of Accomplishments (FY21–23)

- Enhance understanding of how very low-sulfur fuel, low-carbon fuel requirements, and promising biofuel processes will affect the marine fuel supply chain
- Explore how these effects interact and impact indicators such as pricing, number of trips, and demand behavior, along with the potential to meet low sulfur and carbon fuel demand with biofuel supply chains.

- Initial prototype fuel burn model was completed.
  - Validation with fuel burn data from a subset of U.S.-flagged vessels shows overall accuracy within 6% for full-year, global data.
- Refinery modeling shows uniquely viable results when compared to similar refinery analyses.
  - A strong secondary market was identified for biodiesel (direct blending into marine fuels).
  - A good pilot case is to start coprocessing inexpensive pyrolysis oil (py-oils) in a fluid catalytic cracker (FCC) at commercially validated levels (~10 wt% of feed).
- Alternative maritime fuel supply chain analysis has begun, using FTOT and RBEM.
  - Preliminary results show 100% of projected 2040 marine fuel demand at the ports of Seattle and Tacoma could be satisfied with regionally produced biofuels, largely derived from wood residues.

All Milestones Completed on Time

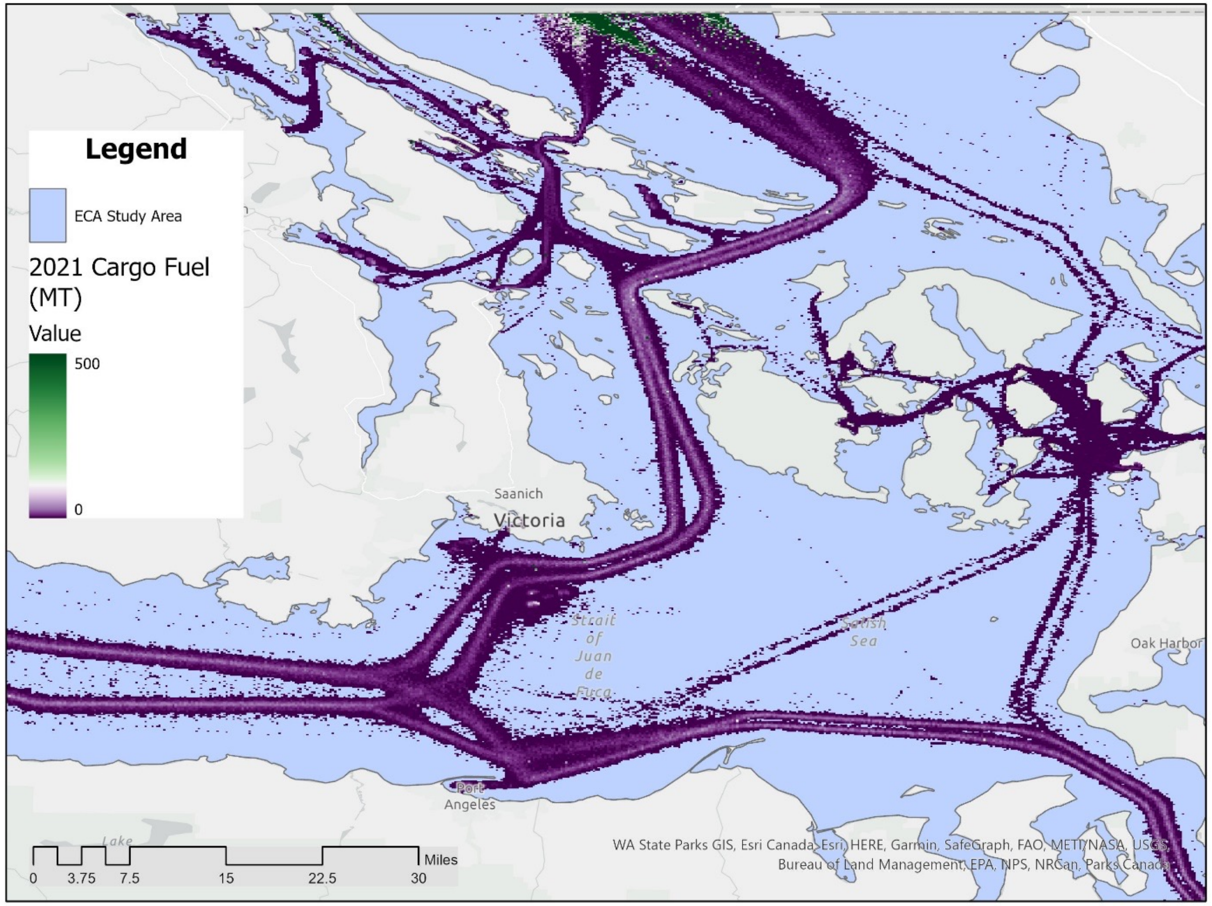
Milestone	End Date
Deliver and draft literature review that includes existing models' trajectories for global fuel prices, given scenarios around regional refinery constraints and demands.	Q2 FY21
Brief BETO on progress related to refinery operations with varying levels of VLSF and determine major ports where MSSIS data will be collected.	Q3 FY21
In coordination with BETO and U.S. Department of Transportation, determine major ports where MSSIS data will be collected; identify source/cost of ship characteristics; and brief BETO on fuel burn methodology to provide the opportunity for direction.	Q4 FY21
Provide the opportunity for direction from BETO by briefing them on the FTOT model and the proposed joint Volpe/NREL analysis; this analysis will result in an FY23 publication.	Q1 FY22

