National Laboratory of the Rockies

Marine Biofuels Supply Potential at Select Global Seaports

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Preface

The maritime sector is undergoing a significant energy transition as operators, ports, and policymakers explore a range of fuels and technologies to improve energy security and reliability. The U.S. Department of Energy (DOE) has articulated an all-of-the-above approach to energy — one that supports the development and deployment of diverse domestic energy sources to strengthen energy security.

Within maritime transportation, this approach recognizes that no single fuel pathway will meet the full range of operational needs across vessel types, trade routes, and port infrastructure. Biofuels represent one option with the potential to support greater domestic fuel production and diversify the fuel supply.

This report was produced by the National Laboratory of the Rockies (NLR) with direction from DOE's Alternative Fuels and Feedstocks Technology Office. It is intended to assist strategic decision-making by ports, operators, fuel producers, and policymakers by providing a fact base on the near-term production potential, cost, and sourcing of marine biofuels, and identifying actions that could support their near-term availability. We welcome inquiries from stakeholders interested in the work.

Acknowledgments

We would like to thank Rohemir Ramirez Ballagas and Evelyne Williams (Formerly of U.S. Department of State), Reed Brown (U.S. Department of State), Ashley Books (Office of International Affairs, U.S. Department of Energy), and Joshua Messner (Alternative Fuels and Feedstocks Office, U.S. Department of Energy) for their guidance and support. We also received support and review from Anthony Sorbera (Contractor to Alternative Fuels and Feedstocks Office, U.S. Department of Energy); Abby Martin, Cato Koole, and Aparajit Pandey (RMI); Joe Boyland (Global Maritime Forum); Matt Langholtz (Oak Ridge National Laboratory); Ryan Calkins (Pacific Northwest National Laboratory); Namrata Nadkarni (Intent Communications); Kirk Waltz (American Bureau of Shipping); Rose Arsers (Northwest Seaport Alliance); Nikesha Radhakrishnan (Maritime and Port Authority of Singapore); Eva Hiew Shu Hui (Singapore Maritime Institute); Juan Pablo Pérez Pérez (Port Authority of Algeciras Bay); Beatriz Gonzalez (Panama Canal); Laura Malo Yague and Tanja Grzeskowitz (Port Authority of New York New Jersey); and others from the maritime sector. We obtained helpful reviews from Eric Tan, Jeff Cook, and Dan Bilello (National Laboratory of the Rockies).

List of Acronyms

CFP	catalytic fast pyrolysis
DCFROR	discounted cash flow rate of return
DCO	distillers corn oil
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
EU	European Union
FAO	Food and Agricultural Organization
FOG	fats, oils, and greases
GMF	Global Maritime Forum
GPG	Green Port Guidelines
HBE	renewable fuel units (Netherlands)
HTL	hydrothermal liquefaction
IMO	International Maritime Organization
ISO	International Organization for Standardization
LNG	liquified natural gas
NY/NJ	New York/New Jersey
MAPONYNJ	Maritime Association of the Port of New York and New Jersey
MFSP	minimum fuel selling price
MPA	Maritime and Port Authority of Singapore
MSW	municipal solid waste
Mt	million tonnes
NLR	National Laboratory of the Rockies
RFNBOs	renewable fuels of non-biologic origin
RFS	renewable fuel standards
RINs	renewable identification numbers
TEA	techno-economic analysis
UCO	used cooking oil
VLSFO	very low sulfur fuel oil

Executive Summary

The maritime sector is essential for the transport of goods and people throughout the world. There is growing interest in expanding the use and production of alternative fuels in the maritime sector amid the global quest for energy resilience. Various fuels are being assessed as candidates to help meet this quest. This report provides an analysis of the near-term potential availability and cost of maritime biofuels at various global seaports.

A resource assessment of selected biomass feedstocks was conducted and informed a techno-economic analysis (TEA) of select conversion pathways to evaluate potential biofuel production quantities and costs. Assessments of the production capacity of existing and announced biofuel projects, infrastructure considerations, and existing maritime biofuel policies were also completed. Three case studies of ports are presented in this report.

The main findings of these assessments demonstrate:

- Ports in populous urban areas with high levels of economic and commercial activity have the highest resource production potential of considered biomass types. Select municipal solid waste (MSW) is typically the most prevalent resource, particularly paper and cardboard waste and plastic waste.
- Resources with established markets (e.g., select fats, oils, and greases [FOG] and vegetable oils) generally have higher prices than those treated as wastes. There is a wider variation in resource prices between international ports than between U.S. ports.
- Biodiesel derived from lipids was found to have the lowest cost, and bio-methanol derived from woody biomass and MSW gasification was found to have the largest supply for feedstocks and technologies included in the analysis. Large feedstock collection radii and feedstock supplies show the strongest correlation with low minimum fuel selling prices.
- Biodiesel has the highest existing and announced production capacity within the countries considered, followed by renewable diesel and bio-methanol.
- Diesel substitutes meeting ASTM D975 standards and biodiesel blends require less infrastructure upgrading and thus have lower costs of implementation compared to other biofuels, such as bio-methanol and bio-intermediates.

Two-thirds of countries and unions considered in this report have biofuel-related policies. Most of these policies neglect, but do not explicitly exclude, maritime applications. With the focus on the near-term potential availability and cost of maritime biofuels, this report emphasizes selecting a group of ports with a diversity of size, existing bunkering capacity, and geography. Researchers aimed to select biomass resources for the resource assessment that were abundant and diverse. A diverse set of conversion pathways were evaluated to produce the marine biofuels included in this report. Figure ES-1 shows the total potential biomass resources at each port in the study based on the resource assessment results. A breakdown of the types of biomass resources available is also presented. Resource assessments were conducted within a reasonable transportation distance to the port. Figure ES-2 presents an aggregate supply curve based on TEA results, showing biodiesel as the biofuel with the lowest minimum fuel selling price and bio-methanol as the biofuel with the highest supply. Production facilities were modeled at the port. Competition for biofuels among other sectors was not considered but could result in a smaller quantity of biofuel available for the maritime sector than what is modeled.

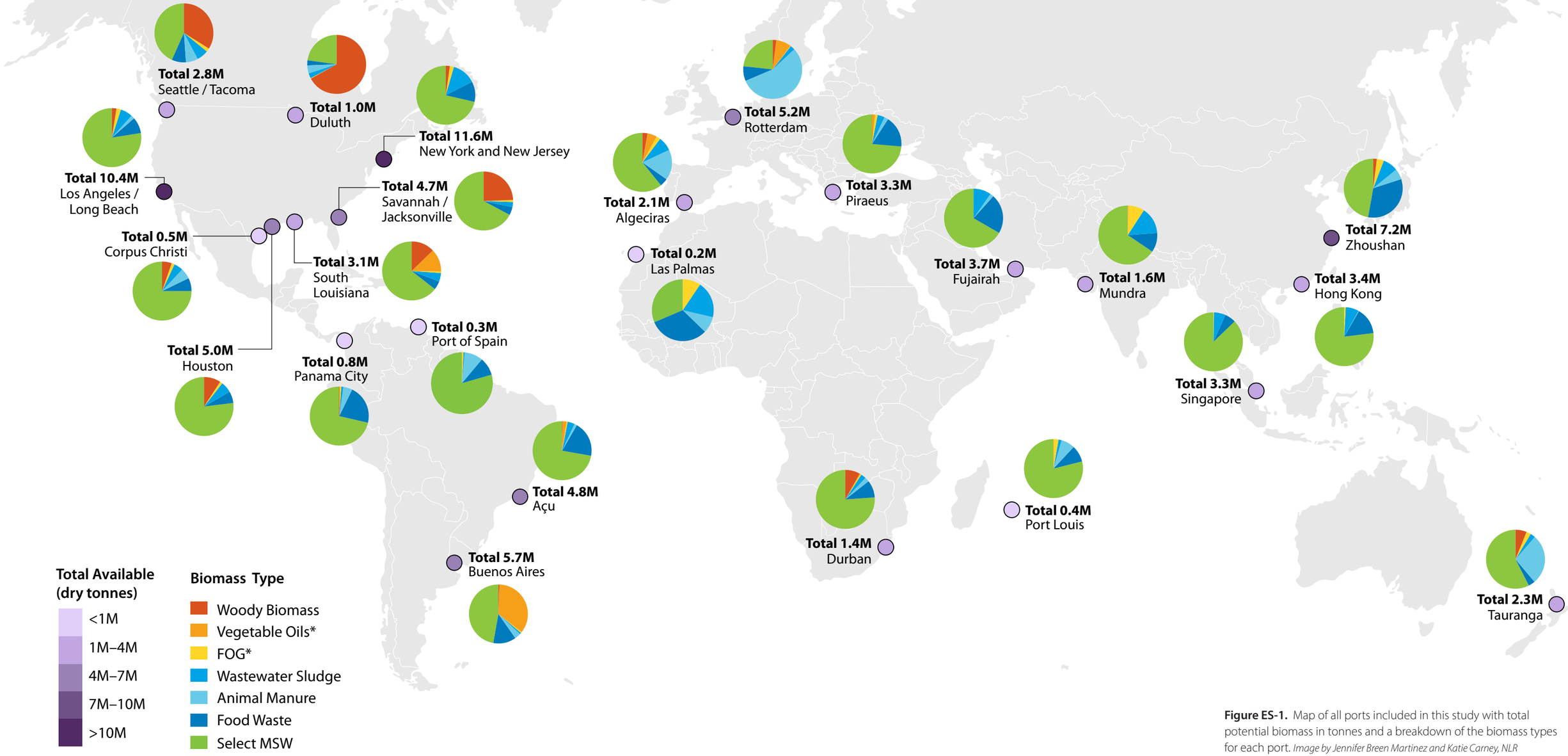


Figure ES-1. Map of all ports included in this study with total potential biomass in tonnes and a breakdown of the biomass types for each port. *Image by Jennifer Breen Martinez and Katie Carney, NLR*

*FOG quantities are presented in wet tonnes.

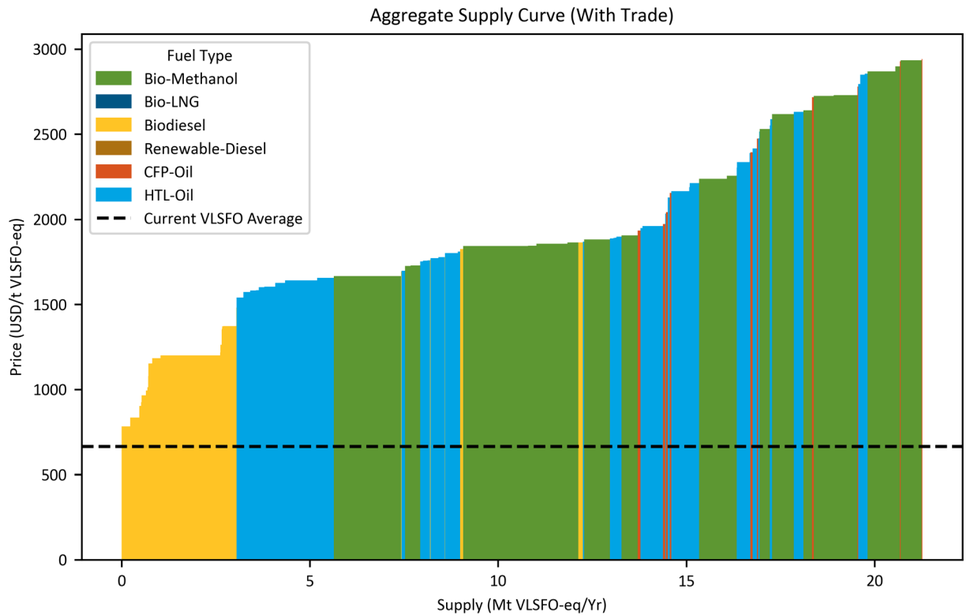


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In addition to providing insights into the potential for local biofuel production at 24 global seaports, three case studies provide an in-depth analysis of port blueprints for various port types —importer, producer, and niche actor. Topics discussed include readiness for and challenges to biofuel bunkering, fuel sourcing, the potential for increasing biofuel demand, and considerations for future development. These case studies could provide information for ports in similar positions. Further research could include analysis of different feedstocks and conversion pathways, blending requirements, trade routes, and ship engine compatibility.

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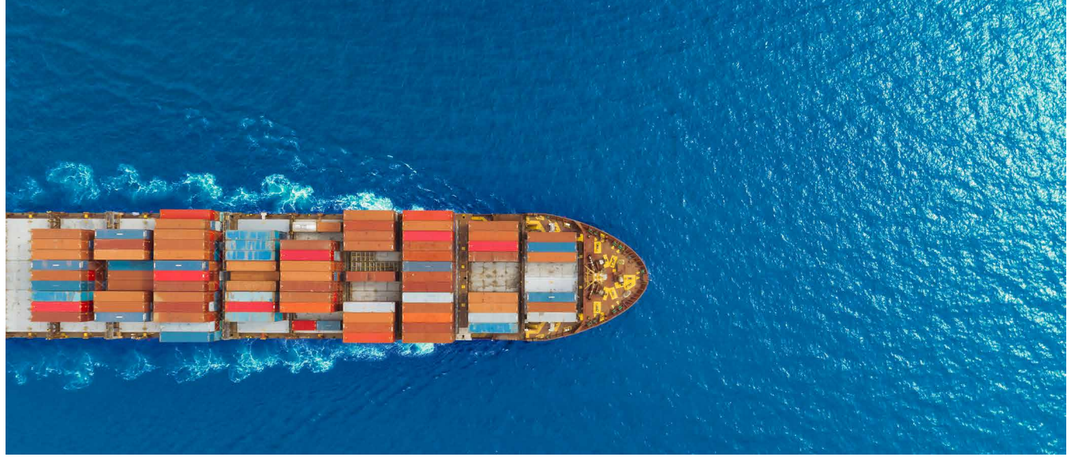


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1. Introduction

Maritime transportation plays a vital role in the global economy, accounting for more than 80% of global trade by volume (United Nations Conference on Trade and Development [UNCTD] 2024). In 2023, maritime transport represented approximately 9% of global transport energy use, and global maritime fuel consumption was roughly 211 million tonnes, with less than 14 million tonnes coming from alternative fuels — 13 million of which was liquified natural gas (LNG) (IMO, n.d.-a). As global trade continues to expand — with cargo volumes growing at an average of 2.75% annually from 2010 to 2024 — energy demand from maritime shipping is expected to rise accordingly (UNCTD 2025). Meeting this growing demand will require an all-of-the-above approach to maritime energy — drawing on a diverse portfolio of fuels and technologies to ensure reliability, security, and affordability of supply. Existing and emerging regulatory frameworks, including International Maritime Organization (IMO) 2030 goals and the European Union's (EU) Fuel EU Maritime regulation, are expected to drive adoption of alternative marine fuels across the industry (IMO 2023; European Commission, n.d.-a). Biofuels are among the alternative fuel options well positioned to contribute to this diversified energy mix, offering a near-term pathway that leverages existing vessel technology and established supply chains.

Recent studies suggest the market penetration of marine biofuels could increase significantly in the coming years, and key marine stakeholders expect to supply 7%–30% of their marine fuel demand with biofuels by 2050 (Simonsen et al. 2021; Tan, Harris, et al. 2021). Multiple studies note biofuels are a viable alternative to conventional marine fuels (Tan et al. 2021; Kass et al. 2018; Mukherjee, Bruijnincx, and Junginger 2020; Gartland and Pruyn 2022; Foretich et al. 2021). In particular, drop-in biofuels generally require minor modifications to existing petroleum fuel infrastructure and thus have the potential to be relatively easily integrated into marine fuel supply chains (Foretich et al. 2021). However, feedstock availability, quality, and cost can be major barriers to large-scale biofuel production, especially given competition for limited biomass resources across multiple end-use sectors.

This report highlights the near-term potential availability, cost, and infrastructure requirements of biofuels around 24 global seaports for use by the maritime sector. It is meant to help form a basis for industry to evaluate their options as they look to adopt alternative fuels.

2. Approach

Twenty-four ports were selected for this study. Selection criteria included geographical diversity, potential biomass availability, existing biofuel policies, and current bunkering volume. Ultimately, a large emphasis was placed on U.S. ports as well as a geographically diverse set of large-scale bunkering ports with a handful of smaller, more niche ports also being considered. Figure 1 maps the location of selected ports, with their estimated bunker volumes, and Table A-1 in Appendix A provides a full list.

The goal of this report is to analyze local biomass resource and fuel production potential at each port to determine how much of each port's demand could potentially be met with biofuels and at what price those fuels could be produced. There is potential for export of these biofuels rather than exclusively local use. However, this report does not examine the import and export potential of the different ports and fuels but instead focuses on resource and fuel pricing at the selected locations.

The use of "port" throughout this report is meant to encompass all entities involved in shipping and refueling at a given location. This includes port authorities, terminal operators, berths, dock owners, and so on. The bunkering volumes discussed within this report refer to all fuel sales that occur at or around a given port location. Bunkering is not necessarily under the direct control nor oversight of port authorities but instead is often carried out by privately operated fuel suppliers at terminals or berths at or near the port.

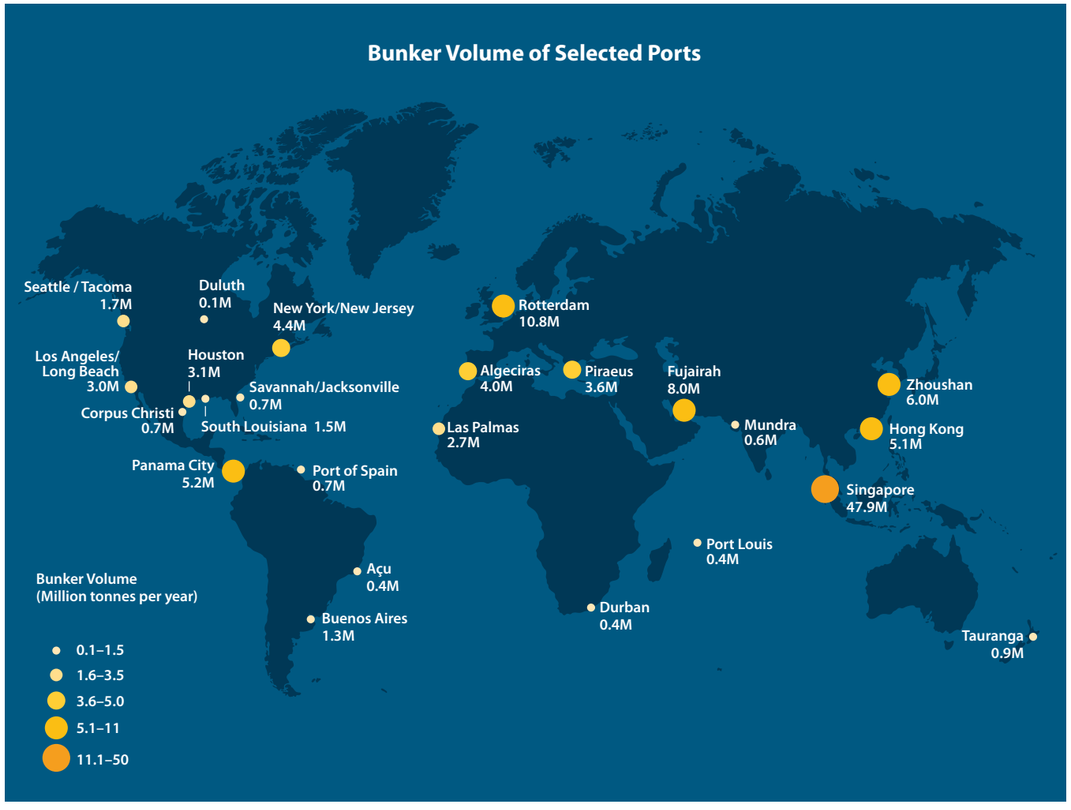


Figure 1. Selected ports and their estimated annual bunker volumes. *Image by Jennifer Breen Martinez and Katie Carney, NLR*



Photo by Werner Slocum, NLR 56116

2.1. Biomass Resources

Biomass resources are abundant and diverse, categorized by their origin and composition. In this study, the following categories of biomass resources were considered:

2.1.1. Lipid-Based Resources

- *Vegetable oils and by-products* considered in this study include rapeseed oil, soybean oil, palm oil, sunflower oil, and distillers corn oil (DCO), a by-product of ethanol production. For international locations, only the percentage of vegetable oils currently allocated to biofuel production in each country was considered, reflecting existing biofuels market and policy dynamics. Since soybean oil is the main vegetable oil produced in the United States, it is also the primary feedstock currently used for biofuels production. Given that a significant portion of soybean oil is used for biofuels in the United States, no restrictions were applied.
- *Fats, oils, and greases (FOG)* include animal fats (e.g., tallow, white grease, and poultry fat) obtained from slaughterhouse and livestock farm waste; rendered used cooking oil (UCO), also known as yellow grease, generated at commercial and industrial cooking operations; and brown grease, or rendered trap/interceptor grease recovered from traps installed in the sewage lines of restaurants/food processing plants and wastewater treatment plants (Milbrandt et al. 2018). For international locations, only UCO was considered because of the lack of verified data on inedible animal fats and brown grease. For U.S. ports, edible animal fats—specifically lard and edible tallow—were excluded from consideration.

2.1.2. Solid Waste Resources

- *Woody biomass* includes logging residues and other removable material left after carrying out forestry operations and site conversions (such as fire reduction thinnings, other forest waste, and small diameter trees), it also includes primary mill residues (materials generated at wood mills when round wood products are processed into primary wood products—e.g., bark, chips, sawdust, and so on), and other forest processing waste, as well as orchard pruning residues. For international ports, only primary mill residues were considered, as the sustainability of forestry operations in other countries could not be verified.
- *Select municipal solid waste (MSW) resources* include paper and cardboard waste, plastic waste, clean urban wood (referred to in this report as MSW wood), textiles and leather, rubber, and yard waste. Food waste is commonly included as part of the MSW stream. However, in this report, it is classified as a wet waste resource because its high moisture content aligns it more closely with other wet waste types, which can undergo similar energy conversion processes.

2.1.3. Wet Waste Resources

This category includes animal manure; wastewater sludge generated during the treatment of sewage; and food waste generated by industrial, institutional, commercial, and residential entities. Animal manure estimates are based on current manure management practices, however changes in those practices may result in greater or lesser quantities being available, particularly for cow manure. Although FOG are often classified as wet waste resources, they were categorized as lipid-based resources in this study because they share similar characteristics and processing methods with vegetable oils.

2.1.4. Excluded Resources

Agricultural (crop) residues were not included in this study because they are not well suited for near-term marine biofuel production. Notably, this study focuses on biofuels in the diesel and marine fuel range, where crop residues are not an ideal primary feedstock. Their low bulk density increases collection and transportation costs, and their complex chemical composition requires additional processing, making large-scale conversion challenging within the near future. Additionally, their high ash content reduces yields in thermochemical pathways such as pyrolysis and gasification. Ongoing R&D efforts continue to address these challenges.

Agricultural residues remain a valuable resource with long-term potential. Advances in pretreatment technologies, logistics, and policy support could improve their feasibility for marine biofuel production in the future. Today, they are already being used in small-scale applications, such as anaerobic digestion and on-site power generation, though these uses fall outside the scope of this analysis.

2.1.5. Biomass Resource Considerations

Because of the highly localized nature of biomass resources, evaluating the impact and viability of individual feedstocks is beyond the scope of this report. There has been extensive research conducted on this topic, and readers are encouraged to review the existing literature and seek out local or regional context to determine feedstock suitability in their area.