Milestone	End Date
Deliver documentation on method for using MSSIS data to calculate vessel fuel burn in the emission control area, with preliminary analysis for the first port	Q2 FY22
Deliver memo on model specifications for adapting RBEM to perform analyses on marine biofuels. This will enable FTOT/RBEM analysis to be completed in FY23.	Q3 FY22
Deliver draft journal article on refinery analysis highlighting results of (1) overall operational and economic impact of IMO on refineries and (2) valuations analysis for marine bio-blendstocks and bio-intermediates	Q4 FY22
Deliver draft journal article related to ports using RBEM and FTOT analysis. The article will analyze potential marine biofuel supply to a selected port region, focusing on feedstock and fuel transportation logistics, siting, policy, and financial constraints.	Q4 FY23

Go/no go on whether project analysis has provided value to BETO and other marine stakeholders in better understanding the dynamics of marine fuel pricing, supply, and demand in helping evaluate the value proposition for BETO engagement

- Fuel Burn Model provides better understanding of fuel burn and emissions.
- Refinery benefits modeling shows there could be financial incentive for refiners to integrate biofuels into VLSF oil.

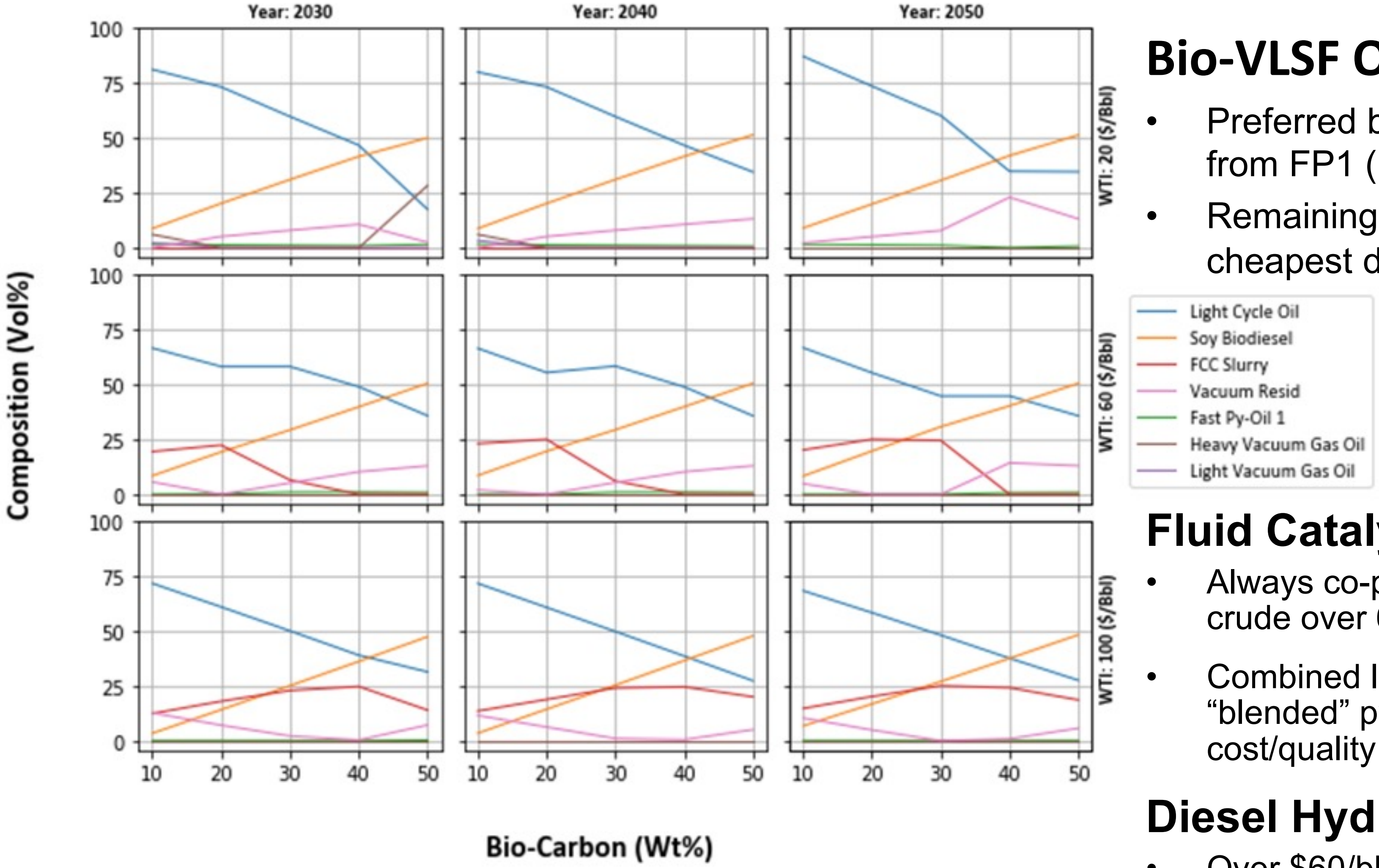
Fuel Burn Model Calculates Potential Fuel Demand.



Snapshot of estimated fuel burn for full-year 2021 cargo vessels in the Port of Seattle area. Cargo vessels account for 60% of the fuel demand in this area.

- For the full-year 2021, the Port of Seattle study area includes:
  - 10,395 vessels
  - 40 million AIS records
- Cargo vessels estimated to consume 5.8 million MT of fuel oil in 2021
- Current prototype model is within 6% of IMO reported overall full-year fuel burn for the validation dataset for 2019
- Vessel-level full-year validation varies by ship type
- Validation assumes IMO-reported values are accurate

Biodiesel and bio-oils could be economically blended



PRELIMINARY RESULTS - DO NOT DISTRIBUTE, QUOTE, OR CITE

Bio-VLSF Oil

- Preferred blendstock is co-processed light cycle oil from FP1 (lowest price py-oil).
- Remaining bio-carbon quota is filled with biodiesel (i.e., cheapest drop-in).

Biodiesel is blended to meet carbon goal.

Pyrolysis oil is blended at $60/bbl.

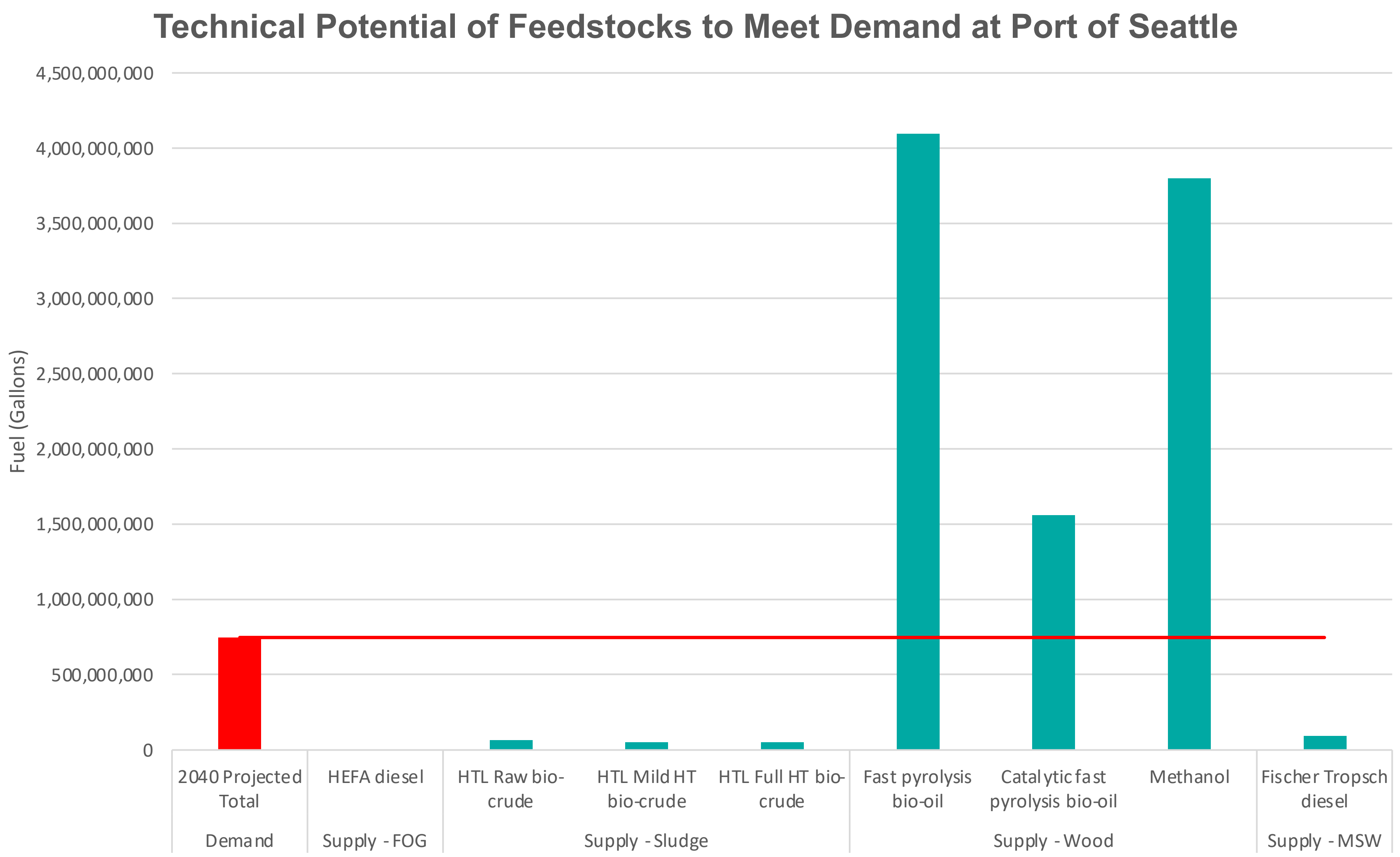
Fluid Catalytic Cracker

- Always co-processed at maximum level (10 wt%) with crude over 60 $/bbl
- Combined lowest and highest quality py-oils to form a “blended” py-oil with (~40 wt% oxygen) and better cost/quality trade-off

Diesel Hydrotreater

- Over $60/bbl, always co-hydrotreated 2 wt% of lowest quality fast py-oil

Feedstock availability varies in meeting fuel demand in 2040.



Bars show available fuel from regional feedstock sources, incorporating techno-economic analysis conversion.

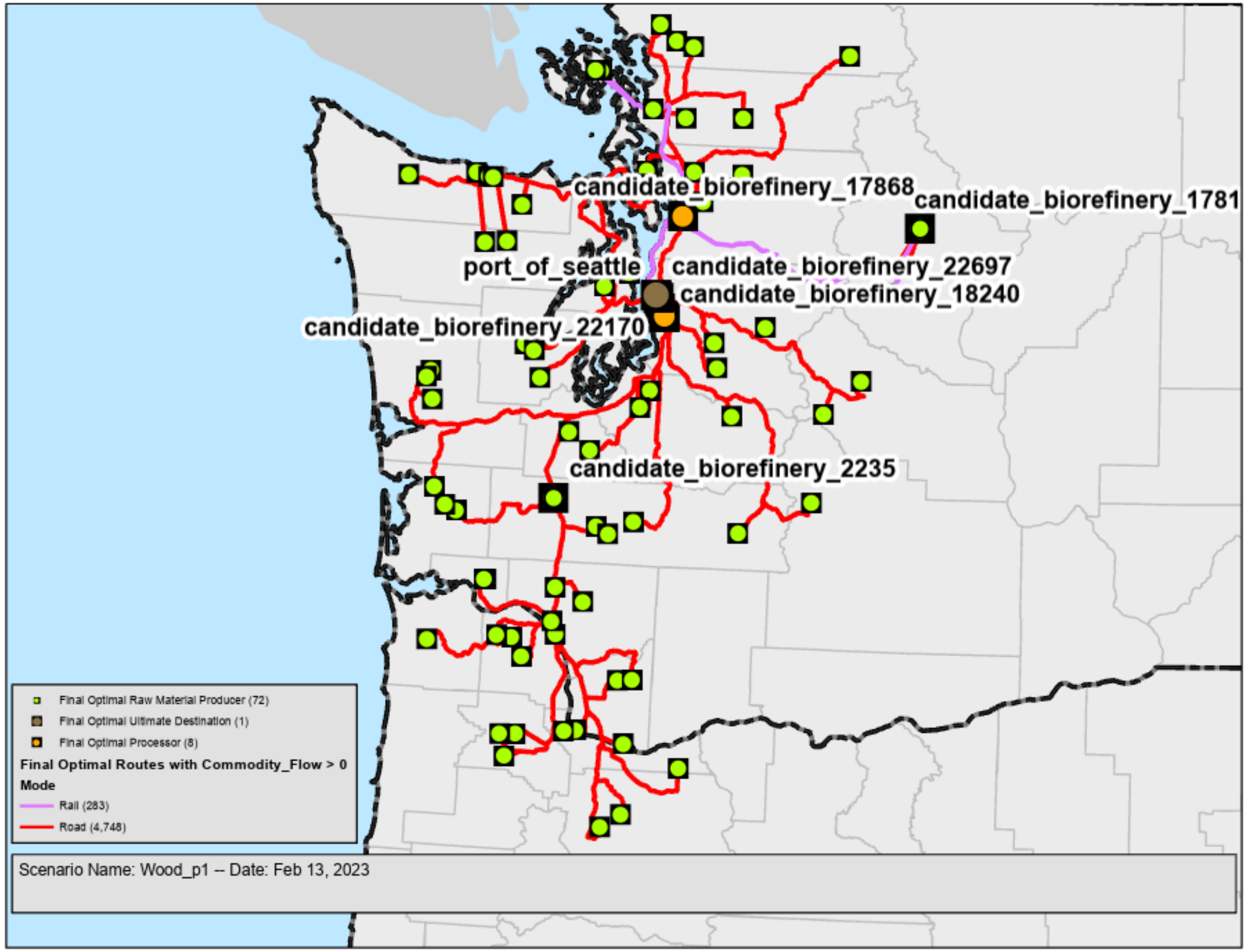
Projected Annual Fuel Demand (2040):
747,650,921 gallons