Although plastic waste is not inherently biogenic, it was included in the biomass resource assessment because these materials are amenable to biological and chemical conversion processes, enabling their integration into bioeconomy pathways. It should be noted that some regulations may not consider waste plastic-derived fuels as qualifying biofuels.



Photo by Alicen Kandt, NLR 18941



Photo from National Biodiesel Board

2.2. Conversion Pathways

A diverse set of process technologies was evaluated for converting various biomass feedstocks into marine biofuels, guided by prior research and potential market relevance (Tan, Harris, et al. 2021; Li et al. 2022). The technologies assessed represent the capabilities needed to process each major feedstock category into viable marine fuels, considering both technical feasibility and commercial maturity. The technologies and associated feedstocks included in this analysis were identified based on their relevance to urban port settings and potential to produce fuels aligned with the maritime industry. The feedstocks and conversion pathways examined here represent a sample of available options; however, due to the limited scope of this analysis, additional pathways were not considered in this report.

For wet wastes, the following technologies were considered:

- **Anaerobic digestion** followed by gas cleanup and liquefaction to yield bio-liquified natural gas (bio-LNG), which provides a renewable, liquified biogas option compatible with marine applications (Bhatt and Tao 2020; Zou et al. 2022; Jalalzadeh-Azar 2010).
- **Hydrothermal liquefaction (HTL)** followed by:
  - Mild hydroprocessing at 350°C to yield a stabilized, low-oxygen (2% by weight—wt%) HTL bio-oil, referred to throughout the report as HTL-oil (Snowden-Swan et al. 2022; Heracleous, Papadopoulou, and Lappas 2024)
  - More severe hydroprocessing at 400°C followed by fractionation to produce a diesel blendstock with properties similar to conventional marine diesel (Snowden-Swan et al. 2022).

For solid wastes, the following technologies were considered:

- **Methanol synthesis** via biomass gasification to produce a syngas that is synthesized into bio-methanol, a popular marine biofuel candidate (Harris et al. 2021)
- **Catalytic fast pyrolysis (CFP)**, using an ex situ fluidized bed configuration (Dutta et al. 2021), which can produce a stabilized CFP bio-oil serving as:
  - A fuel oil substitute with approximately 16 wt% oxygen content, referred to throughout the report as CFP-oil
  - A hydroprocessing feedstock for diesel oil production.

For lipids, the following technologies were considered:

- **Renewable diesel** via dedicated hydrocracking and isomerization reactions (hydroprocessing) (Xu et al. 2022)
- **Biodiesel** through transesterification using a sodium hydroxide catalyst (Al-Sakkari et al. 2020).

These technologies produce four primary categories of marine biofuels: bio-LNG, bio-methanol, bio-intermediates (HTL-oil and CFP-oil), and diesel substitutes. Figure 2 displays possible feedstock routings to each conversion pathway and corresponding marine biofuel category.

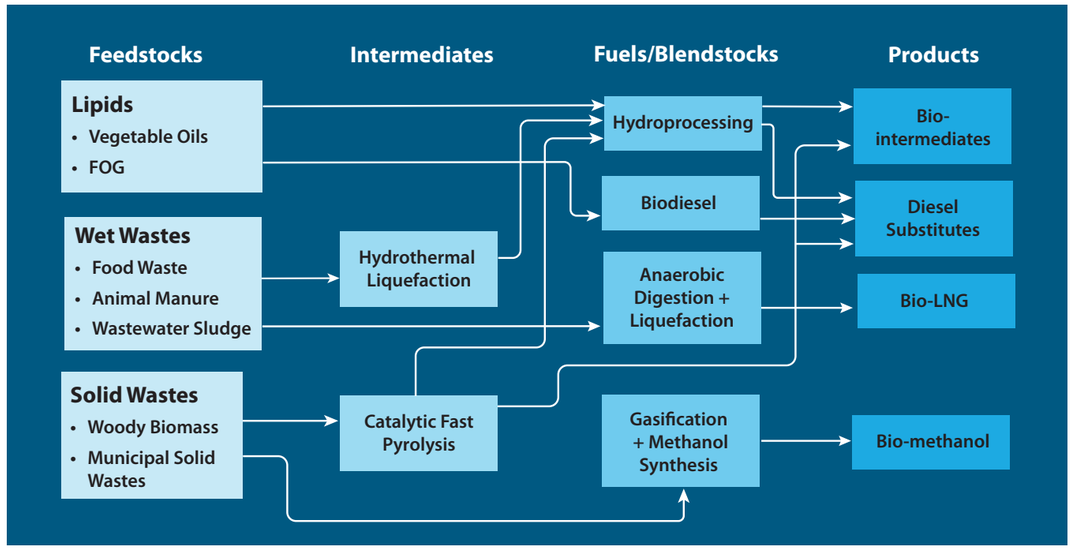


Figure 2. Conversion pathways corresponding to feedstock and marine biofuel product types. *Image by Jennifer Breen Martinez, NLR*

Life cycle assessments corresponding to each port, feedstock, and biofuel combination were not performed because key factors determining impacts, including feedstock and utility (e.g., water, electricity) carbon intensities, are highly context specific.

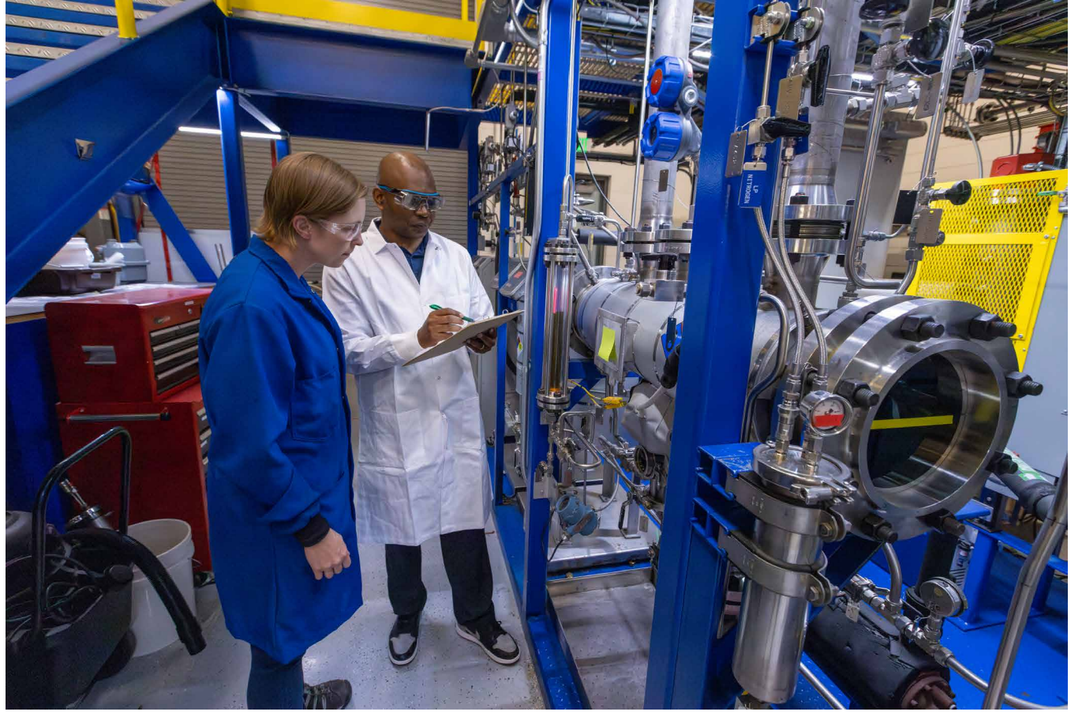


Photo by Agata Bogucka, NLR 91696

3. Methods

3.1. International Resource Assessment

Resource and price data were acquired for each of the 16 international ports. Because port countries vary in size, population, and data availability, the granularity of data considered for ports varied. Given that many of the countries considered in this report are small (less than 100,000 square miles [259,000 square kilometers]), countrywide data were determined to be sufficient. For the larger countries (Argentina, Brazil, China, India, South Africa, and Spain), individual states, provinces, or regions were considered. Additionally, for Hong Kong, only the official Hong Kong Special Administrative Region was considered. Please see Table A-2 in Appendix A for full details of the spatial resolution of the data for each port.

Resource data for the international ports were obtained from an extensive number of sources including government databases, national statistic sites, and international databases such as the Food and Agricultural Organization (FAO) and the World Bank, among others. A full list of sources for each country can be found in Appendix E. Because of data limitations, unless explicitly noted in the data sources, existing uses of biomass resources were not accounted for in this assessment. Instead, the total potential of these resources was estimated, without adjusting for competing demands or current utilization in various applications. Data for each port were processed using a standardized methodology for each feedstock:

Used cooking oil. The total amount of available UCO was obtained directly from a data source. If unavailable, a per-capita collection and recovery calculation was used to approximate the amount of UCO collection possible for each country or region.

Vegetable oils. Data on country-level vegetable oil production, including rapeseed oil, soybean oil, palm oil, and sunflower oil, were obtained from the FAO (FAO 2023). The percentage of vegetable oil used for biofuel production in each country was identified. This percentage was applied to the total vegetable oil production to estimate the quantity of vegetable oils potentially available as a biofuel feedstock in each country or region. Where subcountry-level data were considered, more granular data on regional or provincial vegetable oil production were used. If granular data were not available, a percentage was applied to the

FAO country-level production based on countrywide agricultural trends.

Manure. When possible, data on total animal manure waste were obtained from national sources. When these data were not available, information on the total number of livestock in each country was obtained from the FAO (FAO 2023), or from national sources for subcountry considerations. A ratio of annual manure production per head of livestock was applied (see Table A-5 in Appendix A). Typical manure management systems were identified for relevant global regions (Intergovernmental Panel on Climate Change [IPCC] 2019). Only the percentage of manure managed in lagoons, liquid/slurry, or pits was included. Manure quantities were converted into dry tonnes based on ratios presented in Table A-5.

Sludge. When possible, a total municipal wastewater sludge production quantity was obtained from national sources. When these data were not available, countrywide wastewater treatment volumes were obtained from the World Health Organization, or from various sources for regional or provincial considerations. When regional or provincial volumes were not available, a per-capita production volume was calculated based on World Health Organization data and population and urbanization metrics. A ratio was applied to the total wastewater treatment volume to determine the quantity of sludge produced in dry tonnes (see Table A-5).

Woody biomass. Because of the inability to determine if forests are sustainably managed, no logging residues or other forest removals were included for international ports. Primary mill residues were obtained from the FAO (FAO 2024). These data included solid wood processing residues, sawdust, shavings, bark, other residues, wood chips, and wood particles. FAO reports wood residues in cubic meters. Quantities were converted to dry tonnes using the calculation in Table A-5. Where subcountry-level data were considered, a percentage was applied to the FAO country-level production based on countrywide forestry trends.

Select MSW. When possible, MSW data were obtained from national sources. If country-maintained data did not exist, World Bank data on the quantity and composition of MSW were used (World Bank 2024). For ports where regional or provincial data were considered, more granular MSW data on quantity and composition were obtained from various sources. If regional compositions were not available, World Bank country-level compositions were applied to regional quantities. Ratios were applied to convert food waste, wood waste, and yard waste into dry tonnes (see Table A-5).

Prices were estimated for each resource in each country. To identify prices, information on the existing markets, disposal, or reuse of resources in each country was considered. A weighted average price was calculated for resources with multiple end-uses within a country—for example, wastewater sludge that is both land-applied and landfilled. An estimated fraction of each end-use was used for the weighted average calculation. Organic fertilizer/manure prices were used as a proxy for the land-applied fractions of wastewater sludge and manure when direct market prices were not available. Landfill or incinerator tipping fees were treated as an avoided cost and were thus represented as negative values in the weighted average price calculations. For resources or fractions of resources that have an established market value within a given country, price data were obtained. Price information was acquired from reference papers or other reputable sources, such as market indices, when possible. Where prices did not exist in the literature, global marketplaces such as Alibaba, IndiaMart, Scrapo, and Tradewheel were used to identify prices within each country or region. When prices were negative because of avoided tipping fees, price values were set to zero to align with U.S. port data. All prices were converted to 2023 U.S. dollars.

The resource prices in this assessment represent a snapshot of market conditions around 2024. They do not account for future price changes or potential increases resulting from growing competition for resources. These prices reflect only the cost of purchasing the feedstock and exclude loading and transportation costs unless otherwise noted. Transportation costs were included in the fuel production modeling, whereas loading costs were excluded because of uncertainty. A full list of price sources for each country can be found in Appendix F.

3.2. United States Resource Assessment

Most resource data for the U.S. ports analysis (except soybean oil and DCO) were obtained from the U.S. Department of Energy (DOE) Bioenergy Technology Office's 2023 *Billion-Ton Report* (U.S. DOE and Matthew Langholtz [lead author] 2024). The 2023 *Billion-Ton Report* analyzes the current and potential biomass resource availability within the United States, incorporating different factors such as various market scenarios, economics, and sustainability considerations. Results are based on these factors, which are meant to be conservative approximations of market resource accessibility under economically and sustainably feasible conditions rather than raw or maximum potential resource availability projections. This study uses county-level spatial resolution results from the near-term market scenario, representing potentially available resources over the next 5 to 10 years. Although the *Billion-Ton Report* provides estimates of current biomass resource use at a national scale, it does not offer county-level details unless explicitly noted. Because our analysis relies on county-level data, existing uses of these resources for various applications were not accounted for.

Data were analyzed to determine potential biomass production in dry tonnes per year and average price in 2023 U.S. dollars per dry tonne for each resource type within 50 miles (80 km) and 100 miles (160 km) of selected U.S. ports. Because the original data are reported in 2022 U.S. dollars, an inflation rate of 4.1% from 2022 to 2023 was applied. The resource prices in this assessment do not account for future price changes or potential increases resulting from growing resource competition.

Counties whose borders fall entirely within 50 miles or 100 miles of a port were included in the analysis for that given port and radius size. For counties bisected by either the 50-mile or 100-mile radius, population and tree cover were used as proxies to estimate the location of a resource within a county. The fraction of the county's population within the radius was used to approximate the fraction of the county's food waste and solid waste generated within the radius. A similar process was applied using tree cover to approximate the fraction of a county's wood residue production generated within the desired radius. Tree cover per county was estimated using National Land Cover Database Tree Cover Canopy map (U.S. Forest Service 2023).

Distillers corn oil. Ethanol plants' capacity data (in liters per year) and locations were obtained from the U.S. Energy Information Administration (U.S. EIA, n.d.). Using these data and the following assumptions: 10.6 liters of ethanol per bushel (about 25.4 kg) of corn and an average DCO yield of 0.34 kg per bushel of corn, the amount of DCO on-site at each facility was estimated. These data were used to estimate the quantity of DCO produced within a 50- and 100-mile radius of selected ports.

Soybean oil. Location and capacity data (in bushels per year) for soybean crushing facilities were obtained from the National Oilseed Processors Association and the Iowa Soybean Association (NOPA, n.d.; Iowa Soybean Association, n.d.). The amount of soybean oil produced at each facility was estimated by assuming a typical yield of 5 kg of crude soybean oil per bushel (approximately 27.2 kg) of soybeans. These data were used to estimate the quantity of soybean oil produced within 50 and 100 miles of selected ports.



Photo by Dennis Schroeder, NLR 47037

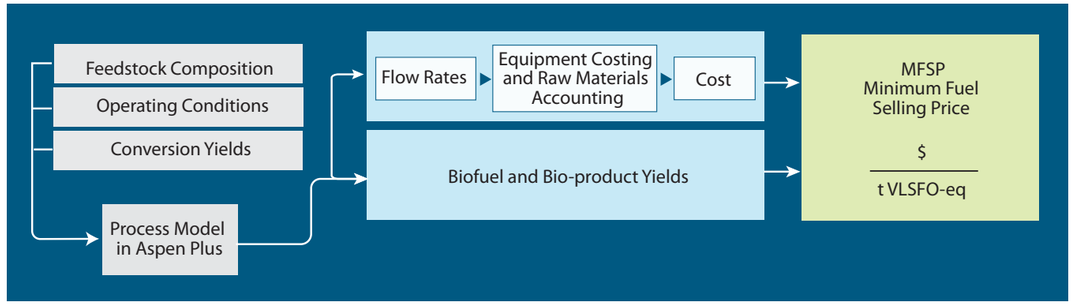


Figure 3. Techno-economic analysis methods, tools, and data flows. *Image by Jennifer Breen Martinez, NLR*

3.3. Techno-economic Analysis

Detailed techno-economic analysis (TEA) was performed for each port, feedstock, and process combination to estimate potential marine biofuel supplies and prices given feedstock resource assessments. TEA was based on (1) process models informed by experimental data to estimate heat and material balances and (2) equipment and raw material costs to estimate process capital and operating costs as shown in Figure 3. With these inputs, total capital investment, variable operating costs, and fixed operating costs were determined and discounted cash flow rate of return (DCFROR) analysis was employed to calculate the minimum fuel selling price (MFSP) for each biofuel.

DCFROR analysis depends on various financial parameters/assumptions, including debt-to-equity ratios, depreciation methods, plant lifetimes, working capital requirements, and startup timelines. To ensure consistent comparisons, assumptions detailed in Table A-3 of Appendix A were applied across all calculations. These assumptions reflected n^{th} plant conditions, implying multiple iterations of each process design were built and operated so that cost reductions through industrial learning have been realized. Although some technologies, such as renewable diesel or biodiesel, are more mature, other technologies considered will likely require additional time beyond the 2030 time frame considered to achieve n^{th} plant economics. Regional variations among port locations were also captured, including select financial parameters (cost of debt, cost of equity, and tax rates), feedstock resource assessments in terms of supply and price, and fuel demands as summarized in Table A-4 in Appendix A.

Feedstock data were integrated with the assumption that biorefineries would be co-located with ports given ports typically have fuel production and distribution infrastructure, skilled workforces, and are often adjacent to dense urban areas that can supply large amounts of solid and wet waste feedstocks, which would benefit biofuel producers. Although some of the ports considered may not have space available for biorefining, detailed analysis on optimal refinery location was outside the purview of this report. Transportation costs to each port were added to feedstock prices found in the resource assessments to estimate delivered feedstock costs used in subsequent TEA. Transportation via trucking with a price of 3.5 cents/wet-tonne/kilometer (km) was assumed, and distances were assumed to equal two-thirds of, or the average distance within, each port's feedstock collection radius. Feedstock water content assumptions were made for each feedstock type, as shown in Table A-6 in Appendix A.

Regional production capacities, determining economies of scale, were limited by total feedstock supplies. Individual plant feedstock thruput capacities were capped according to feedstock type:

- Solid wastes: 2000 dry tonnes (dt)/day
- Wet wastes: 100 dt/day (500 wet tonnes/day)
- Lipids: 2500 dt/day
- Hydroprocessing to upgrade bio-intermediates: 800 m^3/day (5,000 barrels/day).

If the target regional capacity was larger than a single plant's maximum capacity, it was assumed that multiple facilities (or trains) would be developed to meet demand and that production costs would equal that of the maximum plant scale. For the CFP and HTL processes, which can generate bio-intermediates, multiple trains were assumed to feed a single hydroprocessing section with hydrogen production via steam reforming. Similarly, multiple bio-LNG trains were assumed to feed a single gas upgrading and liquefaction system.

Last-mile delivery costs were not included in the TEA, given that production is co-located at the port and delivery of biofuels is generally anticipated to require less significant infrastructure modification as compared to hydrogen-based fuels. Delivery considerations are discussed broadly on a fuel-by-fuel basis in Section 6.

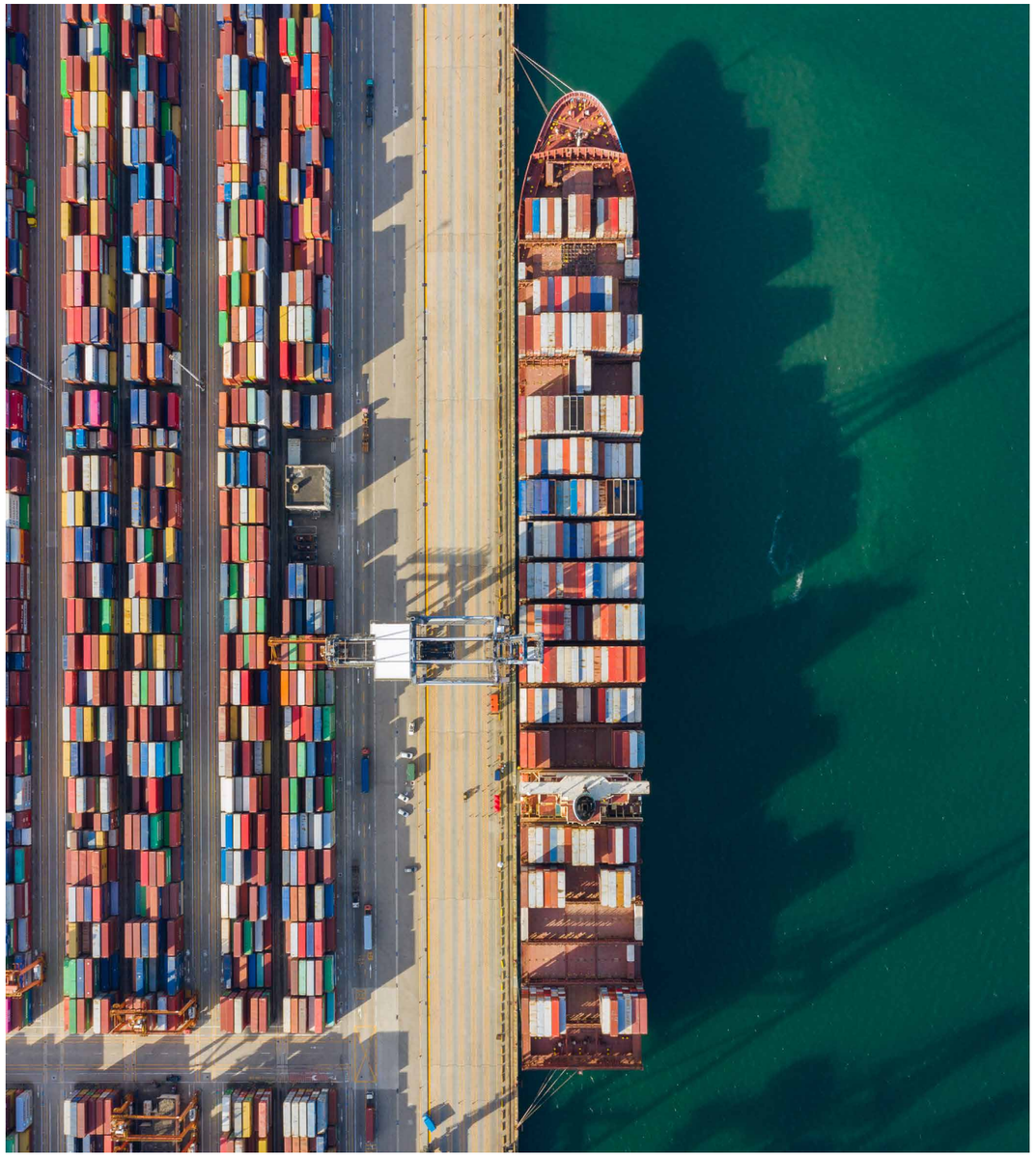


Photo from Getty Images 1365615608

4. Resource Assessment Results

Figure 4 provides a map of biomass resources at selected ports, offering an overview of resource potential. Select MSW is the dominant resource at the evaluated ports, with those in densely populated urban areas exhibiting the highest resource potential. Subsequent figures break down this information in greater detail, allowing for a closer look at specific resource quantities, types, and prices.