Optimal Routing and Cost to Supply Port

Wood Residues—Fast Pyrolysis Processing: Optimal Solution

- **Feedstock:** roundwood, logging residues, and mill fiber
- Eight new biorefineries recommended in optimal solution
- **Demand:** bio-oil supplied via rail and road

Key Metrics		
	Wood Residues	**Pyrolysis Bio-Oil**
Quantity	4.74 million mt	748 million gal
Utilization	18%	100%
Vehicle Miles Traveled	16,121,292	2,145,101
Vehicle Loads	188,854	84,120
Fuel Burn (gal)	2,161,322	272,310
CO_2 Emissions (kg)	16.5 million	3.5 million



PRELIMINARY RESULTS - DO NOT DISTRIBUTE, QUOTE, OR CITE

Decarbonization of Marine Needs Alternative Fuels

Greenhouse gas emissions are increasing.

Bioeconomy can decrease emissions, especially in aviation and marine, but markets are likely to be driven by policy.

A survey of maritime industry leaders[a] listed barriers to decarbonization; first was regulatory uncertainty, and second was availability of zero-carbon fuels.

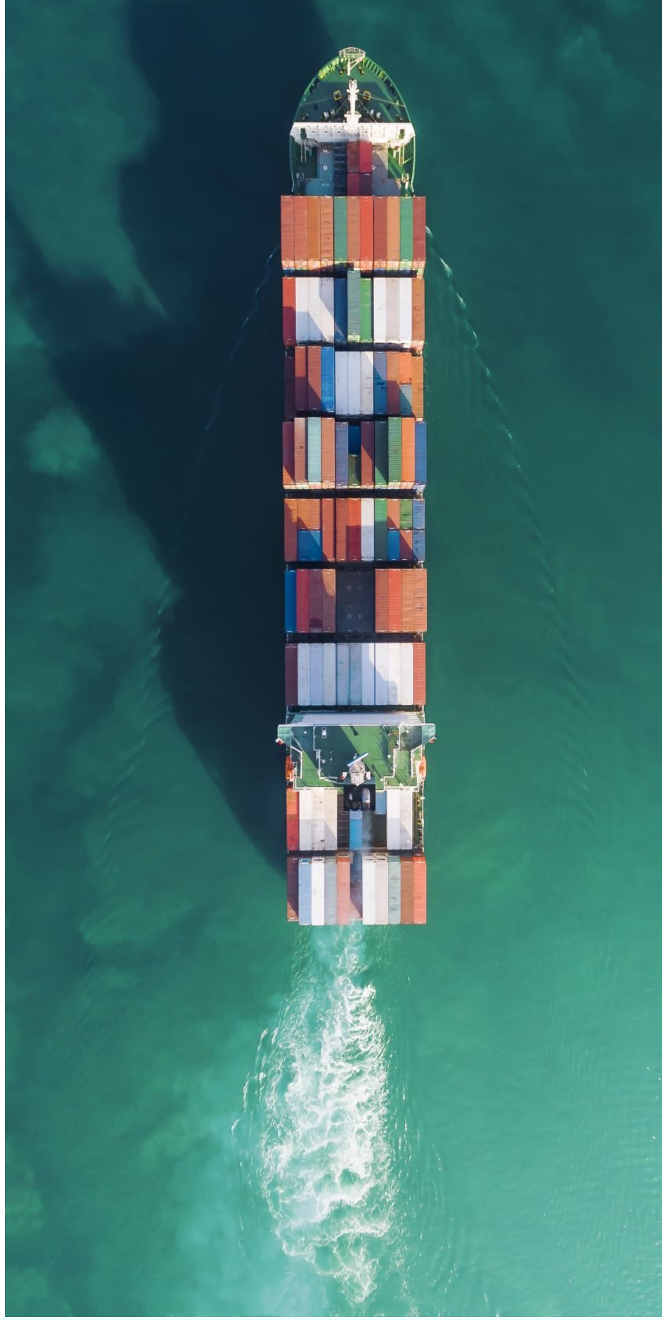
This project helps look at the potential availability of biofuels at ports, given infrastructure, feedstock availability, and specific policy mechanisms.

[a] Global Maritime Forum, MARSH, and IUMI. 2020. *Global Maritime Issues Monitor 2020*. https://www.marsh.com/uk/industries/marine/insights/global-maritime-issues-monitor-2020.html

Impact

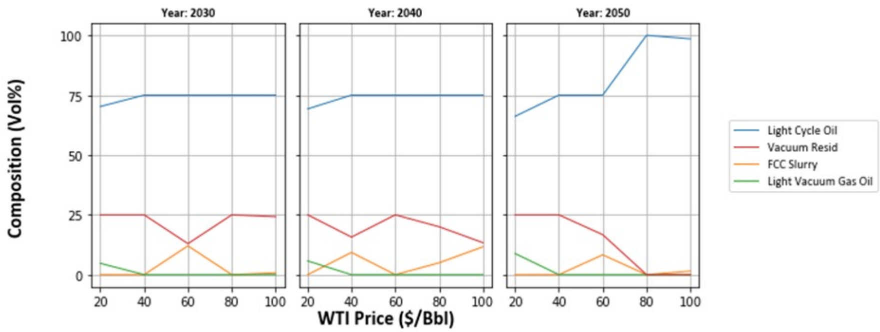
Analysis Will Aid Green Corridors

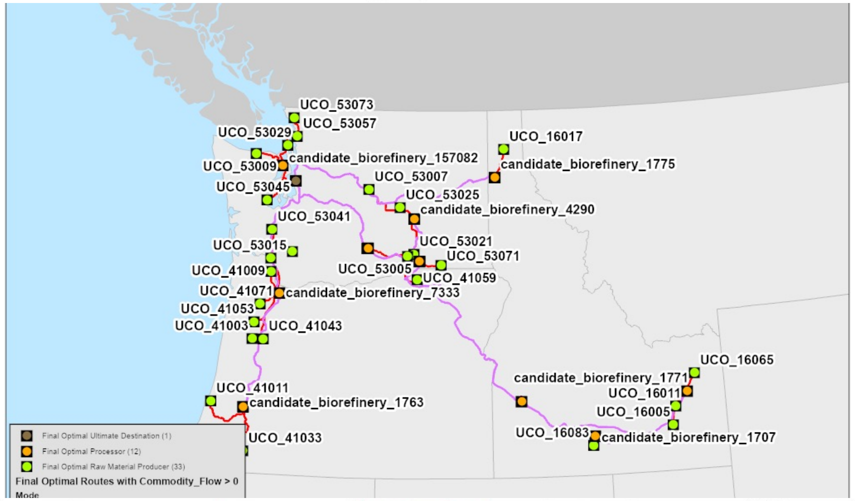
- We are working with Maersk Mc-Kinney Moller Center on feasibility study of a green corridor from Seattle to South Korea.
- We will inform them on possible biomass and biofuel routes near Seattle.
- This work could provide a pathway for analyzing future green corridors.

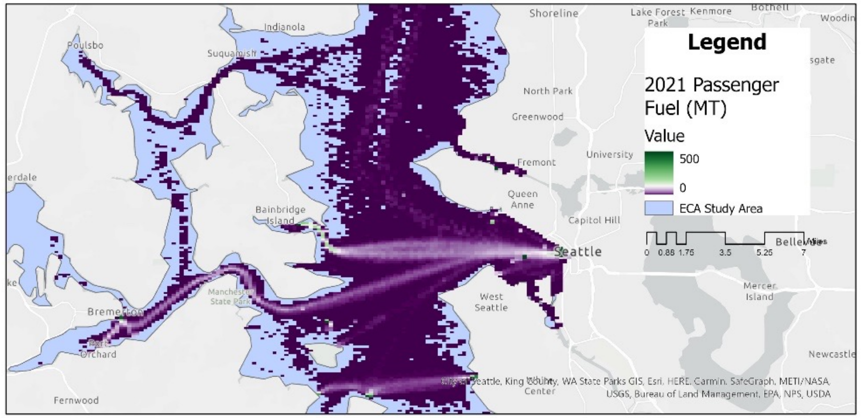


First of their Kind Analyses

- No existing studies on coprocessing biofuels with marine fuel
- Existing fuel burn analyses at aggregate level and historical—this project explores regional and scenario-based marine fuel demand
- No existing domestic region-specific supply chain analysis for marine biofuels
- Studies to be published and to inform industry







This project supports BETO goals.