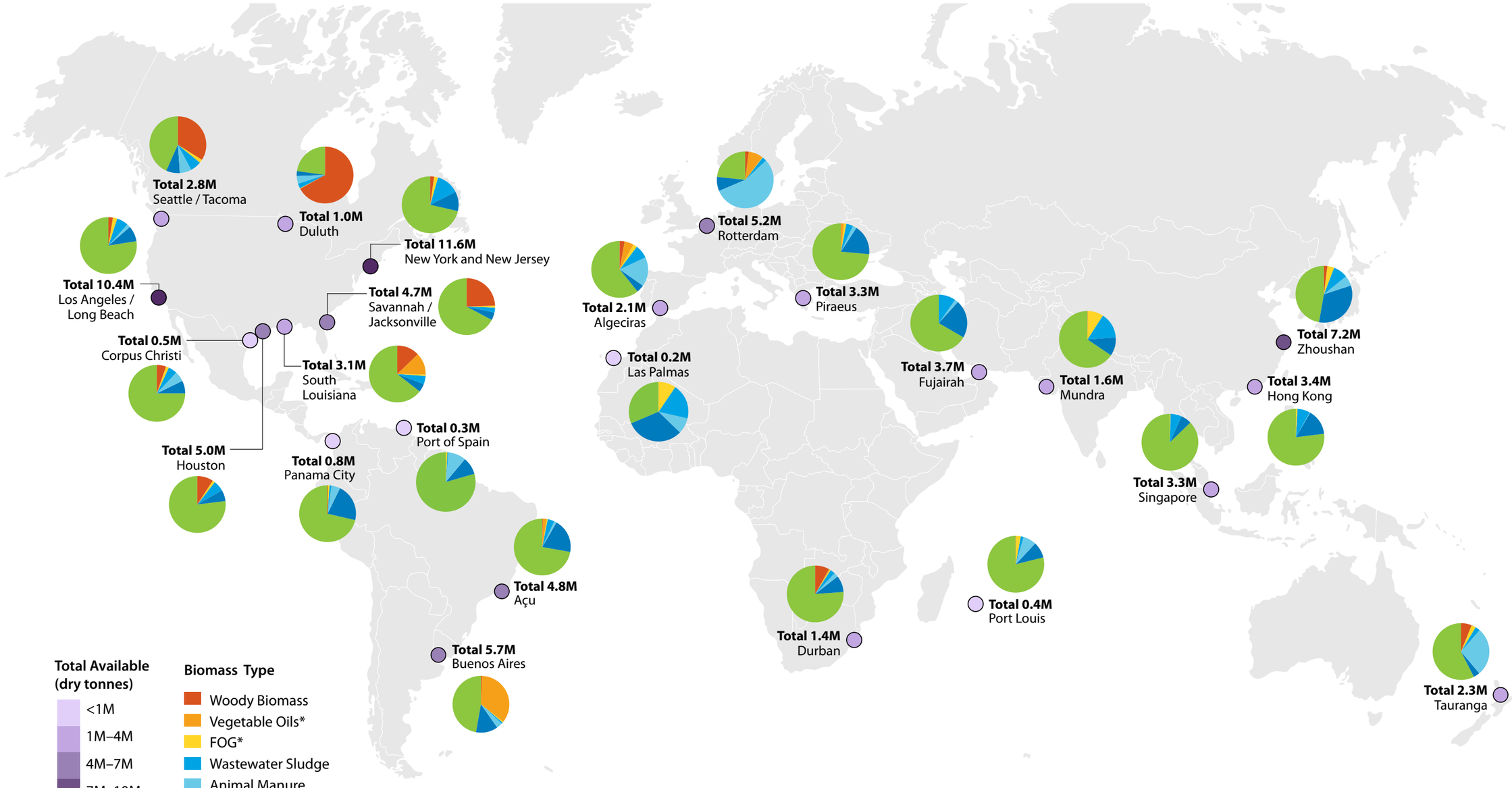


Figure 4. Biomass resource potential by type at selected ports.
Image by Jennifer Breen Martinez and Katie Carney, NLR

*FOG quantities are presented in wet tonnes.

4.1. International Ports

Figure 5 illustrates the biomass resource potential at selected international ports. Although there are differences among individual ports, a few notable trends exist. Solid wastes, particularly plastic and paper and cardboard waste, make up a vast share (36% to 93%) of the available resources across nearly every port. This is, in part, because many of the regions or provinces considered in the larger countries, that is, regions in Argentina, Brazil, China, India, South Africa, and Spain, are in densely populated urban areas. This leads to a high prevalence of urban wastes, such as paper and plastic, as well as municipal wastes, such as wastewater sludge. In smaller countries, such as Panama, Singapore, Trinidad and Tobago, and the United Arab Emirates, these trends are also present. This is likely the result of the relatively small scale of other waste-producing industries, such as forestry or livestock, within these countries.

In general, the areas with the largest population and/or largest geographical areas have the greatest total feedstock potential, whereas smaller, less-populous nations have significantly fewer available resources. Although most ports follow similar trends, a few individual feedstocks stand out. Notably, in the Netherlands, there is a large quantity of manure. This is likely the result of a large dairy industry and the prevalence of western farming techniques, which result in high levels of concentrated manure (IPCC 2019). Both Zhoushan, China, and Açu, Brazil, are notable for their large proportion of food waste. Buenos Aires, Argentina, has a notable amount of vegetable oils, given that the country is a major producer and exporter of soybean oil; approximately 65% of vegetable oils in the country go to biofuel production (OCED/FAO 2016).

There are a number of trends among the international resource prices (Figure 6). Vegetable oils exhibit the highest prices of any feedstock because of the globally established market for these commodities, which serve various applications, including biofuels. UCO is also high in price, for similar reasons—a commodity market for UCO as a biofuel input has developed within recent decades. Plastic waste, paper and cardboard waste, primary mill residues, and manure prices have more loosely established markets, leading to price variability within the $20 to $400 per tonne range, depending on local markets and policies. Resources treated as waste with little to no established markets in these countries, such as food waste, other select MSW, and wastewater sludge, all have purchase prices of $0, reflecting either freely given feedstock or an avoided fee for disposal.

However, for resources without well-established markets, additional costs may arise from logistical, transportation, or processing complexities associated with integrating them into new supply chains. Because of data constraints, the costs of separating certain MSW constituents from the mixed waste stream were not accounted for. Missing price data reflect a lack of the associated resource in the country.

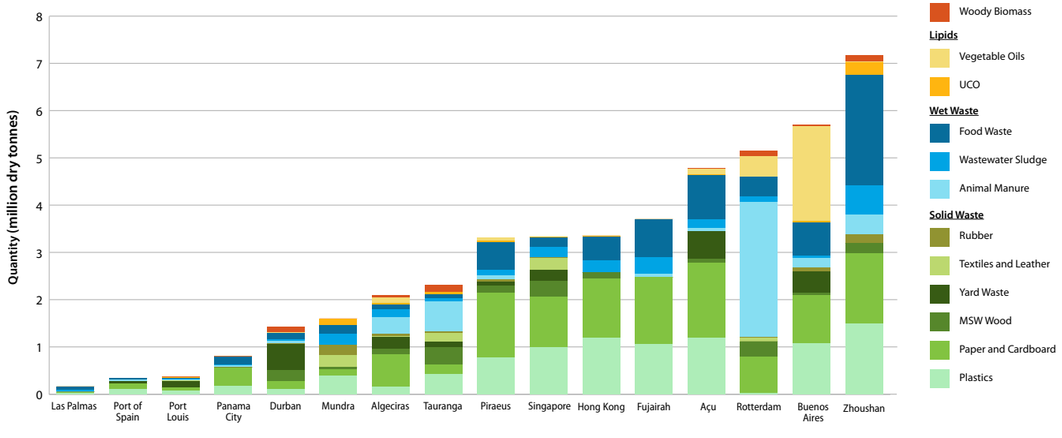


Figure 5. Potential biomass resource availability by type at selected international ports. Data sources for this figure are listed in Appendix E. *Image by Jennifer Breen Martinez and Katie Carney, NLR*

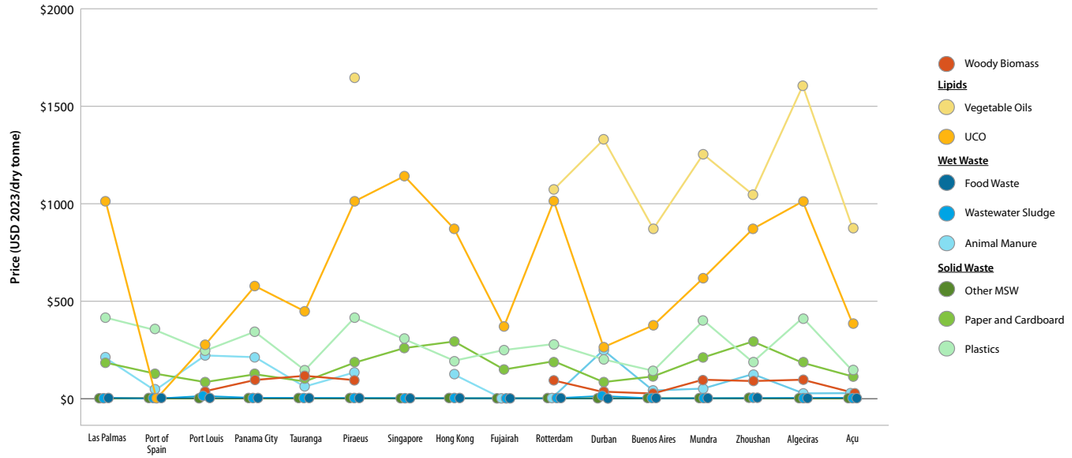


Figure 6. Estimated biomass resource prices at selected international ports. Data sources for this figure are listed in Appendix F. *Image by Jennifer Breen Martinez and Katie Carney, NLR*

4.2. United States Ports

Figure 7 illustrates the biomass resource potential within either a 50-mile or 100-mile radius for selected U.S. ports. For both radius sizes, Los Angeles/Long Beach and New York and New Jersey have the highest resource production. Because many prominent types of waste, especially MSW, food waste, and wastewater sludge, are related to population, it is not surprising that ports near highly populated places have higher resource potential. Select MSW resources, particularly paper and cardboard and plastics, have the highest potential within 50 miles for all port areas except Duluth, where the most abundant feedstock is woody biomass. On average, select MSW resources make up more than 60% of potential resources across all ports. Wet waste (16% on average) and woody biomass (11% on average) are generally the second and third most common resource, followed by lipids as the least common resource (4% on average). The lower proportion of lipids is attributed to the selected

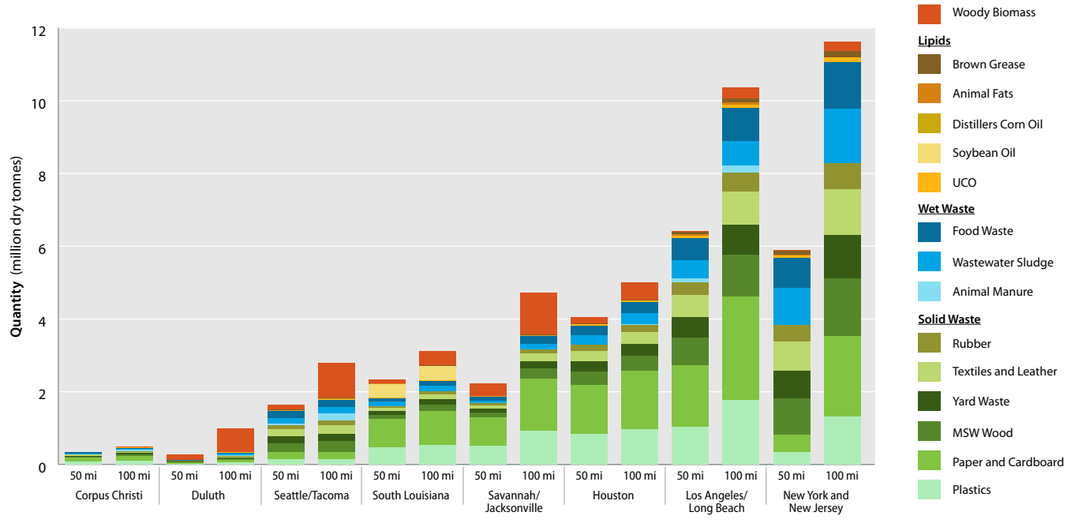


Figure 7. Potential biomass resource availability by type within either a 50-mile or 100-mile radius for selected U.S. ports. Data sources are listed in Section 3.2. *Image by Jennifer Breen Martinez and Katie Carney, NLR*

ports being situated far from regions with high lipids production with a few exceptions. Most production of soybean oil and DCO occurs in agricultural areas such as the Corn Belt. Resource composition remains similar when the collection area radius is expanded to 100 miles. MSW is the most prevalent resource, making up 62% of potential biomass resources, on average, across all ports. On average, the percentage of woody biomass increases from 11% of total resources within 50 miles to 20% of total resources within 100 miles, primarily because the collection area expands beyond urban areas. For the most part, the proportion of wet waste and lipids remains the same when the collection radius is expanded.

Figure 8 illustrates the average resource prices within a 50-mile radius of selected U.S. ports. Resource prices within a 100-mile radius are nearly identical. Flat prices represent the national average, as seen with FOG. Other resources show minor price fluctuations across locations, with food waste exhibiting the largest price swings because of variability in collection costs, regional processing infrastructure, or relevant policy (e.g., organics waste ban).

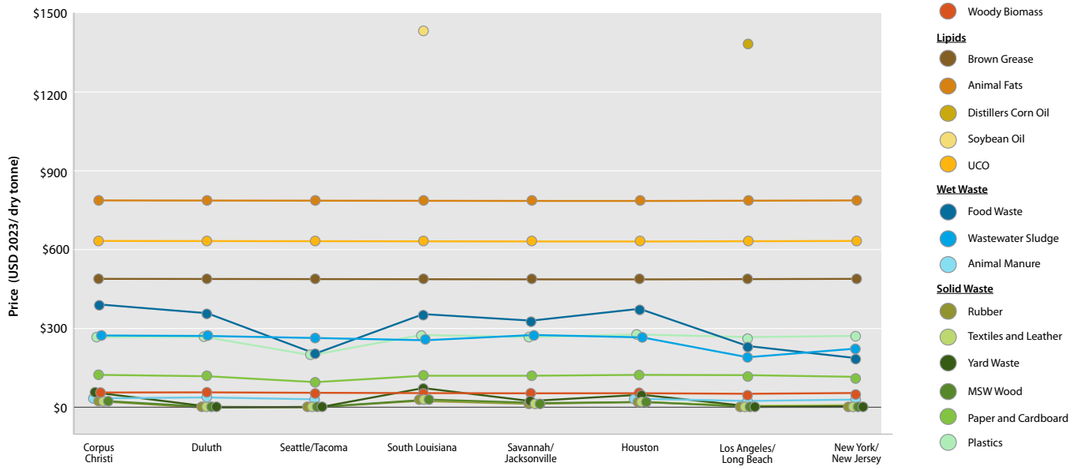


Figure 8. Average biomass resource prices within a 50-mile radius of selected U.S. ports. Data sources are listed in Section 3.2.
Image by Jennifer Breen Martinez and Katie Carney, NLR

Highlights

- The areas with the highest resource potential across all ports are populous urban areas with high levels of economic and commercial activities. Internationally, the highest potential is found at Zhoushan, China and Buenos Aires, Argentina; in the United States, the areas surrounding the ports of Los Angeles/Long Beach and New York/New Jersey have the highest quantities of potential waste resources.
- International and U.S. ports exhibit similar trends for the types of resources available. Generally, resources that are related to population, such as select MSW, food waste, and wastewater sludge make up large percentages of the potentially available quantities, whereas other resources such as lipids and woody biomass (generally produced in less populated agricultural and forested areas) make up smaller percentages.
- Resource prices around international ports show more variation than prices around selected U.S. ports. Internationally, lipids have the highest price followed by solid waste. Within the United States, lipids are also the highest priced resource, followed by wet waste and plastics.



Photo by Dennis Schroeder, NLR 21940

5. Biofuel Production

Regional nth-plant TEA results were combined to form a global marine biofuel supply curve for selected ports, as shown in Figure 9. The curve represents the quantity and MFSP of possible fuel production for the specific port regions considered, based on localized resource assessments and economic inputs. It does not represent a global supply curve and does not factor in carbon intensities of these fuels. Given the highly context-specific nature of this curve, it should not be compared directly to supply curves of other marine fuels in the literature (e.g., Koole et al. 2024) but instead used as a tool for information on the alternative marine fuels landscape.

Results suggest that biodiesel appears to be the lowest-cost marine biofuel option on a global scale. Derived from lipid feedstocks, biodiesel benefits from dense, easily transportable feedstocks that are readily converted into energy-dense diesel fuels with high yield. Biodiesel's compatibility with existing maritime infrastructure and fleets could provide additional cost savings by minimizing

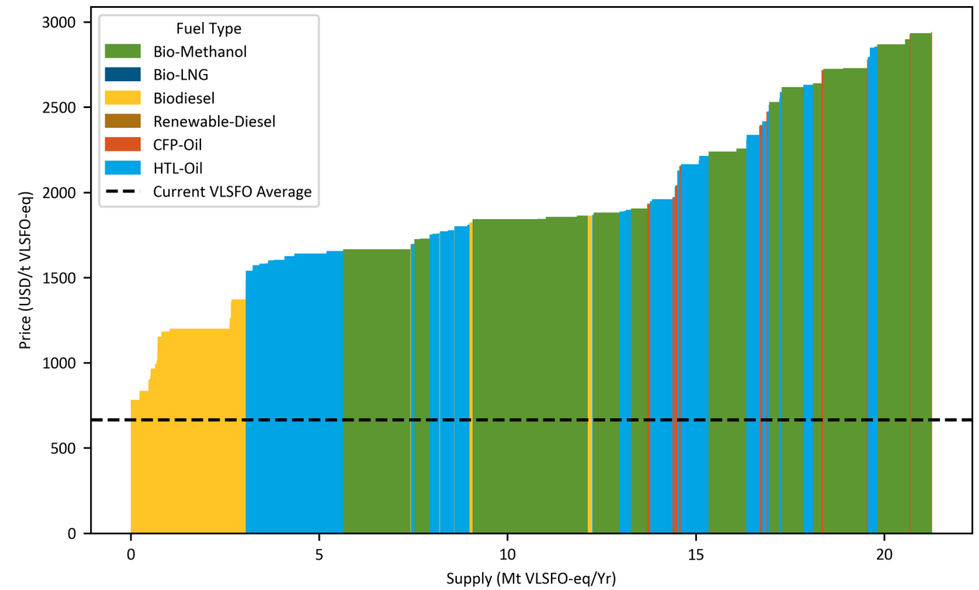


Figure 9. Aggregate supply from selected ports in million tonnes of very low sulfur fuel oil equivalents per year (Mt VLSFO-eq/yr) and minimum fuel selling price (MFSP) in U.S. dollars (USD) per t VLSFO-eq for various biofuel types: bio-methanol, bio-liquified natural gas (bio-LNG), biodiesel, renewable diesel, catalytic fast pyrolysis (CFP) oil, and hydrothermal liquefaction (HTL) oil. VLSFO price represents 2024 average global bunker prices (Ship & Bunker, n.d.). *Image by Nicholas Carlson, NLR*

the capital expenses and deployment timelines required to establish biodiesel capacity. Given these advantages, biodiesel presents a promising short-term solution for increasing biofuel adoption in the maritime sector at a limited scale. However, because of the current limited availability of lipid resources, the scale at which biodiesel could be available to the maritime industry may be small, with results from our resource assessment suggesting potential supplies around 2.9% of total marine fuel demand at the ports considered within this report. Additionally, the maritime industry faces competition from other sectors, such as on-road transportation, for biodiesel supply. This competition for lipid feedstocks from road transport and aviation sectors could drive up feedstock prices, potentially making biodiesel a less economically favorable option over time.

Following biodiesel, HTL-oil upgraded to a fuel oil substitute is the next-lowest-cost option. HTL technologies capitalize on low-cost feedstocks and on the fact that low-sulfur/low-metal biogenic feedstocks are inherently compatible with very low sulfur fuel oil specifications (S&P Global Inc. 2024). Moreover, specifications that are a concern, such as water content and acidity, are remediated with minimal hydrogen consumption using mild hydrotreating for HTL-oil, which significantly reduces capital costs when compared to full upgrading to diesel substitutes. Similarly, small supplies of CFP-oil are observed in the supply curve since catalytically upgrading pyrolysis oils can produce a low-sulfur fuel oil substitute without hydroprocessing.

The largest portion of supply (~50%) is projected to come from bio-methanol derived from woody biomass and select MSW. The high availability of these feedstocks, especially near ports situated close to large urban areas, supports bio-methanol as a key component in the marine biofuel mix. Bio-methanol could act as a supplementary fuel to e-methanol, enhancing supply and creating opportunities for infrastructure economies of scale. Larger production volumes could also enable greater utilization rates, thereby lowering per-unit costs of fuel production and distribution.

The fuel production volumes estimated in this report are based on the feedstock quantities identified in the resource assessments. Production facilities were co-located at ports with the idea that these fuels would feed the maritime industry. However, other sectors with high fuel prices, namely on-road transportation and aviation, are also potential consumers of these fuels. That competition could result in a lower quantity of biofuels being available to the maritime industry. There are also questions around the scalability of some biofuel processes. This analysis does not take into account these factors and could be considered optimistic.

5.1. Potential Production by Port

Individual port production potentials shown as percentages of each port's demand, accompanied by fuel mixture compositions and their aggregate MFSPs, are displayed in Figure 10. The dashed line represents 10% of total port demand being met by alternative fuels—an illustrative example selected to better model fuel demand and biofuel production potential at ports. Overall prices are calculated as weighted averages of each port's fuel mixture. Production prices were capped at an MFSP of $3,000/t VLSFO-eq for the purposes of this analysis.

To identify factors influencing marine biofuel MFSPs, Figure 11 plots correlations between input variables and overall MFSPs for each port location, highlighting characteristics that position a port favorably for marine biofuel supply.

Larger collection radii and feedstock supplies showed strong relationships with lower MFSPs, indicating that achieving economies of scale is a key driver in reducing overall fuel costs. Moreover, aggregate feedstock price had the strongest correlation of any variable considered, although it was counterintuitively a negative correlation, suggesting that higher feedstock prices generated lower biofuel product MFSPs. This implies accessing larger quantities of advantaged feedstocks such as lipids, which might already command a higher market price, is beneficial if total production costs are low. Also, higher port demands displayed a positive correlation with MFSPs, suggesting that meeting higher demands will require higher cost options because of feedstock constraints. These findings underscore the importance of developing reliable feedstock supply chains to achieve larger scales and cost-competitive marine biofuels. Exploring alternative supply chain configurations, such as hub-and-spoke models that aggregate feedstocks over high-density areas and produce biofuels off-site before transporting them to port locations, could unlock economies of scale and contribute to further cost reductions.