The Alternative Marine Fuel Pricing, Supply, and Demand (MPSD) project supports the **transportation strategy pillars** by:

- **BETO Focus Area of Marine:** MPSD evaluates the possibility for marine biofuel to compete in the market.
- **Energy Justice:** MPSD models locations for biorefineries and the feedstock source, which can then be used for local impacts analysis, including environmental justice metrics.

Summary

Value Proposition

- Deliver context for decision makers
- Provide analytical support for strategic facility and supply chain design to meet IMO standards
- Encourage expansion of bioenergy industry
- Establish standard for regional biofuel scenario exploration through system dynamics and geospatial modeling approaches

Key Accomplishments

- An initial prototype fuel burn model has been completed.
  - Validation with annual fuel burn data from a subset of U.S.-flagged vessels shows overall accuracy within 6%.
- Refinery modeling shows uniquely viable results when compared to similar refinery analyses.
  - A strong secondary market has been identified for biodiesel (i.e., direct blending into marine fuels).
  - A good pilot case is to start coprocessing inexpensive py-oils in an FCC at commercially validated levels (~10 wt% of feed).
- Alternative maritime fuel supply chain analysis has begun, using FTOT and RBEM.
  - Preliminary results show 100% of projected 2040 marine fuel demand at the Port of Seattle and the Port of Tacoma could be satisfied with regionally produced biofuels.

Quad Chart Overview

Timeline

- **Start:** January (NREL); June (Volpe) 2021
- **End:** January (NREL); June (Volpe) 2024

	FY22 Costed	Total Award
DOE Funding	$250,000	$750,000 ($450,000 to NREL and $300,000 to Volpe)

Funding Mechanism

FY2021 Lab Call: Data, Modeling, and Analysis

Project Goals

- Enhance understanding of how VLSF, low-carbon fuel requirements, and promising biofuel processes will affect the marine fuel supply chain
- Explore how these perturbations interact and impact indicators such as pricing, number of trips, and demand behavior, along with the potential to meet low sulfur and carbon fuel demand with biofuel supply chains
- Merge innovative thinking in the area of marine fuels within research centers of DOE (NREL) and the U.S. Department of Transportation (Volpe)

End-of-Project Milestone

Deliver draft journal article related to ports using RBEM and FTOT analysis: The article will analyze potential marine biofuel supply to the selected port region, focusing on feedstock and fuel transportation logistics, production facility siting, policy implementation, and financial constraints.