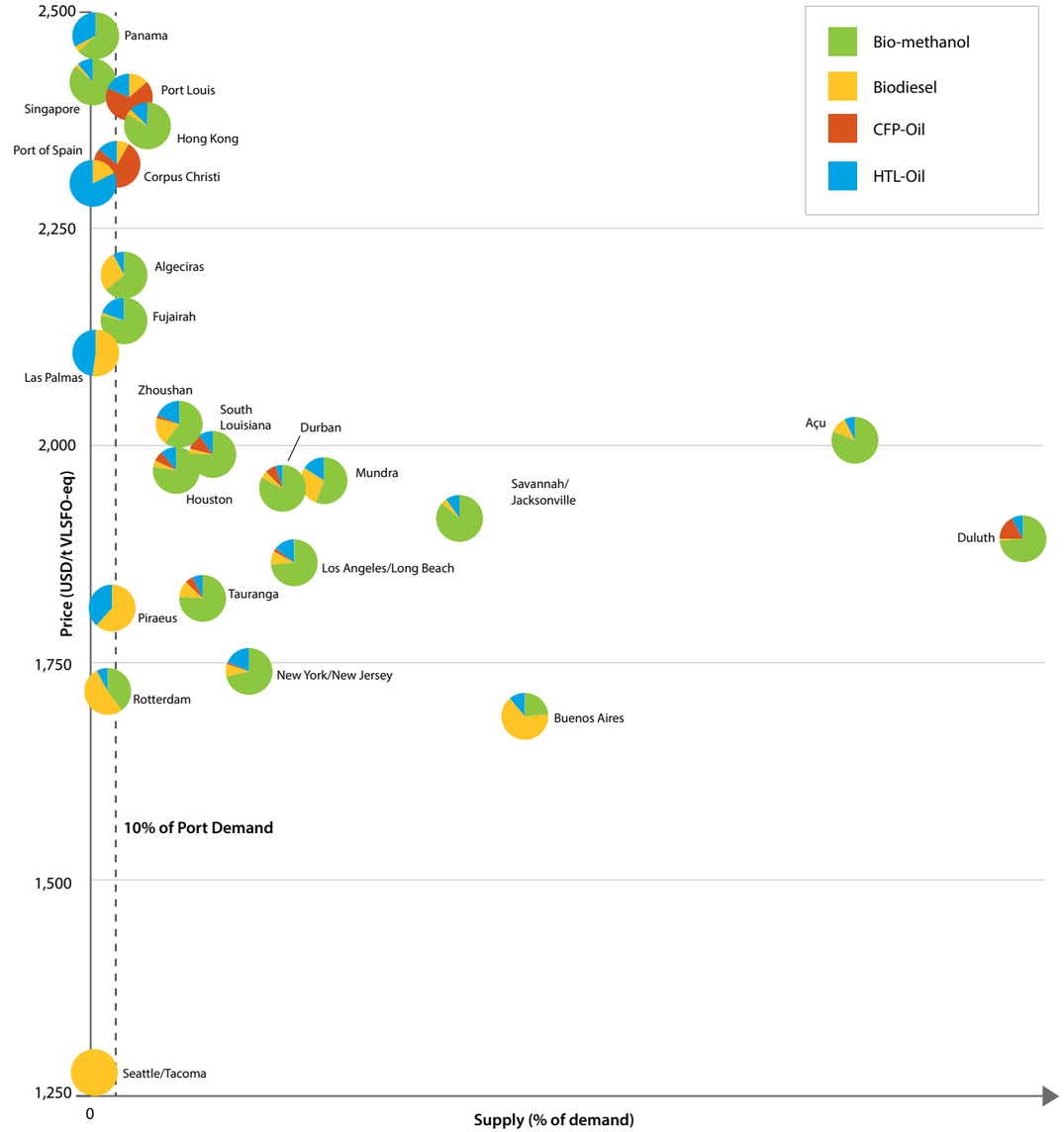


Figure 10. Individual maritime port biofuel supply potentials, fuel mixtures, and aggregate MFSP calculated as the volume weighted average of unique biofuel supplies at each port. *Image by Katie Carney, NLR*



Figure 11. Port variable correlations with aggregate marine biofuel MFSP. Variable combinations closest to 1.00 have the strongest correlations, with orange representing positive correlations (the greater the variable, the higher the MFSP), and green representing negative correlations (the greater the variable, the lower the MFSP, which is desirable). *Image by Jennifer Breen Martinez, NLR*

Highlights

- Biodiesel appears to be a lower-cost marine biofuel option, despite the high cost of lipid feedstocks, because of relatively low conversion costs. However, low lipid feedstock availability and competition with sustainable aviation fuel and diesel markets will likely limit the scale of biodiesel use in the marine sector.
- Results suggest mildly hydrotreated HTL bio-oil derived from wet wastes and bio-methanol derived from solid wastes and woody biomass could provide large volumes of biofuel at higher costs, depending on port characteristics.
- Ports with large feedstock production potentials and marine fuel demands are particularly well poised to supply marine biofuels because of economies of scale.

5.2. Announced Biofuel Capacity

This section considers existing production facilities and project announcements for planned facilities for various biofuels as of early 2025. The dashed line represents 10% of total port demand being met by alternative fuels—an illustrative example selected to better model fuel demand and biofuel production potential at ports. Announcements from the International Energy Agency Bioenergy Facilities database through 2028 were used for renewable diesel, CFP-oil, and bio-LNG (IEA Bioenergy, n.d.). Facilities listed as planned, under construction, on hold, or operational were included. The projected quantities of biodiesel production in 2028 were gathered from the International Energy Agency (IEA 2023c). Announced bio-methanol project capacities through 2030 were gathered from the Methanol Institute and GENA Solutions (Methanol Institute 2024). Because this report does not consider international trade of biofuels, only facilities in the selected port countries were included. However, given that the United States has historically been a major producer of biofuels, U.S. export and import quantities of select fuels can be found in Appendix D. Because fuels are generally easier to transport than feedstocks, countrywide potential capacity was used. The quantities presented here represent total production quantities within each country and do not consider limitations resulting from competing demand from other sectors. Conversion technology pathways used at each facility were not considered. The presented quantities might include biofuels produced via a pathway not examined in this report.

5.2.1. Biodiesel

Potential biodiesel production has the most geographical diversity of the biofuels examined, with projected production in eight of the countries included in the report (IEA 2023c). The United States has the highest projected capacity of 16.4 million tonnes annually by 2028, followed by Brazil with 10 million tonnes of projected capacity. No other country examined in this report has a projected biodiesel production capacity of more than 2.5 million tonnes annually by 2028 (IEA 2023c). The announced production capacity for biodiesel is presented in Figure 12. While individual feedstock data are not available for each project or country, globally most biodiesel is produced from oil crops. This may result in biodiesel not qualifying for FuelEU targets (European Biodiesel Board 2023; Abdelrahman and Abo El-Khair 2025).

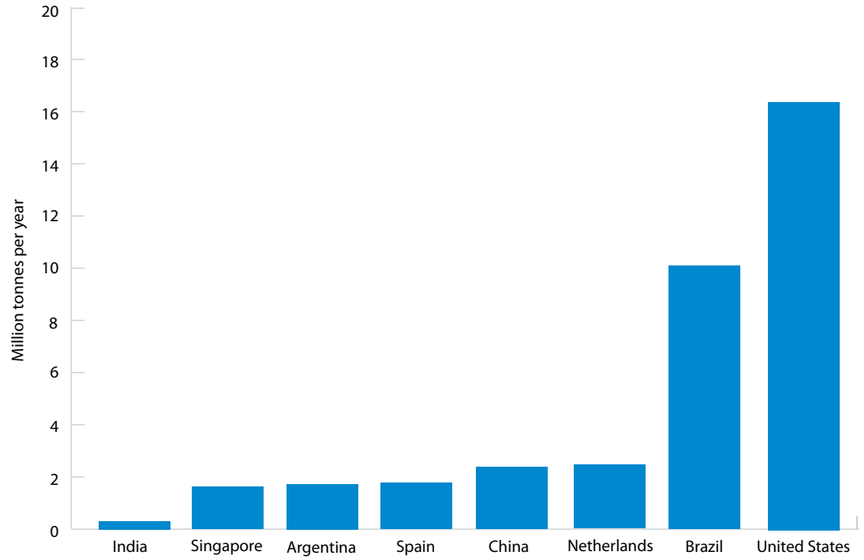


Figure 12. Announced production capacity for biodiesel in million tonnes/year. Projected production capacities were collected from the International Energy Agency world biodiesel production 2028 forecasts (IEA 2023c). *Image by Jennifer Breen Martinez, NLR*



Photo by Agata Bogucka, NLR 91711

5.2.2. Renewable Diesel

There are announced renewable diesel production facilities in seven of the countries examined in this report (IEA Bioenergy, n.d.). Because feedstock information was available for renewable diesel facilities, announced projects were grouped separately if they use or plan to use purpose-grown oil crops as feedstocks. Projects that use oil crops may not qualify to meet FuelEU targets. For facilities that either use or plan to use oil crops as a feedstock, the United States and Panama have the highest announced potential production with each more than 8.6 million tonnes annually. Excluding facilities that use or plan to use oil crops as a feedstock, the United States, Spain, and the Netherlands have the highest production potential with each more than 1 million tonnes annually (IEA Bioenergy, n.d.). The announced production capacity for renewable diesel is presented in Figure 13.

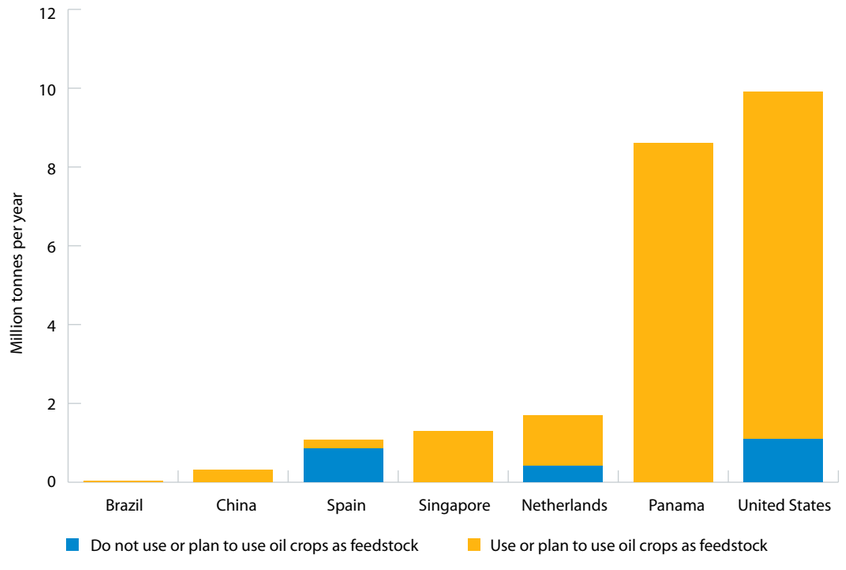


Figure 13. Announced production capacity for renewable diesel in million tonnes/year. Project announcements and planned capacities were collected from the International Energy Agency Bioenergy Facilities database (IEA Bioenergy, n.d.). *Image by Jennifer Breen Martinez, NLR*

5.2.3. Bio-methanol

There are bio-methanol plants announced in four of the countries examined in this report (Methanol Institute 2024). Though the conversion process used at each facility was not available, feedstocks used include biomass, renewable hydrogen, bio-methane, and residual waste, which likely implies the inclusion of additional conversion technology pathways not examined in this report. China has the highest announced production capacity of bio-methanol with 6.8 million tonnes annually. The Netherlands and the United States have the second- and third-highest announced production capacity at 0.85 million tonnes and 0.8 million tonnes annually (Methanol Institute 2024). The announced production capacity for bio-methanol is presented in Figure 14. The quantities presented here are not directly comparable to those presented in Koole et al. 2024 as this report examines only bio-methanol, not combined bio- and e-methanol supply (Koole et al. 2024).

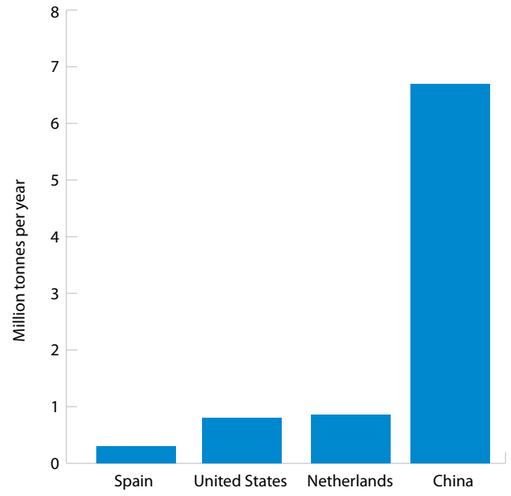


Figure 14. Announced production capacity for bio-methanol in million tonnes/year. Project announcements and planned production capacities were collected from the Methanol Institute Renewable Methanol database (Methanol Institute 2024). *Image by Jennifer Breen Martinez, NLR*

5.2.4. CFP-oil

There are four countries in this report with announced production of CFP-oil (IEA Bioenergy, n.d.). Of those countries, Brazil has the highest announced capacity at 77,000 tonnes. The Netherlands has the second-highest announced production capacity of 50,100 tonnes annually. China and the United States each has an announced production capacity of less than 5,000 tonnes annually (IEA Bioenergy, n.d.). The announced production capacity for CFP-oil is presented in Figure 15.

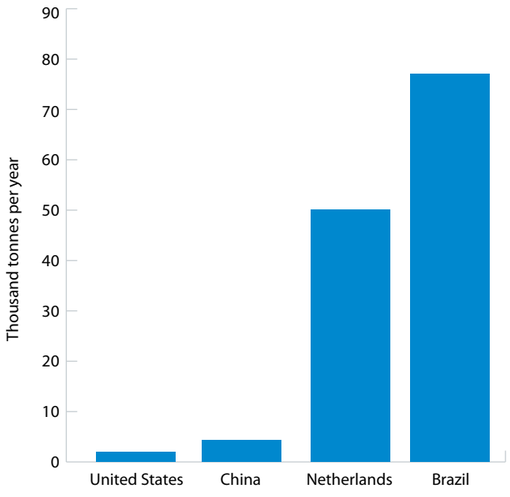


Figure 15. Announced production capacity for CFP-oil in thousand tonnes/year. Project announcements and planned capacities were collected from the International Energy Agency Bioenergy Facilities database (IEA Bioenergy, n.d.). *Image by Jennifer Breen Martinez, NLR*

5.2.5. Bio-LNG

The announced production capacities for bio-LNG are the second lowest of all of the biofuels examined in this report (lowest of the biofuels with at least one active or planned project in the countries examined). The Netherlands and the United States both have announced production capacities of bio-LNG. The United States has the highest announced capacity at 56,200 tonnes annually, followed by the announced capacity of facilities that use or plan to use oil crops as a feedstock in the Netherlands with 15,000 tonnes per year. Facilities in the Netherlands that do not use or plan to use oil crops as a feedstock have a cumulative announced production capacity of 1,300 tonnes annually (IEA Bioenergy, n.d.). The announced production capacity for bio-LNG is presented in Figure 16.

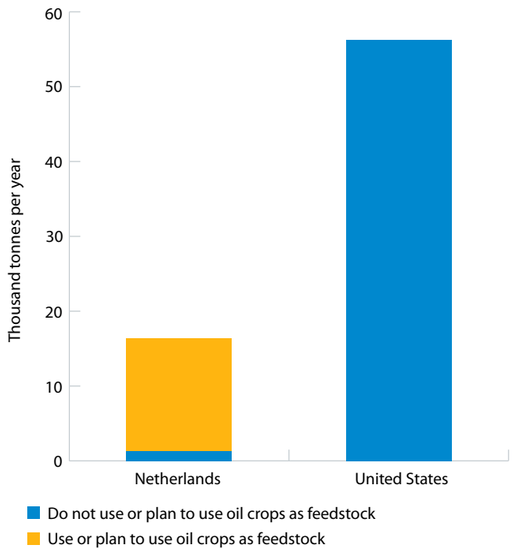


Figure 16. Announced production capacity for bio-LNG in thousand tonnes/year. Project announcements and planned capacities were collected from the International Energy Agency Bioenergy Facilities database (IEA Bioenergy, n.d.). *Image by Jennifer Breen Martinez, NLR*

5.2.6. HTL-Oil

There are operational and planned HTL projects globally, including in North America, Europe, and Australia. However, there are no active or proposed projects to produce HTL-oil in the countries examined in this report (IEA 2025). Demonstration plants around the world indicate an interest in producing HTL-oil and could contribute to the construction of more commercial plants (Collard, Wijeyekoon, and Bennett 2023).

Highlights

- Biodiesel and renewable diesel are currently the most-produced alternative fuels in terms of both geographic diversity and existing and announced capacities.
- Most existing and announced renewable diesel facilities use or plan to use oil crops as a feedstock. Globally most biodiesel is made from oil crops. Fuels produced from oil crops will likely not qualify for FuelEU targets.
- Bio-LNG has the lowest announced production capacity of the alternative fuels examined and has the least geographic diversity of existing or announced projects.
- Current and planned production capacity could influence which fuel types are bunkered at selected ports.

6. Infrastructure Considerations

This section covers infrastructure to transport, store, blend, and deliver marine fuels to end-users. Introducing new marine fuels at ports requires coordination among regulators and stakeholders to allow legal and safe bunkering of these fuels. Although ports do not typically buy or sell marine fuels, they can take on the role of bringing together these stakeholders to enable alternative fuel availability at or near a port. Many of the fuels evaluated in this study are available at ports today. Other ports could consider reviewing processes, best practices, and lessons learned from ports currently offering fuels of interest. Port authorities will need to be actively involved in approving, permitting, handling documentation requirements, and establishing bunkering locations/operations for these fuels. Another consideration is how to move marine biofuels from the point of production to a vessel. Multiple modes of transit are used to move imported and domestically produced marine fuels (Figure 17). The modes of transport depend on where the fuel was produced or imported, volumes, and infrastructure availability. For longer distances, petroleum products are moved primarily by pipeline, whereas biofuels are commonly moved by rail and barge. Both petroleum products and biofuels are delivered to terminals where they are stored separately, blended to the requested ratio, and delivered to vessels for refueling.

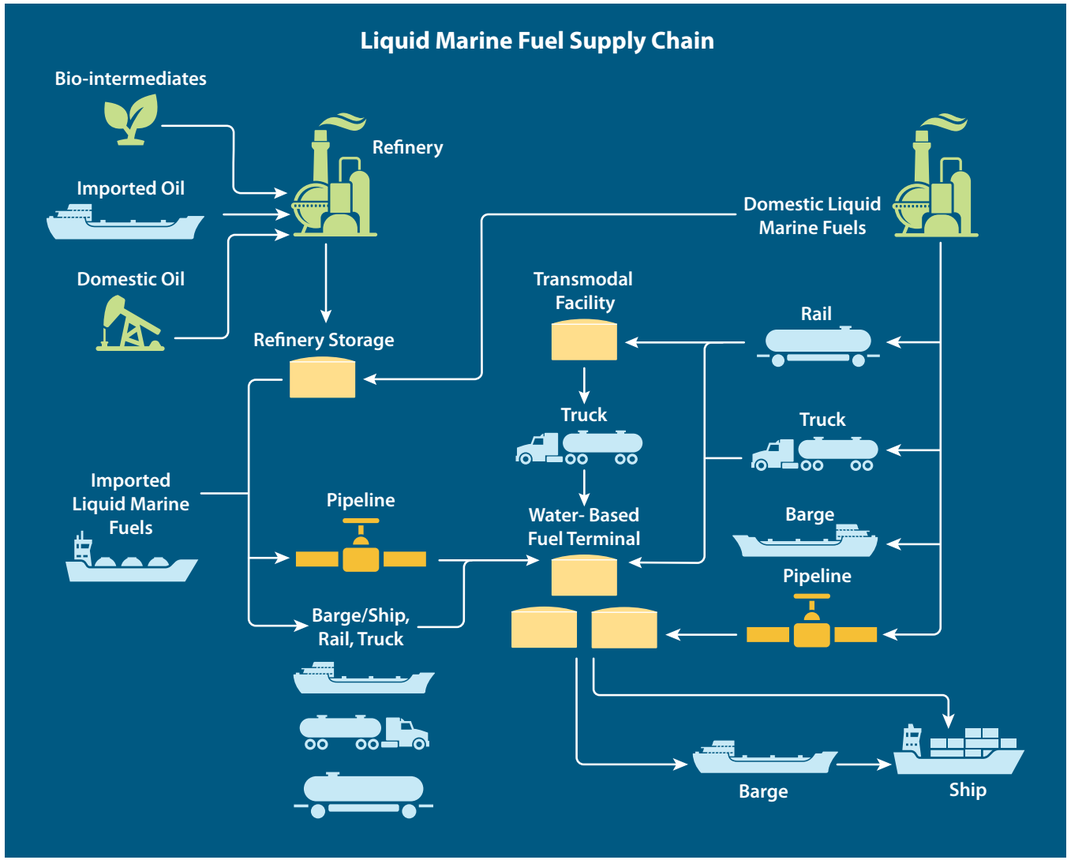


Figure 17. Marine fuel supply chain. *Image by Jennifer Breen Martinez and Katie Carney, NLR*

There are multiple methods for refueling vessels. They include truck-to-ship; ship-to-ship; and terminal-to-ship, also known as shore-to-ship (Table 1). Truck-to-ship is used for smaller vessels such as ferries and tugboats. Trucks are usually used for demonstrations of bunkering new fuels. The same trucks refueling vessels are used to deliver fuels to other end-users, allowing for flexibility and shared infrastructure costs. Ship-to-ship refers to bunker barges or tankers meeting a ship at a specified location for refueling; this is the most common method for large vessels. The ability to use existing infrastructure for biofuels depends on fuel properties. Considerations for bunkering method by fuel type are shown in Table 2. Diesel substitutes meeting ASTM D975 or biodiesel blends can typically be delivered by existing tankers and barges after a clean out.

Bio-methanol and bio-LNG would likely be delivered via dedicated vessels; the ability to convert existing chemical tankers or barges to deliver biofuels will likely depend on cost compared with a new barge/tanker and if it needs to be dedicated solely to a single fuel. IMO Type II chemical tankers are required for biodiesel blends above B25 and for bio-methanol and bio-LNG.

Terminal-to-ship involves refueling a vessel at a berth by hose or pipeline, depending on distance. Terminals routinely store, blend, and distribute biodiesel and renewable diesel to a variety of end-users, including onboarding to ships for fuel deliveries elsewhere, indicating that this infrastructure could be used to refuel vessels.

Table 1. Bunkering Methods and Considerations

Considerations	Truck-to-Ship	Ship-to-Ship	Terminal-to-Ship
Advantages	• Low investment • Bunkering at a berth • Flexibility to use truck for other end-users • Initial method to demonstrate bunkering of new fuels.	• Flexibility for bunkering location • Fast bunkering rates • Large volumes.	• Large storage capacity • Fast bunkering rates • Bunkering at a berth • Existing infrastructure for some alternative fuels.
Disadvantages	• Slow bunkering rates • Small volumes • Increased traffic at ports.	• High investment for some alternative fuels.	• Permanent location and use of port space • High investment

Sources: (ABS 2024) and National Laboratory of the Rockies (NLR) evaluation.

Table 2. Considerations for Bunkering Method by Fuel Type[a]

Fuel Type	Truck-to-Ship	Ship-to-Ship	Terminal-to-Ship
Renewable diesel and diesel substitutes	• Same methods as very low sulfur diesel.	• Same methods as very low sulfur diesel.	• Same methods as very low sulfur diesel.
Biodiesel	• Biodiesel is delivered to end-users by truck.	• Use of existing barge/tankers after tank cleaning.	• Tanks and lines are heated.
Bio-methanol	• Most common method currently.	• Limited availability.	• Future potential.
Bio-LNG	• Most common method currently.	• Increasingly available with dedicated bunkering vessels.	• Less common but potential for ports with LNG import/export facilities.

[a]Biointermediates are not included in this table. Research on materials compatibility and communication with stakeholders and infrastructure owners are needed to determine acceptance in existing infrastructure.

[b]Refers to diesel substitute fuels that meet ASTM D975 fuels quality specifications.

Sources: (ABS 2024) and National Laboratory of the Rockies (NLR) evaluation.

The costs for delivering fuel to an end-user are small when compared with production costs, particularly for emerging fuels. Fuel movements are determined by location of fuel production and end-user in addition to the infrastructure available to move the fuels. Costs to move petroleum products between ports on tankers fluctuate and recently have shown a high degree of variability between the United States and other international markets (U.S. DOE 2022). Generally, pipeline is the cheapest method of transport followed by barge/tanker with higher rates for rail. Trucking of fuel is highly cost competitive for short distances. For the fuels evaluated in this report, diesel substitutes meeting ASTM D975 would not incur additional costs for storage, blending, and distribution; biodiesel cost may be slightly higher because of winter handling, whereas emerging fuels such as bio-LNG and bio-methanol may experience even higher costs because of deployment of infrastructure, bunkering barges, and related equipment.

Ports evaluating the marine biofuels in this study might consider the following:

- **Diesel substitutes**: Several evaluated fuels are "drop-in," meaning they meet conventional fuel standards. Renewable diesel and hydrotreated diesel from HTL- and CFP-oil meet the same petroleum diesel fuel quality specification ASTM D975. These fuels can be used in existing diesel infrastructure without changes or investment. This results in business-as-usual for refueling vessels using the same bunkering equipment and infrastructure as is used for conventional marine diesel. The cost to transport renewable fuels meeting ASTM D975 is the same as conventional marine fuels. Costs may vary based on location of production and availability of infrastructure.
- **Biodiesel**: As a long-term commercial fuel, terminals know how to handle, blend, and store biodiesel. The shortest lead time and lowest costs would be incurred by using a marine-based terminal that already stores biodiesel. Existing bunker barges and tankers can be used to deliver biodiesel once tanks and lines are cleaned, and it is recommended to use dedicated tank(s) on bunkers. Note that IMO requires the use of Type II chemical tanks for blends above B25. Biodiesel typically costs more compared with petroleum products to move from production facilities to terminals since it is moved by rail and truck rather than pipeline.
- **Bio-LNG**: Bio-LNG is chemically like conventional LNG, meeting the same fuel quality specifications. LNG infrastructure costs are high, as LNG requires refrigeration or high pressures to maintain a liquid state. Bio-LNG could be deployed at ports with existing LNG infrastructure to reduce costs and timeline to deploy the fuel.
- **Bio-methanol**: Bio-methanol is chemically identical to methanol and meets the same fuel quality specifications. Although methanol is commonly available near ports because it is used in multiple industrial applications, this infrastructure is not widely available for bunkering. Methanol's fuel properties require the use of specific equipment and operations to reduce risks, including IMO Type II chemical tankers. Methanol bunkering is limited compared with other alternative fuels.
- **Bio-intermediates (CFP-oil, HTL-oil)**: Bio-intermediates are less familiar to infrastructure owners, and some properties may impact existing infrastructure. It would require research to determine impacts and compatibility with existing infrastructure materials prior to storage. Based on experience with on-highway transportation fuels, it takes years to develop data to enable the use of existing infrastructure.

Although considerations regarding in-vessel fuel use are largely outside the scope of this report, diesel substitutes, including renewable diesel and biodiesel, have been successfully used in existing ship engines with and without blending with conventional fuels and generally do not require engine modification for use. Bio-LNG, along with conventional LNG, and bio-methanol are typically used in dual-fuel vessels, requiring new investments from ship operators. Bio-intermediates could potentially be used in existing engines once impacts have been studied. There are no known demonstrations of bio-intermediates in ship engines.

6.1. Diesel Substitutes

Diesel substitutes considered in this study include biodiesel, HTL-diesel, CFP-diesel, and renewable diesel.

6.1.1. Renewable Diesel, HTL-Diesel, and CFP-Diesel

Renewable diesel, HTL-diesel, and CFP-diesel meet the ASTM D975 specification for conventional diesel, allowing them to be used in all existing infrastructure and engines without modifications or investment. These fuels serve as a direct replacement for existing marine diesel and can use the same bunkering facilities. Renewable diesel production facilities in the United States primarily deliver their fuel to terminals on the West Coast by rail and tanker/barge (U.S. EIA 2024). The location of renewable diesel production facilities and proximities to ports will determine infrastructure used to move the fuel to marine-based terminals, where it is business-as-usual to deliver these fuels to vessels.

6.1.2. Biodiesel

Biodiesel is a widely available commercial fuel, and terminals throughout the world have a history of handling, storing, and blending it. Biodiesel is delivered to terminals by truck, rail, and barge/tanker—pipeline movements are far less common. Many of the countries with ports in this study have biodiesel production facilities. Biodiesel has been used in vessels and delivered by bunker barges. B100 is often blended with conventional diesel or renewable diesel to reduce impacts of cold weather, as B100 can gel at higher temperatures (–3°C to 15°C or higher) compared with petroleum diesel (–12° to –9°C) (McCormick and Moriarty 2023). Currently, the most common biodiesel blend level in the industry is B24. Above-ground storage tanks and fuel lines for B100 should be heated in moderate and cold climates. B100 is not compatible with some hoses, gaskets, and metals, including polypropylene, polyvinyl, Tygon, some nitrile rubber components, lead, tin, or zinc (galvanized surfaces). If there is uncertainty with materials used in equipment, the vendor or original equipment manufacturer should be contacted to determine compatibility.

Cleaning bunker barges and storage tanks when switching fuels stored is a best practice. Estimated costs for cleaning a bunker barge for capacity of 20,000 to 50,000 barrels is estimated at $250,000 to $400,000 (Kass et al. 2022).

6.2. Bio-LNG

Bio-LNG chemical properties are nearly identical to conventional LNG, allowing it to be used in all existing LNG refueling infrastructure. Bio-LNG can be directly injected into LNG pipelines or other infrastructure without blending. It is anticipated that bio-LNG producers may be located far from ports, and an accounting system of book-and-claim would be used to decouple the location of production from the location of end-use (Pérez Pérez 2025). This allows the purchaser of bio-LNG to receive credit for the environmental attributes of the fuel. This has been a successful model for renewable natural gas used as an on-road transportation fuel (Kinder Morgan 2024). In this model, existing LNG infrastructure could be used to "supply" bio-LNG at ports, with no modifications or additional investment needed. To physically bring bio-LNG to ports, using existing LNG infrastructure is the best option for both economics and lead time. LNG is available at 96 ports, including at 7 of the ports evaluated in this study (Sea-LNG 2024b).[1,2] The Port of Jacksonville's coordination of multiple organizations and government regulators to enable LNG and a bio-LNG demonstration can serve as an example as other ports prepare for bio-LNG (Sea-LNG 2024a; Advanced Biofuels 2021). Standards for bunkering LNG are established with International Organization for Standardization (ISO) (ISO 2021). In the United States, the U.S. Coast Guard is developing recommendations to reduce barriers and improve bulk transport of LNG and bunkering (USGS 2024).

Generally, dedicated LNG bunker barges are used for deliveries. As of late 2024, there were 60 LNG-dedicated barges with another 13 on order (Bahtic 2024a). A primary limitation has been the high cost, estimated at $50 million, for a barge with 7,500 m^3 capacity (Bureau Veritas 2020). A third option is shore-based refueling from a terminal where a ship comes into a berth connected by a hose to a nearby tank or potentially by a pipeline where the distance is longer. This option is more common for inland shipping as well as for refueling barges, tugboats, and other vessels with less draft and more flexibility in refueling times. LNG terminals, typically built for import and export activities, require high capital to build, estimated at $500 million to $2 billion (Tank Terminals 2024).

6.3. Bio-methanol

Bio-methanol chemical properties are identical to methanol, and both meet the same fuel quality specifications and can be used in the same infrastructure. Methanol is a widely available chemical used to produce a variety of products. Although there are 122 ports with methanol storage nearby, the existing methanol infrastructure is designed for handling methanol as a chemical commodity rather than for its use as a marine fuel in bunkering operations. At the start of 2024, 10 ports were bunkering methanol, with an additional 11 expected. Most bunkering has been done by truck-to-ship (Chambers 2024; DNV 2023). Methanol fuel properties differ significantly from conventional marine fuels and should be used in dedicated trucks, tanks, pipes, lines, and associated equipment certified for methanol use. Concerns with methanol's low flash point and toxicity require specific equipment and procedures, including equipment certified for methanol use, maintenance, spill protection, and recertification tests (American Bureau of Shipping [ABS] 2024). It is anticipated that ports will require a return vapor system to address toxicity (ABS 2024). ISO is reviewing "Ships and marine technology—Specification for bunkering of methanol fueled vessels," which will cover key elements for bunkering methanol, including transfer systems, operational procedures, risk assessment, safety protection, and personnel training (ISO 2025).

Analysis on methanol infrastructure cost in the literature report estimated bunkering costs ranging from $325/t VLSFO-eq for a bunkering volume of 50,000 t/year to less than $75/t VLSFO-eq for a bunkering volume of 300,000 t/year (Koole et al. 2024). It was reported in 2015 that conversion of a bunkering vessel for methanol was estimated at $1.5 million, adjusted for inflation that would be roughly $2 million in 2025 (volume not provided) (The Maritime Executive 2015).

6.4. Bio-intermediates

Bio-intermediates, including HTL-oil and CFP-oil, are under consideration as fuels. Historically, bio-intermediates have not been used as fuels and are upgraded into end-use fuels and chemicals. Because of this, there is limited information on the impacts of bio-intermediates on existing fuel delivery infrastructure. High viscosity associated with some bio-intermediates would be an issue for pipeline shipments requiring specially designed equipment. High sulfur and/or oxygen content is also an issue for pipeline shipments.

It is anticipated that bio-intermediates research would be needed to identify any impacts or risks to infrastructure and to demonstrate compatibility with materials including elastomers, metals, and plastics. The experience of introducing ethanol blends above 10% and biodiesel blends into infrastructure required years of research and coordination with infrastructure owners and regulatory agencies to obtain permission to enable sales of these fuels.

Highlights

- Mode of fuel transport depends on where the fuel was produced or imported, volumes, and infrastructure availability. For longer distances, petroleum products are moved primarily by pipeline, whereas biofuels are commonly moved by rail and barge.
- Renewable diesel and other diesel substitutes meeting ASTM D975 use the same infrastructure as existing marine fuels without modification.
- Biodiesel is handled by many terminals and can be used in existing bunker barges after tanks and lines are cleaned at blends up to B24.
- Bio-LNG and bio-methanol are emerging marine fuels that will require more consideration and could be initially deployed to ports with conventional methanol and LNG infrastructure.
- Bio-intermediates will require further research to determine compatibility with existing infrastructure.

[1] SEA-LNG's Bunker Navigator provides details on marine LNG infrastructure: https://sea-lng.org/bunker-navigator-introduction/.

[2] Ports in this study with LNG infrastructure include Long Beach/Los Angeles, Savannah/Jacksonville, Rotterdam, Algeciras, Las Palmas, Port of Spain (Trinidad and Tobago), and Zhoushan.

7. Biofuels Policy With Potential Maritime Applications

Policy mechanisms can impact biofuel availability, cost, infrastructure, and deployment. Many nations lack comprehensive biofuel policies, and those that do have biofuels policies often do not explicitly include maritime applications. Understanding policy landscapes is a key aspect related to the deployment of biofuels in the maritime industry. Of the countries and unions examined in this report, thirteen have policies potentially or explicitly regarding maritime biofuel, or some level of production of biofuels. Broader policies focused on the transportation sector as a whole can, in some cases, also be applied to the maritime sector but through voluntary participation. Policy mechanisms investigated in this section include blending mandates, credit trading systems, grants and loans, tax incentives, subsidies, market and job development programs, and social and rural integration programs.

In October 2025, a vote to advance the IMO Net-Zero Framework, which would have established mandatory fuel intensity standards and an emissions pricing mechanism for large ocean-going vessels failed, with the United States leading opposition to the measure. The U.S. position reflects a broader all-of-the-above energy approach that supports fuel diversity and domestic energy production across multiple pathways — including biofuels — rather than mandating specific fuels or pricing mechanisms. The framework's future status remains uncertain.

At a national scale, biofuel policies with potential maritime applications are currently employed in Brazil, China, the Netherlands, Spain, India, Panama, South Africa, the United Arab Emirates, and the United States, as well as the EU. In this section, key biofuel initiatives, with and without maritime applications, are outlined and categorized by type of policy. All discussed policy types have the potential to be applied to maritime, although many currently are not.

Blending mandates are the most commonly implemented policies to promote biofuel use in the transportation sector (Ebadian et al. 2020). These require fuel suppliers and retailers to blend a certain percentage of biofuel with conventional fossil fuels, often with specific targets and timelines for increasing the blend percentage over time. Countries employing on-road blending mandates for both ethanol and biodiesel include Argentina, Brazil, China, the EU, Greece, India, and South Africa, while Panama has a mandate only for ethanol. The EU and Singapore also employ blending mandates for sustainable aviation fuel, which are notable as they are the only governing bodies in this analysis employing blending mandates beyond the on-road sector. One long-standing blending mandate is Brazil's biodiesel mandate (USDA 2023b). The blend ratio, set at 2% in 2005 (USDA 2023b), has been progressively increased through the passage of scheduled resolutions, with biodiesel making up 14% of all diesel fuel as of March 2025 (Hydrocarbon Processing 2025). The Netherlands and the United States do not have formal blending mandates but support fuel blending through indirect incentives.

Credit trading systems aim to achieve regulatory compliance for fuels by allowing participants to buy, sell, and trade credits associated with certain quantities or attributes of fuels. These credits often represent a quantifiable volume of biofuels produced or blended, or the quantity of emissions avoided through biofuel use. Obligated parties meet fuels targets by acquiring and retiring a certain number of credits annually. Those that produce, blend, or use more biofuels than required can sell their excess credits. Penalties can be issued to those that fail to meet the fuels obligations. Credit trading systems are used in Brazil, the Netherlands, and the United States. At the national level, the U.S. Environmental Protection Agency (EPA) employs tradable renewable identification numbers (RINs) to monitor adherence to its renewable fuel standards (RFS) (U.S. EPA 2024). The RFS Program mandates obligated parties (e.g., refiners, importers of gasoline and diesel) to meet a renewable volume obligation by acquiring a certain number of RINs. RINs are generated by blending fuels and can be purchased from other parties (U.S. EPA 2024). Similar credit trading schemes exist at the state level in the United States (e.g., California Low Carbon Fuel Standard) for on-road transportation, although they focus on the carbon attributes of fuels instead of fuel volumes (California Air Resources Board, n.d.). Although the U.S. federal trading schemes exclude the maritime industry, the Netherlands' renewable fuel units (HBE) system demonstrates how tradable credits can be successfully applied to encourage greater marine biofuel deployment. Because broader EU policy excludes maritime fuel, Dutch marine biofuel suppliers have the option to participate in generating tradable renewable energy units through the HBE, which has increased biofuel use for the maritime sector (Barthel 2022; Sustainable Ships, n.d.).

Grants and loans are used to fund research and development of biofuel technologies, expand biofuel infrastructure, or promote production of certain feedstocks or fuels. These have been employed by Brazil, Spain, and the United States to support biofuel use. Among the provisions in Spain's economic Recovery, Transformation and Resilience Plan (PRTR) is funding for biogas projects, with 76.5 million euros allocated to 81 proposals under the first proposal call. Globally, grant-based programs could be adapted to support the growth of biofuels in the maritime sector.

Tax incentives aim to lower the overall cost of biofuels. They can include tax exemptions, reductions, credits, or rebates. Biofuel tax incentives are seen in Argentina, Panama, and the United States. As an example, in the United States, federal tax credits have historically supported liquid biofuel production, most recently through the Section 45Z Clean Fuel Production Credit, which provides per-gallon tax incentives for eligible domestic biofuel production (Alternative Fuels Data Center, n.d.).



Photo from Getty Images 2168138647

Subsidies are financial contributions provided by governments to support biofuel producers. These can take various forms, such as direct payments, grants, or price supports, to lower the production costs of biofuels, making them more competitive with traditional fossil fuels. These are employed by the Netherlands, Panama, and South Africa. South Africa's Biofuels Regulatory Framework of 2020 employs subsidies to meet its penetration target of 4.5% renewable liquid fuel by volume set by the Biofuels Industrial Strategy 2007 (South African Dept. of Mineral Resources and Energy 2020). As of 2020, South Africa's biofuels are more expensive than fossil fuels (South African Dept. of Mineral Resources and Energy 2020). To address this cost disparity, this framework seeks to provide financial aid to both biofuel farmers and manufacturers, with manufacturers competing for funding (South African Dept. of Mineral Resources and Energy 2020). Notably, only first-generation biofuels are eligible for subsidies, as they were deemed to have higher job creation potential (South African Dept. of Mineral Resources and Energy 2020).

Market and job development programs aim to create new markets and jobs in the biofuel industry by collaborating with industry leaders and providing training programs for workers. India's Skill Council for Green Jobs created an industry-led council to lead vocational training and educational programs for renewable energy jobs, including biofuels, ultimately training 500,000 individuals (IEA, n.d.-c).

Social or rural integration programs aim to stimulate the rural economy through purpose-grown biofuel feedstock production by investing in smaller farms. Brazil's Social Fuel Seal granted special certification to small farmers and producers to promote rural inclusion in biodiesel production. Similarly, South Africa's Biofuel Regulatory Framework mandated financial and technical support for new Black farmers participating in biofuel feedstock production (South African Dept. of Mineral Resources and Energy 2020).

Policies with explicit references to marine fuels are limited and varied. Significant implementation is seen primarily in the EU, which administers the FuelEU Maritime Regulation for the purpose of reducing emissions within the maritime sector. This regulation applies to commercial ships larger than 5,000 gross tonnage with the purpose of shipping cargo and/or passengers. Vessels meeting these criteria are required to reduce emissions by 80% of 1990 levels by 2050 at an increasing rate—the earliest beginning with a 2% reduction in 2025. This regulation applies to 100% of the energy used for ships remaining within an EU member state or between EU member states, and 50% for ships arriving or departing from an EU member state to or from a nonmember country. Ships that do not meet the reduction requirements will need to pay a penalty, dependent on the difference in energy from compliant and noncompliant sources. As of 2030, ships will also be required to use onshore power supply for electricity at key EU member states' ports (ABS, n.d.). Notably, only biofuels derived from waste product are eligible to be counted (V Group Limited, n.d.), and renewable fuels from non-biologic origins will be double-counted through 2033 (ClassNK 2024). This could restrict the use of some biofuels to meet these targets. Beyond the EU, China has employed pilot programs to test biodiesel blends on certain maritime routes, mandated by its National Energy Administration to fulfill China's 14th Five Year Plan for Renewable Energy and the 14th Five-Year Plan for Bioeconomic Development (USDA 2024a; Hayley 2023).

All of these policy mechanisms have the potential to be tailored to support biofuels within the maritime industry. However, policy mechanisms are beneficial to biofuel deployment only if they are effective and enforceable. Within this analysis, four common themes were identified that resulted in existing biofuel policies being less effective than their potential. First, low enforcement is often observed in nations that lack implementing measures to enforce mandates or targets. This can be seen in nations with few resources to enforce policy or where enforcement is delegated to regional governments (USDA 2024a). Second, inadequate resources to meet targets can result from overly ambitious mandates that exceed a nation's fuel production or financial capacity (IRENA 2018). Last, inconsistencies in standards and fuel definitions complicate transnational applications of certain biofuel policies; this has been especially true for sustainable aviation fuel (Brown and Khan 2024). Although biofuels have not yet been widely applied to the maritime sector, these inconsistencies are likely to present challenges because of the similarly global nature of shipping. As biofuel policies are developed or revised, ensuring these four common issues are adequately addressed may result in more effective biofuel deployment within the maritime sector.

A full outline of all the policies considered in this report can be found in Appendix C.



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Highlights

- Two-thirds of countries and unions considered in this report have biofuel-related policies. Most of these policies do not explicitly include or exclude maritime applications, making it uncertain how they may apply to marine fuels. The EU and China are unique in having policies or mandates that explicitly relate to biofuel use in the maritime sector.
- Policy mechanisms employed by the countries in this analysis to support biofuel production and deployment include blending mandates, credit trading systems, grants and loans, tax incentives, subsidies, market and job development programs, and social and rural integration programs.
- Common themes among ineffectual biofuels policies are poor enforcement mechanisms, inadequate resources to meet targets, and transnational policy differences. These shortcomings often overlap.
- Conversely, countries with more long-standing, established biofuel policies (United States, EU, Brazil) have larger quantities of existing biofuel production (Section 5.2) likely due to established biofuels infrastructure, enforcement mechanisms, and market stability.

8. Case Studies

Three ports were selected to provide a deeper look at potential avenues for implementing marine biofuels at ports and to provide considerations for generating supply and demand. They were chosen because they have different bunkering experience profiles and potential biofuel availabilities. They serve as examples of distinct opportunities for marine biofuels. Singapore was selected as an example of a large-scale bunkering port with high levels of anticipated fuel imports. Singapore represents ports that have already taken steps toward biofuels bunkering and have historically played a role in driving the industry. New York New Jersey was selected to serve as an example of a mid-scale bunkering port with high potential for local biofuel production. New York New Jersey represents prominent commercial ports that have yet to explore alternative fuel bunkering in depth. Mundra was selected as an example of a niche bunkering port with a smaller current bunkering market. Mundra represents ports with the potential to capitalize on domestic biofuel production or imports to become regional leaders in bunkering of select biofuels.

8.1. Singapore

8.1.1. Background

Singapore, as the world's largest bunkering hub by volume of fuel, bunkered approximately 54.9 million tonnes of fuel in 2024, approximately five times more than that of the next-largest bunkering hub. Singapore has played a pivotal role in driving the maritime sector's adoption of alternative fuels, achieving a notable milestone with 1.34 million tonnes of alternative fuels sold in 2024, the most recorded in a single year (Hakirevic Prevljak 2025). Specifically, the sale of biofuel blends grew from 0.52 million tonnes in 2023 to 0.88 million tonnes in 2024 (MPA Singapore 2025a; 2025c). Its extensive bunkering infrastructure and strategic location provide significant advantages in becoming a leader in biofuel bunkering, though limited feedstock resources locally (Figure 5) mean much of the biofuel supply would likely be imported.

8.1.2. Biofuel Production Potential

Singapore's domestic biofuel production capacity, given the chosen feedstocks and conversion technologies, is estimated to be slightly below 1 million tonnes VLSFO-eq per year, based on available feedstock and an MFSP cap of $3,000/t. However, production costs are relatively high for all potential biofuel types (Figure 18).

At an illustrative demand of 10% biofuels by 2030, Singapore would need to supply approximately 5 million tonnes of alternative fuels. Figure 19 highlights Singapore's challenges related to feedstock availability and the ability to domestically produce enough biofuels to meet this target, with local production slightly below 1 million tonnes VLSFO-eq; Singapore would likely need to import fuel to meet bunkering demand.