Additional Slides

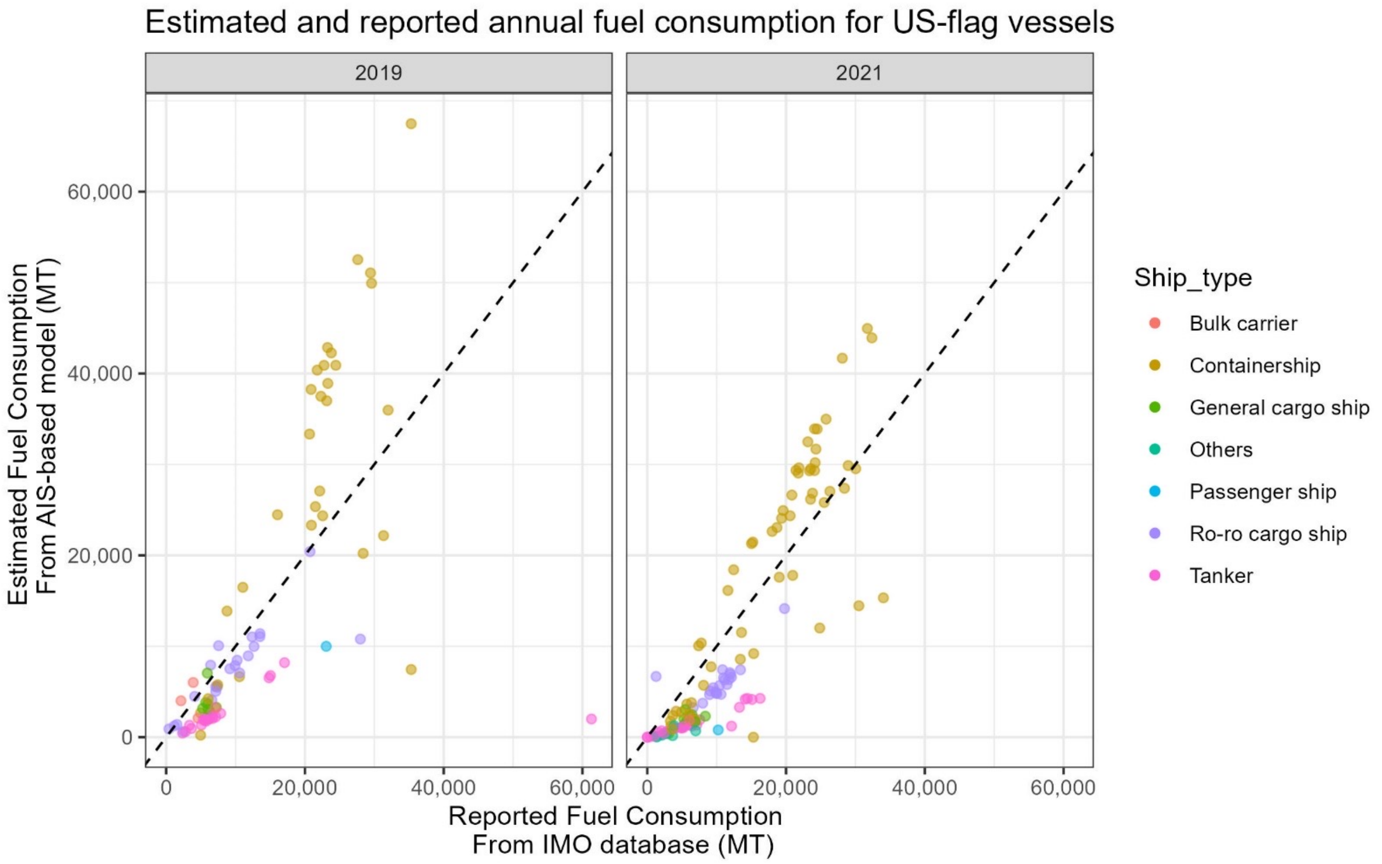
Acronyms

AIS	automatic identification system
BETO	Bioenergy Technologies Office
CFP	catalytic fast pyrolysis oil
EPA	U.S. Environmental Protection Agency
FAME	fatty acid methyl ester
FCC	fluid catalytic cracker
FT	Fischer-Tropsch
FTOT	Freight and Fuel Transportation Optimization Tool
FOG	fats, oils, and greases
FP	fast pyrolysis oil
HEFA	hyrdoprocessed esters and fatty acids
IMO	International Maritime Organization
IUMI	International Union of Marine Insurance
LHV	lower heating value
MFSP	minimum fuel selling price
MPSD	Alternative Marine Fuel Pricing, Supply, and Demand
MSSIS	Maritime Safety and Security Information System
NREL	National Renewable Energy Laboratory
Py-oil	pyrolysis oil
RBEM	Regional BioEconomy Model
SDI	Systems Development and Integration
SFOC	specific fuel oil consumption
VLSF	very low sulfur fuel
Volpe	Volpe National Transportation Systems Center

Publications, Patents, Presentations, Awards, and Commercialization

- Carlson, Nicholas, Michael Talmadge, Emily Newes, and Robert McCormick. "A Refinery Perspective on Decarbonizing with Marine Biofuels." Forthcoming.
- Atnoorkar, Swaroop, Kelcie Kraft, Kristin Lewis, Emily Newes, and Kevin Zhang. "Meeting Maritime Fuel Demand with Regional Alternative Fuels: A Case Study of the Port of Seattle." Forthcoming.

Validation of Fuel Burn Model



Relationships by ship type between estimated fuel burn from the Volpe AIS-based model and reported fuel burn from the IMO GISIS database for all available US-flag carriers.

- Validation with global, full-year data for 83 vessels in 2019 and 126 vessels in 2021
  - Data from 12 million AIS pings, covering 15 million nautical miles of travel
- Initial prototype model within 6% of IMO reported overall full-year fuel burn for validation dataset for 2019
- Mean absolute error for vessel-level full-year validation is 50%
- References:
  - Jalkanen et al. 2009
    https://doi.org/10.5194/acp-9-9209-2009
  - Johansson et al. 2017
    https://doi.org/10.1016/j.atmosenv.2017.08.042

Future Work

- Expand scope and detail of prototype fuel burn model
  - Include auxiliary engine model and improve trip identification
  - Expand analysis to additional ports and develop scenario testing functions
- Refinery modeling could be expanded to have a broader sensitivity study of key metrics.
- Continue alternative maritime fuel supply chain analysis using FTOT and RBEM
  - Harmonize FTOT and RBEM models to align transportation (FTOT) and economic (RBEM) components
  - Add emissions optimization to FTOT optimization approach