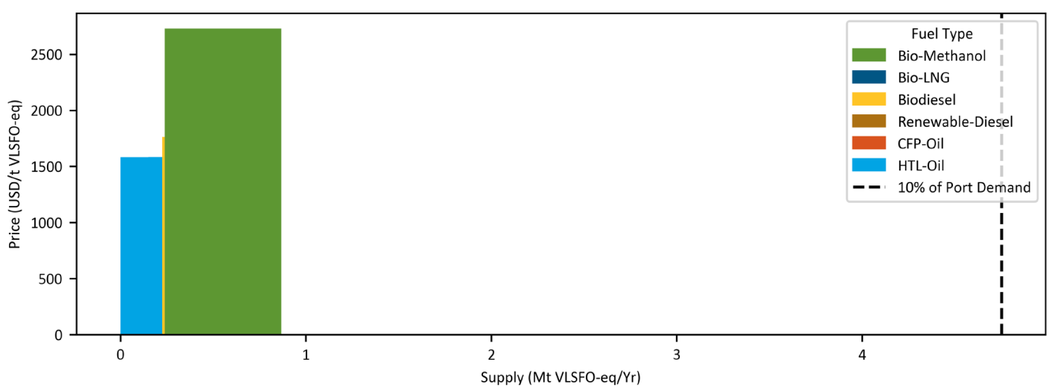


Figure 18. Singapore's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. The dashed line represents the quantity required to meet 10% of port fuel demand. *Image by Nicholas Carlson, NLR*

Local production cannot meet Singapore's estimated demand of approximately 5 million tonnes VLSFO-eq.

8.1.3. Readiness for Biofuel Bunkering

Singapore has made considerable progress in preparing for biofuel bunkering, supported by its biofuel infrastructure and policies. As of early 2025, biodiesel blends of up to B50 are commercially available at the port with ongoing trials of up to B100 (MPA Singapore 2025c). In February 2024, Vitol Bunkers welcomed its first specialized biofuel bunker barge to Singapore. The barge complies with the IMO Type II chemical bunker tanker classification required for biodiesel blends over B25 and is capable of bunkering blends up to B100 (Habibic 2024b). The port completed its first B100 bunker in August 2024 and plans to continue advancing biofuel bunkering, including B100, in the future (Chakravarty 2024). Bunkering of bio-LNG is also currently available at the port and could be expanded through use of existing LNG infrastructure (Sea-LNG 2023).

Regarding methanol, the Port of Singapore has taken many steps toward commercial bunkering. The world's first ship-to-containership bio-methanol bunkering was completed at Port of Singapore in July 2023 (MPA Singapore 2023a), and in December 2023, the port welcomed its first methanol bunkering vessel (Habibic 2024a). Since then, further testing has been completed, including ship-to-ship bunkering of blended methanol, and the port's first successful simultaneous bio-methanol bunkering and cargo operation, both completed in May 2024. Building on these trials, MPA launched a formal methanol bunkering licensing framework in early 2025 and awarded five-year licenses to three suppliers effective January 1, 2026, with demand for methanol in Singapore potentially exceeding one million tonnes per annum by 2030 (MPA Singapore 2025d; 2024).

8.1.4. Bunkering Policies and Standards

The Maritime and Port Authority of Singapore (MPA) has developed a framework for licensed bunker suppliers to provide certified biofuels. All bunker fuels supplied in the Port of Singapore shall adhere to ISO 8217 standards and require Proof of Sustainability from a recognized scheme such as the International Sustainability and Carbon Certification (MPA Singapore n.d.). MPA has also developed a provisional national standard on specifications of marine biofuel (WA 2:2022) to complement international standards (MPA Singapore, n.d.). This standard serves as a guideline for bunker suppliers, craft operators, surveyors, shipowners, buyers, and testing laboratories, ensuring consistency and quality in biofuels. Historically, Singapore bunkering standards have been highly influential in shaping how port authorities globally approach similar bunkering challenges (Ship & Bunker 2024).

8.1.5. Fuel Sourcing

To reach a quantity of 5 million tons annually, Singapore would likely need to import alternative fuels. The port has taken significant steps to secure alternative fuel supplies. In 2024, bunker sales of biofuel blends at the port totaled 0.88 million tonnes, growing from 0.52 million tonnes of biofuel sales in 2023 (MPA Singapore 2025c). The MPA has signed memorandums of understanding with partners such as Shell to expand the availability of biofuels and bio-LNG at the port (MPA Singapore 2023b). Following a formal licensing process, MPA awarded methanol bunkering licenses to three suppliers effective January 1, 2026, marking the transition from pilot trials to regulated commercial supply (MPA Singapore 2025d).

Additionally, Neste Singapore—one of the world's largest renewable diesel refineries—could play a role in supplying biofuels to the port for bunkering. On January 8, 2025, Neste and KPI OceanConnect completed their first delivery of renewable diesel to Singapore's maritime sector, in partnership with local marine service provider Global Energy (Neste Corporation 2025). Partnering with companies that already have local infrastructure, capacity, and expertise in scaling biofuel production could help strengthen Singapore's domestic capacity.

8.1.6. Demand Generation

The port is well positioned to drive biofuel demand via its involvement in several initiatives, including five shipping corridors—maritime routes between two or more ports that showcase alternative fuels and advanced technologies—which have significant potential to increase the demand for marine biofuels. It is estimated that the Rotterdam-Singapore corridor alone could reach a demand of up to 5 million tonnes per year of bio-LNG, e-methane, and bio- and e-methanol in 2028 (Bahtic 2024b). Additionally, Singapore's Green Port Programme and Green Ship Programme incentivize vessels using alternative fuels by offering up to a 100% reduction in port dues for Singapore-registered ships and ocean-going vessels calling at the Port of Singapore (MPA Singapore 2025b).

8.1.7. Considerations for Continued Bunkering Leadership

Singapore has positioned itself as a pioneer in advancing the maritime sector's adoption of alternative fuels. Expanding the use of biofuels such as biodiesel, renewable diesel, bio-LNG, bio-methanol, and bio-intermediates may require proactive efforts to build supply chains, stimulate market demand, and align operational practices with international standards. The following are potential best practices that Singapore and other large bunker ports might consider for increasing the bunkering of biofuels, developed in part from other alternative fuel bunkering considerations presented in the literature (Koole et al. 2024).

Enhancing Biofuel Availability

- Ports might consider defining measurable goals for biofuel integration, such as voluntary or market-driven targets for biofuel adoption in marine bunkering. Such goals could signal commitment to scaling the supply of biofuels and help build confidence among fuel producers and ship operators about future demand.
- Leading bunker ports could expand partnerships for biofuel sourcing and strengthen collaborations with established biofuel exporters. A focus on sourcing biofuels from suppliers that meet international standards may be beneficial for ensuring global consistency.
- Leading bunker ports might consider facilitating the development of bio-intermediates such as CFP-oil and HTL-oil by supporting feasibility studies, pilot projects, and collaboration with fuel suppliers, engine manufacturers, and others to evaluate their marine fuel potential and infrastructure impacts.

Strengthening Market Demand

- Ports could consider integrating biofuels into new or existing initiatives, and/or highlighting biofuels as an effective option to meet IMO 2030 goals. For example, leading bunker ports might consider encouraging biofuel use within their shipping corridors, particularly by highlighting their near-term availability compared to other alternative fuels.
- Leading bunker ports might consider leveraging economic incentives to drive adoption, such as extending or enhancing port fee reductions for vessels using alternative fuels such as biofuels. Such incentives could reduce the cost gap and encourage greater uptake of these fuels.

Aligning Operational Practices

- Leading bunker ports could collaborate on international biofuel standards, working with other ports to align environmental certifications, quality standards, and operational protocols for biofuels. Harmonized approaches may lower barriers for ship operators and fuel producers in adopting biofuels.
- Leading bunker ports might consider providing logistical and technical support for first-mover vessels using biofuels by ensuring infrastructure compatibility and coordinating refueling standards with other major bunkering hubs.

Through these strategies, Singapore and other leading bunker ports may strengthen their positions as global hubs for marine biofuels while supporting the maritime industry's adoption of alternative fuels.

8.2. New York/New Jersey

8.2.1. Background

The Port of New York/New Jersey (NY/NJ) is the largest port on the U.S. East Coast and a significant player in global shipping. With its strategic location as a gateway to the Northeast and extensive infrastructure, the port has the potential to become a leader in the adoption of alternative marine fuels. The port itself is a landlord port, with no bunkering operators or fuel storage facilities as tenants; current fueling occurs via tank farms and bunker barges outside of the port. For ease of discussion, the use of "the port" within this case study refers to the Port Authority and its jurisdictional area along with all other fueling operators and infrastructure located within proximity to the port. As one of the busiest port regions in the United States, the port has significant potential to drive demand for biofuels.

8.2.2. Biofuel Production Potential

The port region demonstrates considerable potential for biofuel supply relative to other ports considered in this analysis but faces challenges in meeting the illustrative 10% of demand entirely with biodiesel, the lowest-cost fuel considered in this analysis. Instead, given current feedstock availability, the lowest-cost means to meet the illustrative demand is with both biodiesel and bio-methanol. Total biofuel production potential at the port is approximately 3.1 million tonnes VLSFO-eq (Figure 20), given the feedstocks and conversion technologies included in this analysis.

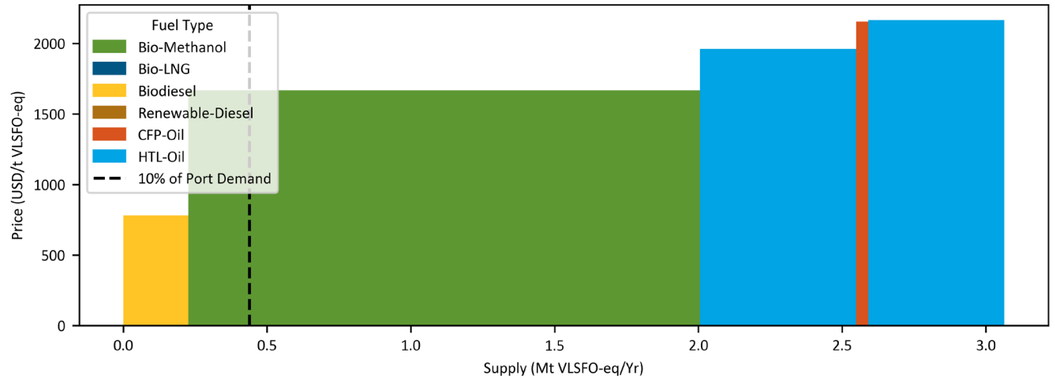


Figure 19. PANYNJ's potential biofuel production based on feedstock quantity and a maximum production price of $3,000/t VLSFO-eq. The dashed line represents the quantity required to meet 10% of port fuel demand. *Image by Nicholas Carlson, NLR*

Figure 20 illustrates that the area surrounding the Port of NY/NJ has the potential to produce relatively large quantities of biodiesel and bio-methanol at the lowest cost of any other port in the study—estimated at approximately $783 and $1667/t VLSFO-eq, respectively. The port's location is in the heart of a very large urban center with a high quantity of waste lipids and MSW feedstocks. Given this potential for low-cost production, the port could leverage existing and potentially increased local demand, as well as export opportunities, to secure fuel producers in the region and become a global leader for biofuel bunkering.

8.2.3. Readiness for Biofuel Bunkering

At present, the Port of NY/NJ and surrounding fuel operators have limited infrastructure for alternative fuel bunkering (Dan-Bunkering, n.d.; Integr8 Fuels, n.d.). However, the Port Authority has set targets, including to reduce direct operational emissions under the Port Authority's control by 50% by 2030 and to achieve net-zero emissions by 2050 (PANYNJ 2023a). As part of this strategy, the port plans to support the adoption of alternative fuels for ocean-going vessels and harbor craft. The Maritime Association of the Port of NY/NJ (MAPONYNJ) recognizes the need for stakeholders, governments, and providers to work together to enhance the port's storage, bunkering, and fuel transfer systems. In late 2024, MAPONYNJ held a symposium to bring together public and private stakeholders in the industry to discuss trends, challenges, and opportunities related to the adoption of alternative marine fuels (MAPONYNJ 2024).

8.2.4. Challenges to Biofuel Bunkering

Although the port's location in the heart of a dense urban center is beneficial for feedstock availability, it may present unique challenges that can complicate the development and implementation of new fuel bunkering infrastructure. The urban environment surrounding the Port of NY/NJ restricts the amount of space available to the port, which could hinder the port's ability to develop the required infrastructure for handling and storing new fuel types.

Operating within a densely populated area subjects the port to stringent environmental and safety regulations, which can extend the time frames for obtaining necessary permits and approvals for new bunkering projects, potentially delaying the adoption of alternative fuels. In addition, the introduction of new fuels, particularly those requiring specialized handling, may raise concerns among local communities about potential health and safety risks (Neo and Sahu 2024). Addressing these concerns may require comprehensive community engagement and the implementation of robust safety measures, adding complexity to project development.

The high volume of vehicular traffic in urban areas can complicate the transportation of alternative fuels to and from the port. This congestion may lead to logistical challenges and increased costs associated with fuel delivery. Modifying current port operations to accommodate new fuels requires careful planning to minimize disruptions. The dense urban setting can exacerbate these challenges because there is limited flexibility to adjust existing workflows and infrastructure.

8.2.5. Fuel Sourcing

A demand for biofuels of approximately 0.44 million tonnes per year could potentially be met through local production, given high resource availability and relatively low production costs in the region. There is potential to produce approximately 1.75 million tonnes VSLFO-eq of relatively low-cost bio-methanol from MSW feedstocks surrounding the port and approximately 0.25 million tonnes VLSFO-eq of biodiesel from lipid feedstocks. By leveraging this production potential, as well as existing biodiesel production and transportation infrastructure, the port could not only meet demand but also potentially export surplus fuels.

8.2.6. Demand Generation

Port of NY/NJ's high throughput and strategic location—as the largest port on the U.S. East Coast, gateway to one of the most concentrated consumer markets in North America, and fast access to inland and northern markets (PANYNJ, n.d.)—offer significant opportunities to generate demand for biofuels. Integrating biofuels into new shipping corridors—such as potential corridors connecting Port of NY/NJ with European or South American ports—could increase adoption and scale production. The port already has a Clean Vessel Incentive Program, encouraging ocean-going vessels calling at the port to make voluntary improvements to their engines, fuels, or technologies by providing financial incentives to these operators, charters, and agents (PANYNJ n.d.). The program provides an Alternative Fuel Incentive of $3,000 per qualifying call for vessels that can successfully demonstrate the use of an alternative fuel (PANYNJ 2023b).

8.2.7. Considerations for Future Development

To solidify a position as a leader in biofuel bunkering, the Port of NY/NJ and similar ports might consider moving quickly to add capabilities for biofuel bunkering. Given the potential for locally produced, low-cost biodiesel and bio-methanol, it could be advantageous for Port of NY/NJ to focus expanded bunkering capacities on those fuels. As a mid-level bunkering port globally, moving quickly to install capabilities could help to position Port of NY/NJ, and similarly sized ports, as leaders for supply of alternative fuels.

Along with installing physical infrastructure, best practice for integrating biofuel bunkering is to collaborate with other ports, shipping lines, producers, and international standards organizations to ensure consistent standards and certification protocols for biofuels (Wingrove 2023). In addition, engaging port communities early in the implementation process of alternative fuels to provide information and hear community concerns might help to reduce misconceptions or opposition that could delay implementation, particularly for ports located in dense urban communities (Child 2021).

Continuing collaboration among local stakeholders could create connections between potential biofuel producers and marine terminal suppliers. These connections may result in greater certainty for producers to move forward with fuel production projects in the area. Capitalizing on the robust national fuel transportation infrastructure might also assist with meeting demand in lieu of local production.

The port could continue to foster demand through the continuation of a robust Clean Vessel Incentive Program, and other ports may benefit from instituting similar programs that provide appropriate incentives to alternative fuel users. Ports might also foster demand through participation in shipping modernization initiatives such as green corridors. Although outside of the port's purview, working with regulators to explore opportunities to enact a state or regional fuel standard or tax incentive policy similar to other U.S. states (e.g., the Low Carbon Fuel Standard in California), but which includes the maritime sector, might help to lower fuel costs and increase demand for alternative fuels.

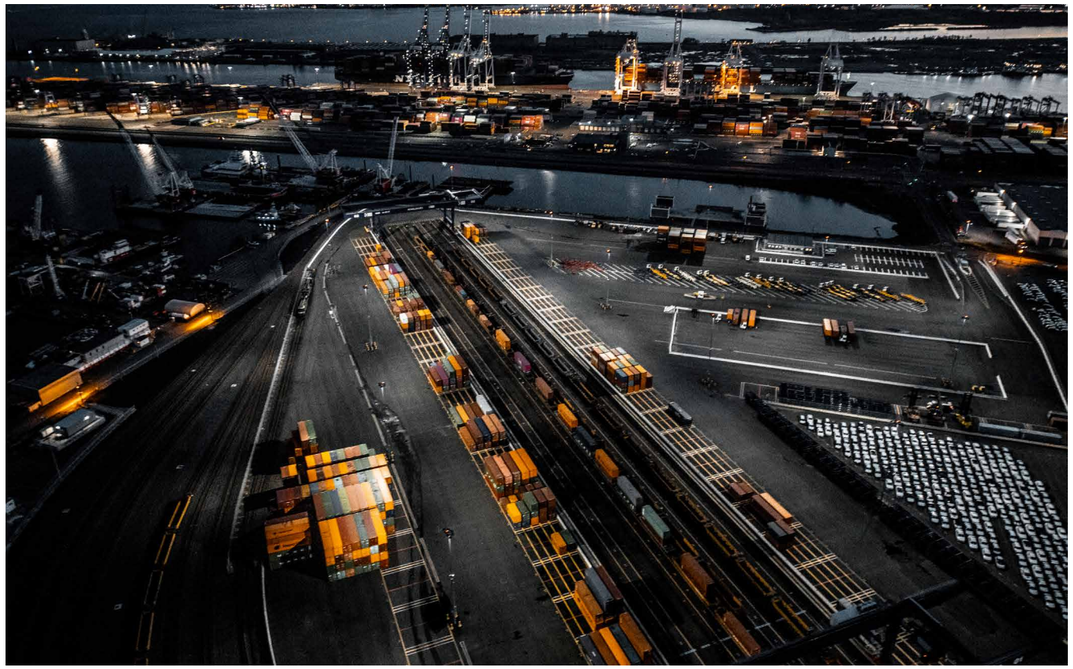


Photo from Getty Images 1183442221

8.3. Mundra, India

8.3.1. Background

Mundra Port, located on the western coast of India, is the country's largest commercial port. It plays a vital role in facilitating trade and economic activity in the region, serving as a key maritime gateway for both national and international trade routes (Maritime Gateway 2023). Current bunkering volumes at Mundra Port are estimated at approximately 0.8 million tonnes per year, positioning the port as a growing regional hub for marine fuel supply. At an illustrative demand of 10% biofuels by 2030, Mundra would need to supply around 80,000 tonnes annually.

Mundra could potentially meet demand through local production of biodiesel (Figure 20). The cost of production is low to moderate in comparison to production costs in other countries. Based on the surrounding feedstock availability, there is also the potential to produce approximately 0.23 million tonnes VLSFO-eq of low-to-moderate-cost HTL-oil.

In 2021, the Indian Ministry of Ports, Shipping, and Waterways published its Maritime India Vision 2030 (Ministry of Ports, Shipping, and Waterways 2021). The Maritime India Vision is intended as a guide to strengthen the country's maritime sector through concerted interventions. There are more than 150 initiatives in the plan, including a Sustainable and Green Maritime Sector focus area. In May 2023, the Ministry of Ports, Shipping, and Waterways released their "Harit Sagar" Green Port Guidelines (GPG). The guidelines call for a reduction in carbon emissions per ton of cargo by 30% by 2030 and 70% by 2047 compared to levels from fiscal year 2022–2023, and net-zero by 2070. Key regulations in the guidelines include green ammonia bunkering and refueling facilities established at major ports by 2035, at least one LNG bunkering station installed by 2030, and introduction of incentive measures such as queue priority or berth due rebates for vessels running on alternative fuels (Ministry of Ports, Shipping and Waterways 2023). Although these requirements do not apply directly to Mundra, as it is not classified as one of the 12 "Major Ports," the port will likely need to adopt similar practices to remain competitive in the national and global maritime markets (Naveiro and Garcia Mateo 2021; Sneha 2024).

8.3.2. Readiness for Biofuel Bunkering

Mundra Port's existing infrastructure is largely tailored to traditional fuels, with VLSFO, high sulfur fuel oil, and marine gas oil services available (Adani Natural Resources, n.d.). The port has multiple tanks dedicated to bunkering operations, and nearly all jetties at the port are equipped with 12- and 16-inch pipelines for supplying bunker fuel. The port also has a dedicated barge berth to support ship-to-ship bunkering (Adani Natural Resources, n.d.).

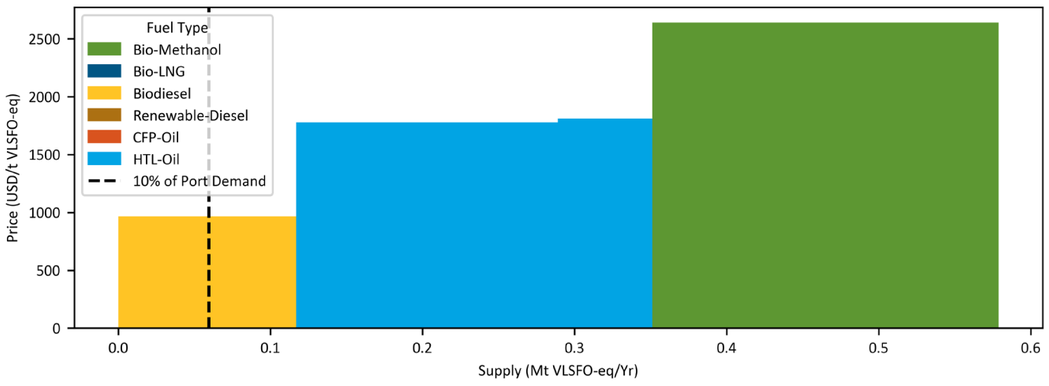


Figure 20. Mundra Port's potential biofuel production based on feedstock quantity and a maximum production price of $3,000/t VLSFO-eq. The dashed line represents the quantity required to meet 10% of port fuel demand. *Image by Nicholas Carlson, NLR*



Photo from Getty Images 1152010591

8.3.3. Fuel Sourcing

Given Mundra's smaller bunkering market, it may be advantageous to focus alternative fuel efforts on a single fuel. Biodiesel appears to be the most logical, given its local production potential and the relative ease at which existing infrastructure can be modified for biodiesel handling. Mundra could either work locally to secure a production contract or import the fuel, if local conditions and economics make this a more favorable option.

8.3.4. Generating Demand

Although Mundra Port is not included within the list of "Major Ports" required to meet India's GPGs, the port will likely need to implement similar practices to retain its relevance and competitiveness (Naveiro and Garcia Mateo 2021; Sneha 2024). The port already has experience with incentive measures for alternative-fueled vessels from when it offered a 50% discount to vessels using LNG for a 6-month period in 2021 (Maritime Gateway 2021). The port could use this experience to further generate demand for marine biofuels.

8.3.5. Considerations for Future Development

Mundra Port could leverage its exclusion from the GPG requirements as an opportunity to position itself as a national leader in biofuel bunkering. With the 12 Major Ports, as defined by the GPG, required to install ammonia and LNG bunkering infrastructure by 2035 and 2030, respectively, Mundra has the unique opportunity as one of the country's largest ports excluded from these regulations to direct investments into other biofuel bunkering and supply instead. By acting quickly to secure supply and upgrade necessary infrastructure for 1 to 2 key biofuels, Mundra, and similarly niche ports, could position themselves as regional biofuel bunkering leaders.

Highlights

- Ports could utilize mechanisms, such as vessel incentive programs, and leverage efforts such as Shipping Corridors to help generate demand for biofuels at their ports.
- Large bunkering ports that have historically imported fuels to meet demand could benefit from proactive efforts to build alternative fuel supply chains, support trials and research on developing fuels, and align operational bunkering practices with international standards.
- Ports that show high production potential for biofuels could benefit from moving quickly to initiate biofuel bunkering capabilities at their ports and from working collaboratively with port and regional stakeholders to drive the production, transport, and bunkering of those fuels.
- Ports in more niche markets (e.g., ports that don't have huge production potential and/or are not current bunkering leaders) could capitalize on the opportunities biofuels present by acting quickly to select and initiate bunkering of 1 to 2 key biofuels to position themselves as key regional players for those fuels.
- Ports in high-density urban areas could work to streamline implementation of biofuel bunkering and use by engaging port communities early in the process and providing information on the safety and use of these fuels to prevent public misconceptions or opposition.

9. Discussion and Conclusions

This report provides important insight into the possibility of biofuels being produced locally near 24 seaports. In general, ports near a large population and/or having a large resource collection radius have the greatest total resource potential. Select MSW resources, particularly plastic and paper/cardboard waste, make up a vast share of the potential resources across nearly every port. These resources are best suited for bio-methanol or CFP bio-intermediate production, although they could also be converted to other biofuels using processes not covered in this report. Resources with established markets (e.g., vegetable oils and FOG) exhibit the highest prices of any feedstock but still present lower-cost options to produce marine biofuels because of reduced upgrading requirements and subsequent costs.

Bio-methanol, biodiesel, and renewable diesel (although not preferred herein on a purely economic basis) lead as near-term marine biofuel choices, which is no surprise, considering they are the most commercially available of the conversion processes considered. They are followed by partially upgraded HTL and CFP bio-intermediates that, although less mature technologies, also require less processing. Bio-LNG also presents an interesting opportunity for ports with plentiful wet waste resources and existing gas processing infrastructure. Bio-LNG also has the opportunity to be produced away from ports and purchased through a credit system without the need to be physically transported to port, as long as ports have infrastructure for LNG bunkering in place. Ports with access to higher supplies of lower-cost feedstocks at which production could exceed local fuel demand could become candidates for increased bunkering or increased fuel exports in the future. These ports exist mainly in the Americas (of the 24 ports selected).

Factors that could limit the local production and implementation of biofuels at a seaport include inadequate local resource supply for conversion to biofuels, logistical challenges (e.g., resource collection, separation), limited infrastructure for transporting resources and fuels, constrained land for new fueling facilities, and potentially limited capital available for investment in facilities and infrastructure. Policy could play an important role in jumpstarting investment in biofuels. Of the 18 countries and unions examined in this research, 12 have policies potentially or explicitly regarding maritime biofuel, or some level of production of biofuels. Broader policies focused on the transportation sector as a whole can, in some cases, also be applied to the maritime sector but often through optional, not mandatory, participation. Other countries have policies encouraging biofuel deployment, but they exclude maritime as an acceptable use.

There are important topics that are not considered in this report. There may be a need for blending these biofuels (e.g., biodiesel, renewable diesel, bio-methanol, and bio-LNG) with their conventional counterparts, at least in the short term as production of biofuel ramps up. In addition, discussion around ship engines and their compatibility with these biofuels was considered outside the scope of this report. Potential trade routes for biofuels were not analyzed, although the ports that have the potential to supply more biofuels than their bunkering demand were noted (Figure 10). Finally, biofuel scalability and potential to supply sectors other than maritime were also not explored.

To conclude, there is significant potential for biofuel production surrounding many global ports considered in this study. To implement these fuels will take a joint effort among many stakeholders, including fuel producers, ports, and terminal and ship operators. The case studies in this report provide potential directions for ports to consider to drive the implementation of biofuels at various port types. Ports will likely need to work within their own local contexts for fuel production and sourcing and port readiness and safety. They will also need to work within the global context to align with international standards and generate reliable demand. Although efforts to bring together stakeholders and drive implementation of alternative fuels are already underway, reports such as this, which provide continued knowledge and support on various aspects of alternative fuel production and use, may play a role in providing confidence and understanding within the maritime industry.

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Appendix A. Reference Information for Resource Assessment and TEA

Table A-1. Selected Ports

Port	Bunker Volume (million tonnes/yr)	Year
Port of Singapore, Singapore	47.88	2022
Port of Rotterdam, Netherlands	10.80	2022
Port of Fujairah, United Arab Emirates	8.03	2022
Port of Zhoushan, China	6.02	2022
Port of Panama City, Panama	5.20	2022
Port of Hong Kong, China	5.12	2022
Port of New York and New Jersey, United States	4.42	2022
Port of Algeciras, Spain	4.00	2022
Port of Piraeus, Greece	3.60	2019
Port Houston, United States	3.10	2020
Ports of Los Angeles/Long Beach	2.96	2022
Port of Las Palmas, Canary Islands	2.73	2022
Ports of Seattle/Tacoma, United States	1.70	2019
Port of South Louisiana, United States	1.50	2022
Port of Buenos Aires, Argentina	1.30	2022
Port of Tauranga, New Zealand	0.90	2017
Port of Corpus Christi, United States	0.70	2022
Ports of Savannah/Jacksonville, United States	0.70	2016
Port of Spain, Trinidad and Tobago	0.70	2016
Port of Mundra, India	0.60	2008
Port of Açu, Brazil	0.40	Approximation for 2026
Port Louis, Mauritius	0.40	2017
Port of Durban, South Africa	0.40	2023
Port of Duluth, United States	0.05	2023

Table A-2. Spatial Resolution of Feedstock Data Considered at International Ports

International Ports	Spatial Resolution	Area (square miles)	Area (square km)
Port of Singapore	Countrywide	281	728
Port of Hong Kong	Hong Kong SAR	426	1,103
Port Louis	Countrywide	790	2,046
Port of Spain	Countrywide	1,981	5,131
Port of Las Palmas	Canary Islands	2,893	7,493
Port of Rotterdam	Countrywide	16,158	41,849
Port of Panama City	Countrywide	29,120	75,420
Port of Fujairah	Countrywide	32,300	83,657
Port of Algeciras	Andalusia Region	33,819	87,591
Port of Açu	Espirito Santo and Rio de Janeiro Provinces	34,757	90,020
Port of Durban	KwaZulu-Natal Province	36,433	94,361
Port of Zhoushan	Zhejiang Province	39,300	101,787
Port of Piraeus	Countrywide	50,949	131,957
Mundra Port	Gujarat State	75,685	196,023
Port of Tauranga	Countrywide	103,483	268,019
Port of Buenos Aires	Buenos Aires Province	118,754	307,571

In general, resource collection areas for international ports were limited to approximately 100,000 square miles (259,000 square km) to keep transportation costs low. For countries greatly exceeding this size, regional, state, or provincial data were used. In these cases, only the state or province where the port is located was considered, except for two countries: (1) Spain, where data for the Andalusia region were more widely available and aligned better with transportation parameters than state-level data; and (2) Brazil, where the province of Rio de Janeiro was too small relative to realistic transportation distances, so the neighboring province of Espirito Santo was also included.

Table A-3. TEA Cost Modeling Parameters Used for DCFROR Analysis

Parameter	Value
Cost Year	2023
Plant Life	30 years
Equity/Debt	30/70%
Loan Term	10 years
Construction Period	3 years
Year 1 Expenditure	8%
Year 2 Expenditure	60%
Year 3 Expenditure	32%
Working Capital	5% of fixed capital investment
Startup Time	3 months
Revenues During Startup	50%
Variable Costs During Startup	75%
Fixed Costs During Startup	100%
Depreciation	7-year MACRS
Transportation Cost	0.051 $/Ton-Mile
Inflation	2%

MACRS = modified accelerated cost recovery system.

Source: (U.S. IRS 2024)

Table A-4. Regional Port Assumptions Used for TEA

Port	Latitude	Longitude	Collection Radius (miles)	LCOE ($/MWh)	Cost of Debt	Cost of Equity	Tax Rate	Demand (Mt VLSFO-eq/yr)
Corpus Christi, USA	27.81	–97.40	100	18.46	8.00%	12.00%	25.00%	10.1
Duluth, USA	46.76	–92.10	100	30.00	8.00%	12.00%	25.00%	
Houston, USA	29.61	–95.03	100	23.86	8.00%	12.00%	25.00%	43.3
Los Angeles/Long Beach, USA	33.74	–118.26	100	40.40	8.00%	12.00%	25.00%	41.4
New York and New Jersey, USA	40.68	–74.10	100	40.40	8.00%	12.00%	25.00%	61.5
Savannah/ Jacksonville, USA	32.12	–81.14	100	30.00	8.00%	12.00%	25.00%	
Seattle/Tacoma, USA	47.61	122.35	100	79.22	8.00%	12.00%	25.00%	24.2
South Louisiana, USA	30.06	–90.56	100	23.86	8.00%	12.00%	25.00%	21.5
Singapore, Singapore	1.32	103.70	9	48.68	8.00%	12.00%	17.00%	696.2
Rotterdam, Netherlands	51.93	4.18	72	34.99	8.00%	12.00%	25.80%	120.2
Fujairah, United Arab Emirates (UAE)	25.17	56.36	101	29.69	8.09%	12.09%	25.00%	109.0
Panama City, Panama	8.96	–79.56	96	30.00	8.97%	12.97%	25.00%	73.1
Algeciras, Spain	36.19	–5.41	104	28.48	8.97%	12.97%	25.00%	55.9
Piraeus, Greece	37.95	23.62	127	30.32	10.04%	14.04%	22.00%	50.3
Las Palmas, Spain	28.14	–15.43	30	26.07	8.97%	12.97%	25.00%	37.7
Tauranga, New Zealand	–37.65	176.20	181	30.00	8.00%	12.00%	30.00%	
Mundra, India	22.75	69.69	155	30.00	8.97%	12.97%	30.00%	
Port Louis, Mauritius	–20.15	57.49	16	30.00	8.97%	12.97%	15.00%	
Durban, South Africa	–29.89	31.02	108	28.68	10.04%	14.04%	27.00%	
Buenos Aires, Argentina	–34.64	–58.34	194	30.68	17.56%	21.56%	35.00%	17.9
Açu, Brazil	–21.84	–41.02	105	30.45	10.04%	14.04%	34.00%	5.0
Port of Spain, Trinidad and Tobago	10.64	–61.50	25	30.45	10.04%	14.04%	30.00%	9.8
Zhoushan, China	29.98	121.67	112	20.00	8.54%	12.54%	25.00%	83.7
Hong Kong, China	22.30	114.16	12	20.00	8.09%	12.09%	16.50%	69.9

Mt = million tonnes; MWh = megawatt-hour.

Table A-5. Ratios and Conversions for International Feedstock Calculations

Material	Ratio	Unit	Source
Sludge	0.24	kg wastewater sludge/m^3 wastewater treated	https://www.researchgate.net/profile/Joshua-Boltz/publication/313774106_Biofilm_Reactor_Technology_and_Design/links/58a59e0f92851cf0e397bd20/Biofilm-Reactor-Technology-and-Design.pdf
Food waste	0.25	dry tonnes/wet tonne	https://www1.eere.energy.gov/apps/bioenergy/bto-2023-billion-ton-report/index.html
MSW wood	0.8	dry tonnes/wet tonne	https://www1.eere.energy.gov/apps/bioenergy/bto-2023-billion-ton-report/index.html
Green waste	0.6	dry tonnes/wet tonne	https://link.springer.com/chapter/10.1007/978-3-030-84180-5_4
Cattle	29	kg manure/head/year	https://www.researchgate.net/publication/317756788_Manure_from_Our_Agricultural_Animals_A_Quantitative_and_Qualitative_Analysis_Focused_on_Biogas_Production
Buffalo	19	tonnes manure/head/year	https://www.researchgate.net/publication/317756788_Manure_from_Our_Agricultural_Animals_A_Quantitative_and_Qualitative_Analysis_Focused_on_Biogas_Production
Sheep	3	tonnes manure/head/year	https://www.researchgate.net/publication/317756788_Manure_from_Our_Agricultural_Animals_A_Quantitative_and_Qualitative_Analysis_Focused_on_Biogas_Production
Goat	2.7	tonnes manure/head/year	https://www.researchgate.net/publication/317756788_Manure_from_Our_Agricultural_Animals_A_Quantitative_and_Qualitative_Analysis_Focused_on_Biogas_Production
Swine	2.5	tonnes manure/head/year	https://www.researchgate.net/publication/317756788_Manure_from_Our_Agricultural_Animals_A_Quantitative_and_Qualitative_Analysis_Focused_on_Biogas_Production
Poultry	0.19	tonnes manure/head/year	https://www.nlr.gov/docs/fy09osti/44808.pdf
Beef cattle manure	0.08	dry tonnes manure/wet tonne manure	https://www1.eere.energy.gov/apps/bioenergy/bto-2023-billion-ton-report/index.html
Swine manure	0.1	dry tonnes manure/wet tonne manure	https://www1.eere.energy.gov/apps/bioenergy/bto-2023-billion-ton-report/index.html
Dairy cattle manure	0.13	dry tonnes manure/wet tonne manure	https://www1.eere.energy.gov/apps/bioenergy/bto-2023-billion-ton-report/index.html
Poultry manure	0.25	dry tonnes manure/wet tonne manure	https://extension.uga.edu/publications/detail.html?number=B1245&title=maximizing-poultry-manure-use-through-nutrient-management-planning
Mill residues	117.5	oven dry kg/m^3 residue	https://www.ruraltech.org/projects/conversions/briggs_conversions/briggs_ch07/chapter07_combined.pdf

Table A-6. Feedstock Property Assumptions

Group	Resource	Density (t/m^3)	Water Content (Wt%)	Ash Content (Wt%)
Solid Waste	Woody biomass	0.3	0.3	0.0175
	Select MSW	0.6	0.05	0.05
Wet Waste	Food waste	0.2	0.8	0.053
	Manure	1.05	0.8	0.15
	Sludge	1.05	0.8	0.15
Lipid Based	Vegetable oils	0.9	0	
	FOG	0.9	0	
	UCO	0.9	0	0

Appendix B. Individual Port Supply Curves

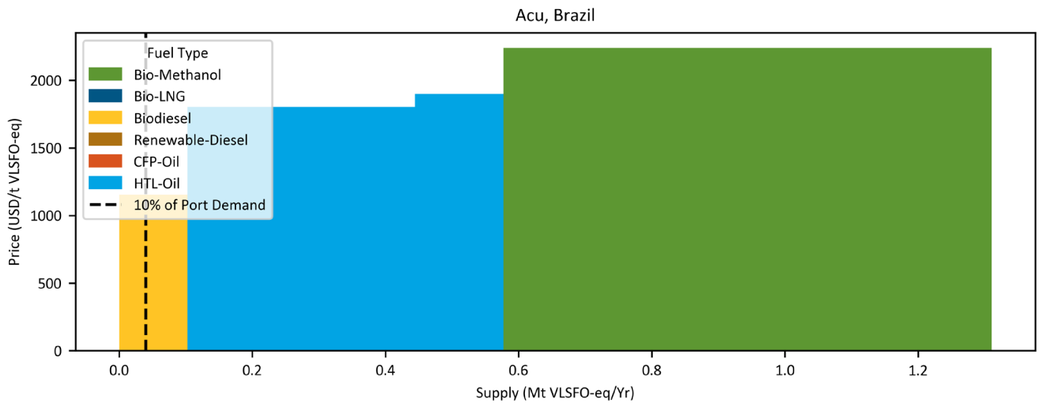


Figure B-1. Port of Açu's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

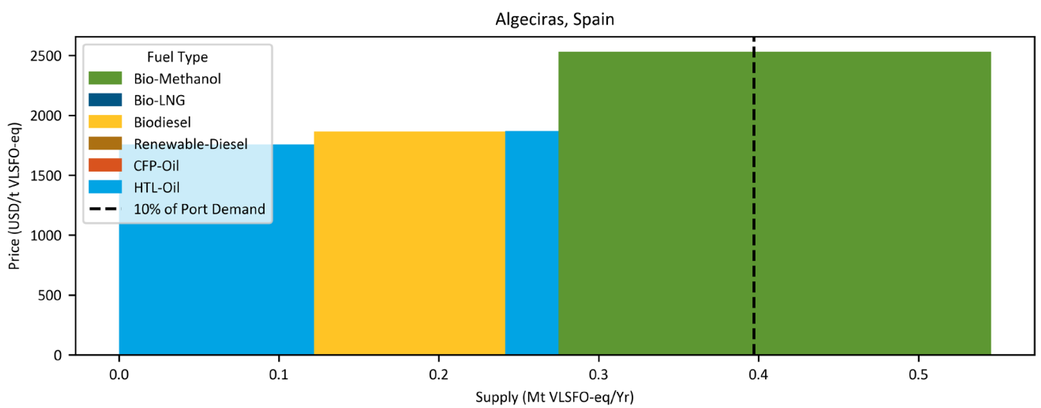


Figure B-2. Port of Alegciras' potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

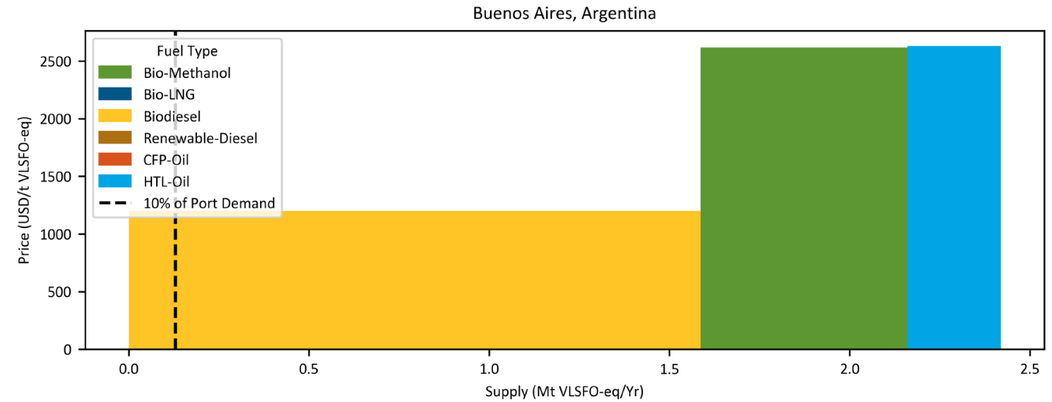


Figure B-3. Port of Buenos Aires' potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

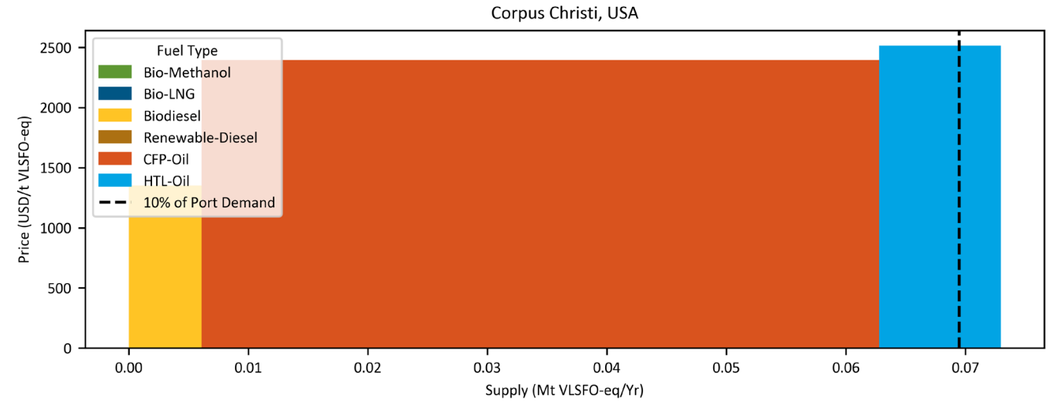


Figure B-4. Port of Corpus Christi's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

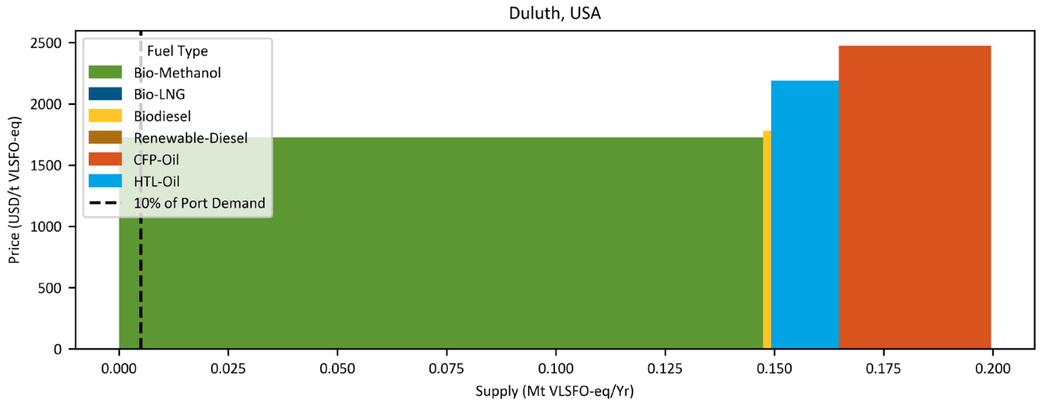


Figure B-5. Port of Duluth's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

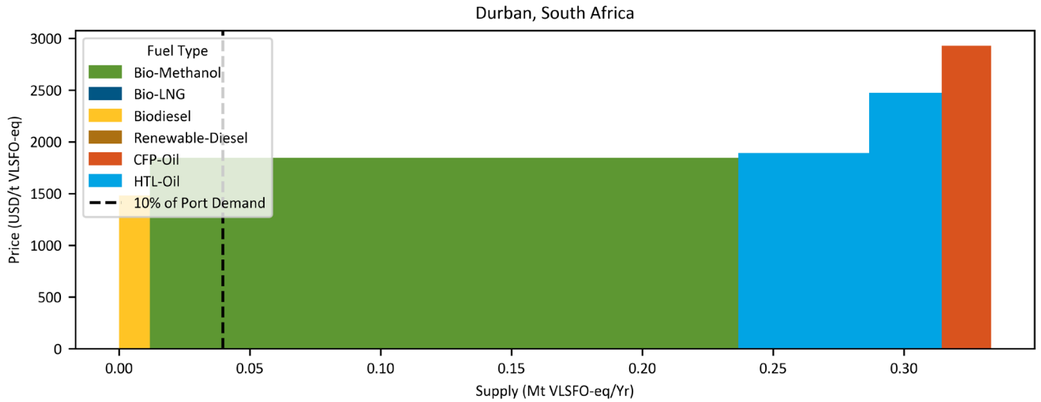


Figure B-6. Port of Durban's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

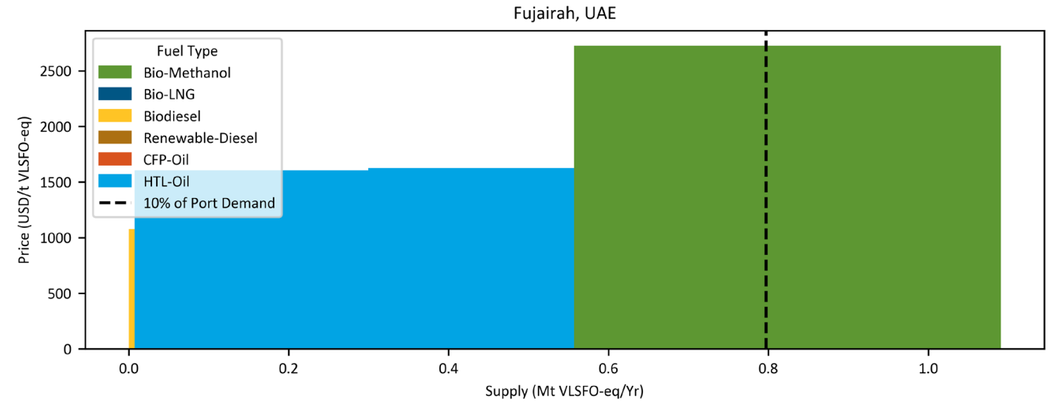


Figure B-7. Port of Fujairah's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

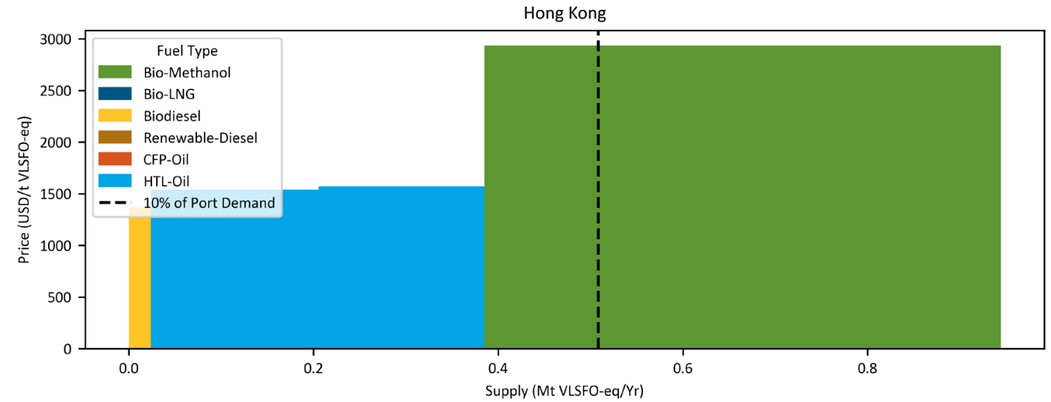


Figure B-8. Port of Hong Kong's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

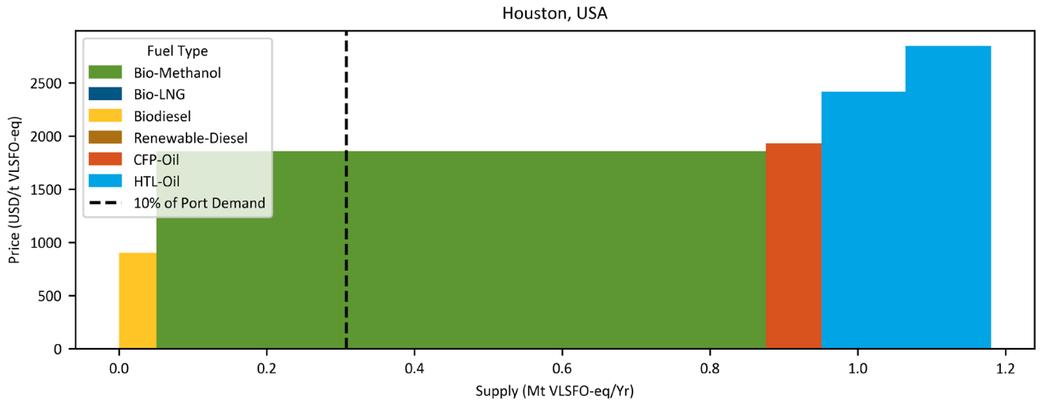


Figure B-9. Port of Houston's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

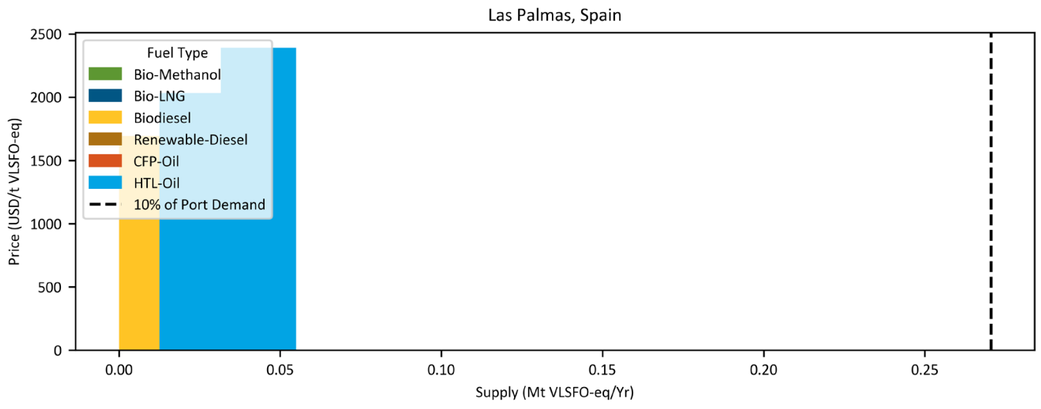


Figure B-10. Port of Las Palmas' potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

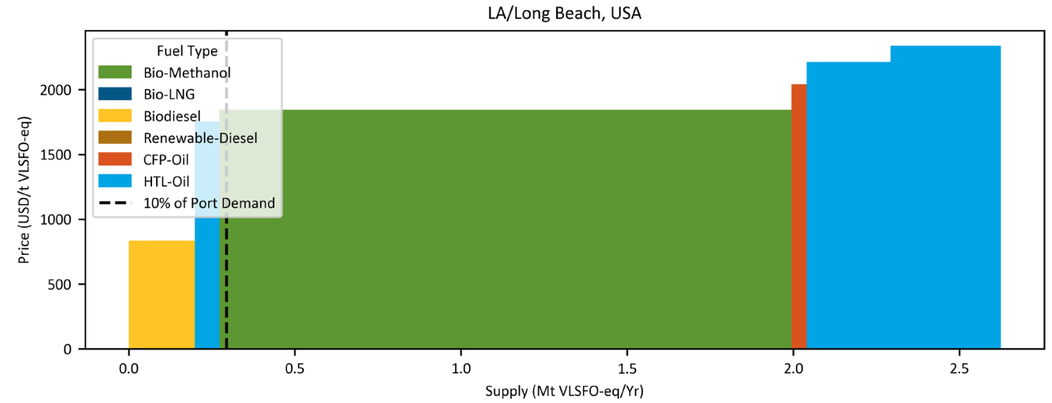


Figure B-11. Port of Los Angeles/Long Beach's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

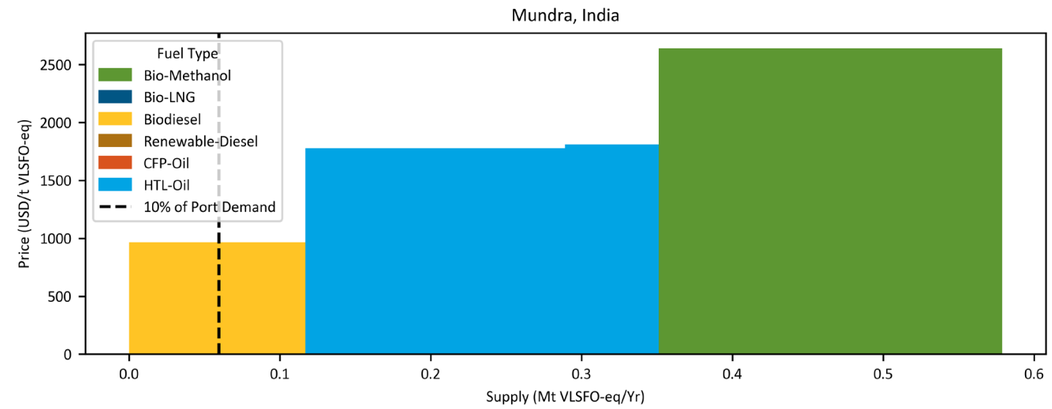


Figure B-12. Port of Mundra's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

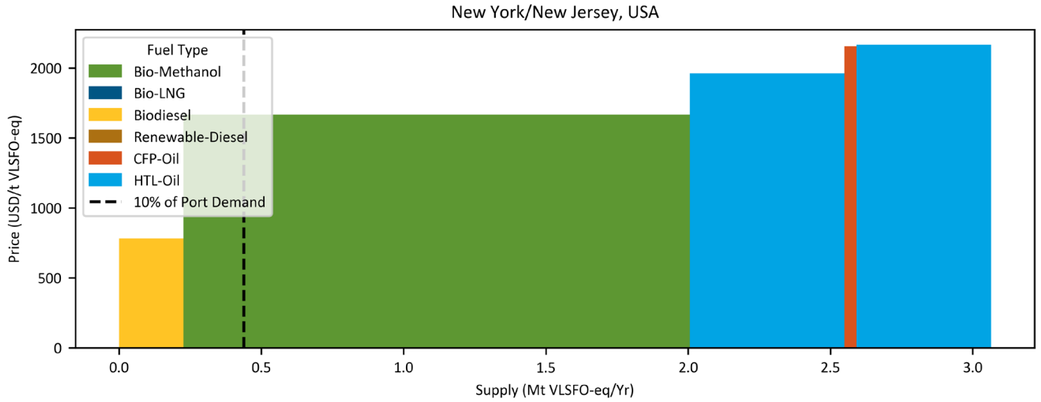


Figure B-13. Port of New York/New Jesey's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

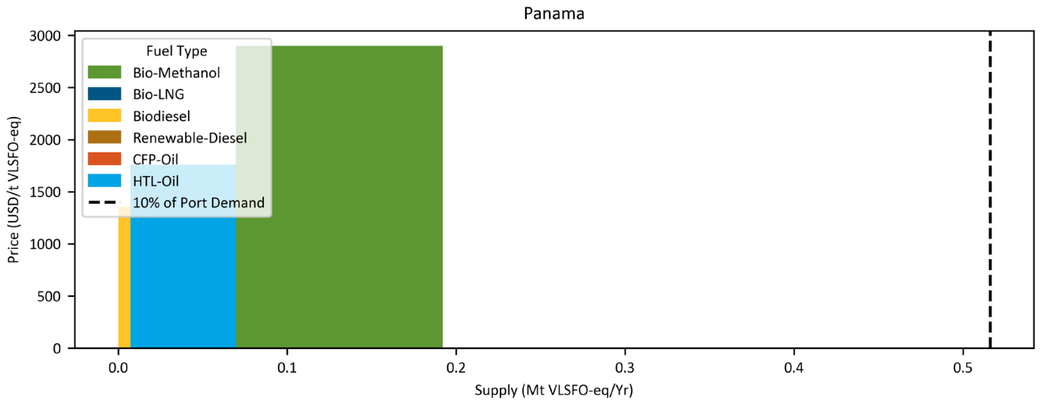


Figure B-14. Port of Panama's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

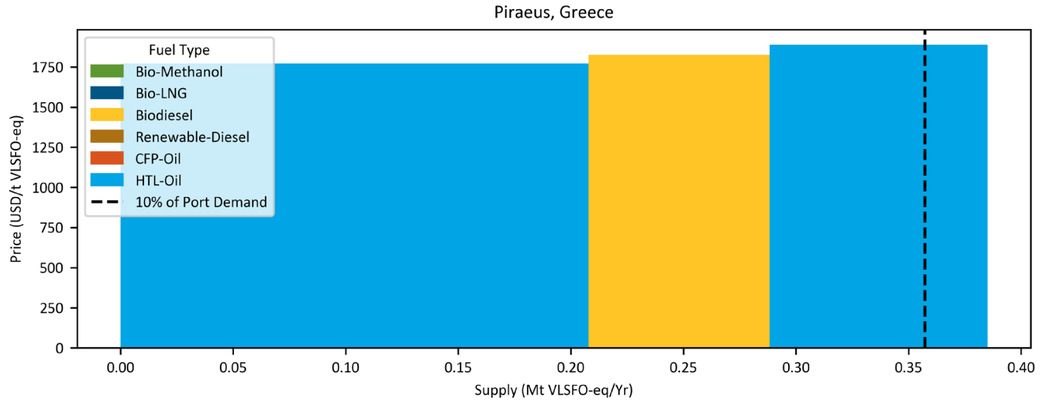


Figure B-15. Port of Piraeus' potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

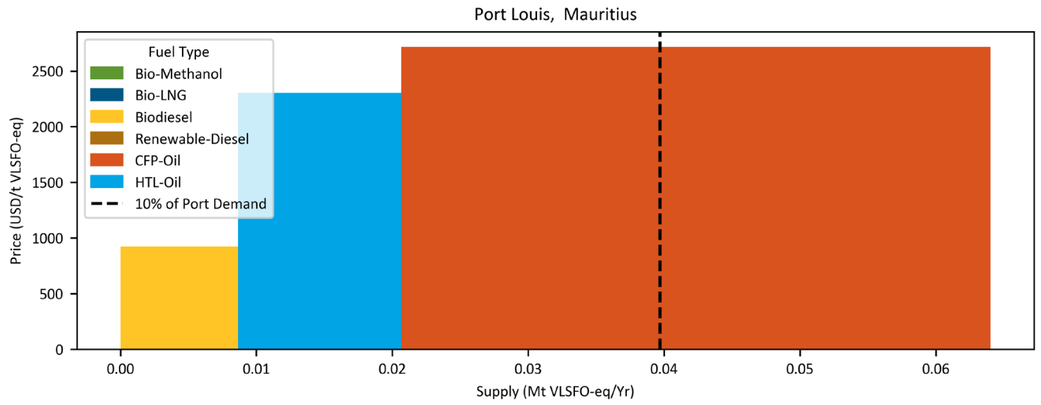


Figure B-16. Port Louis' potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

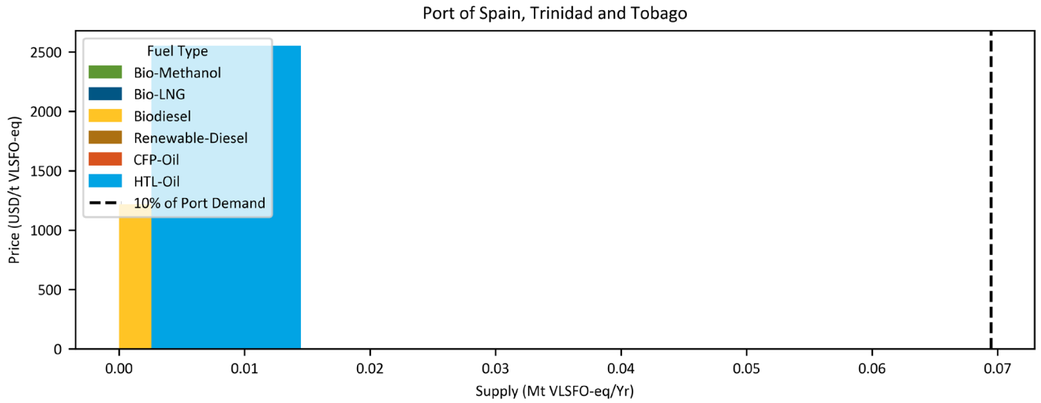


Figure B-17. Port of Spain's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

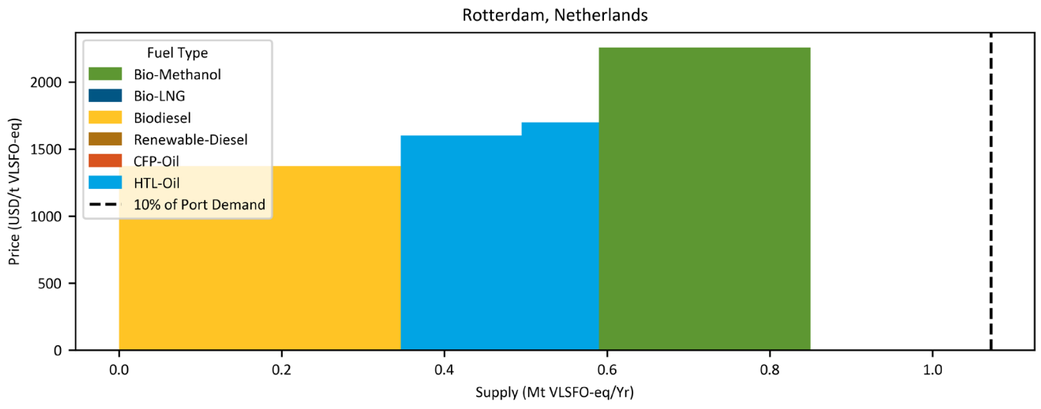


Figure B-18. Port of Rotterdam's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

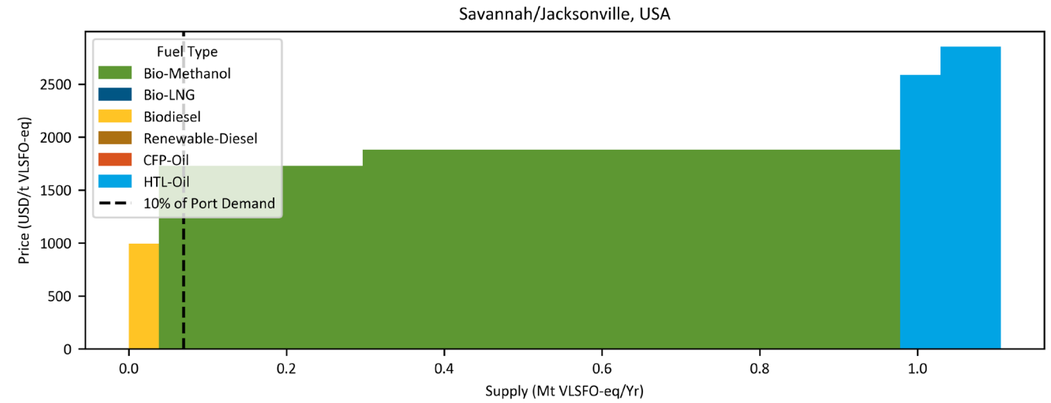


Figure B-19. Port of Savannah/Jacksonville's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

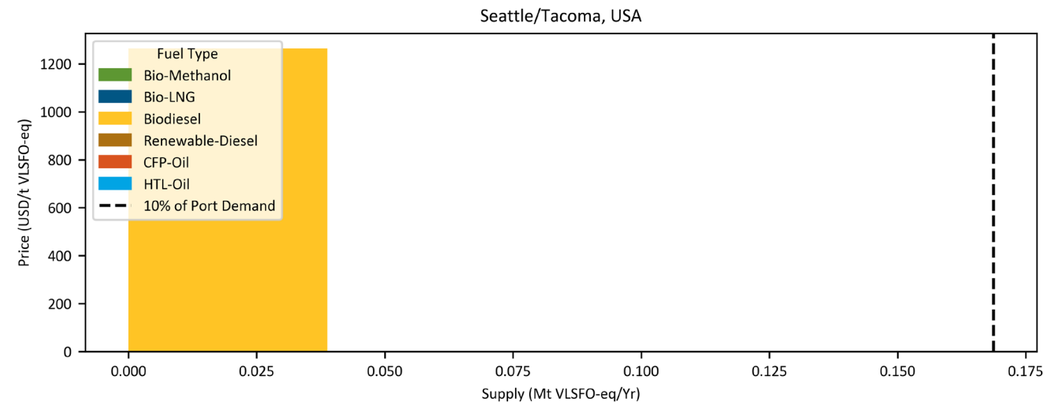


Figure B-20. Port of Seattle/Tacoma's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

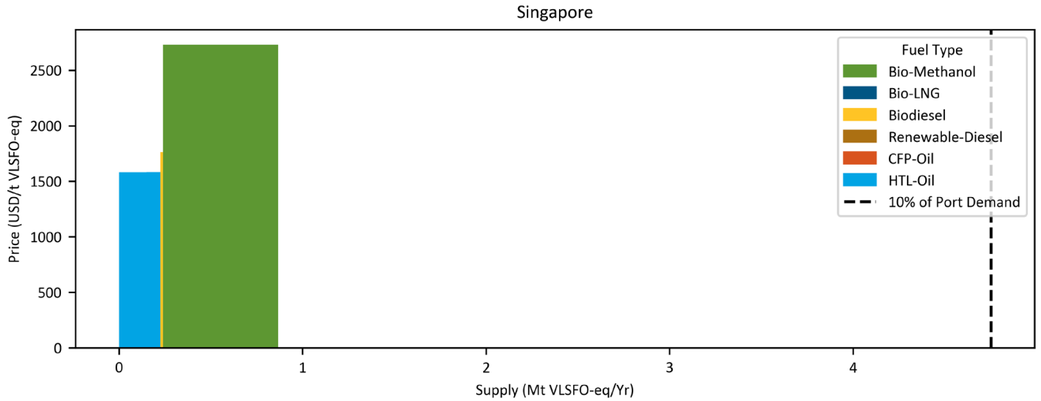


Figure B-21. Port of Singapore's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

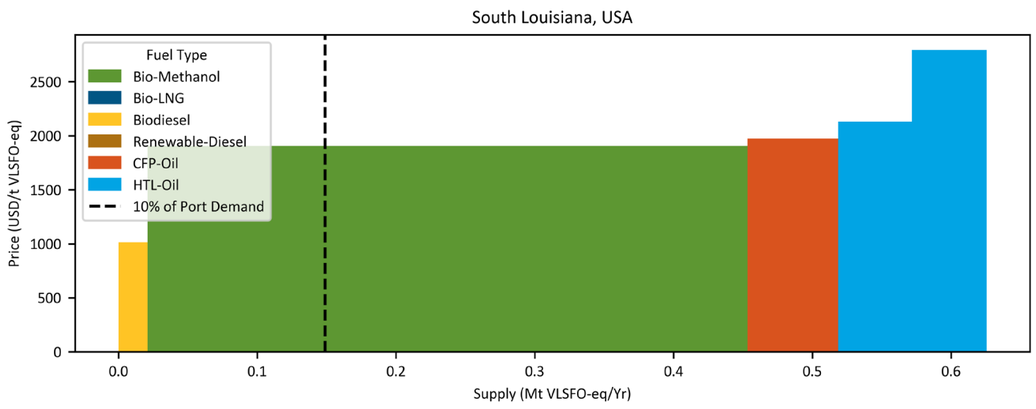


Figure B-22. Port of South Louisiana's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

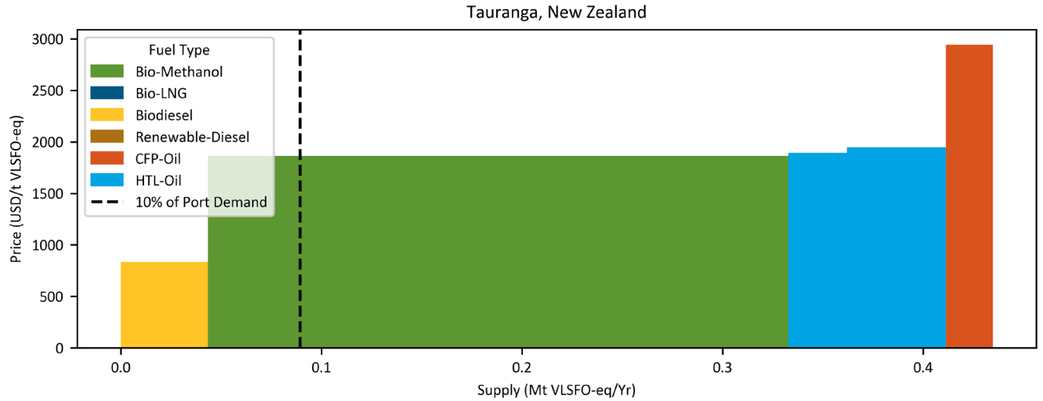


Figure B-23. Port of Tauranga's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

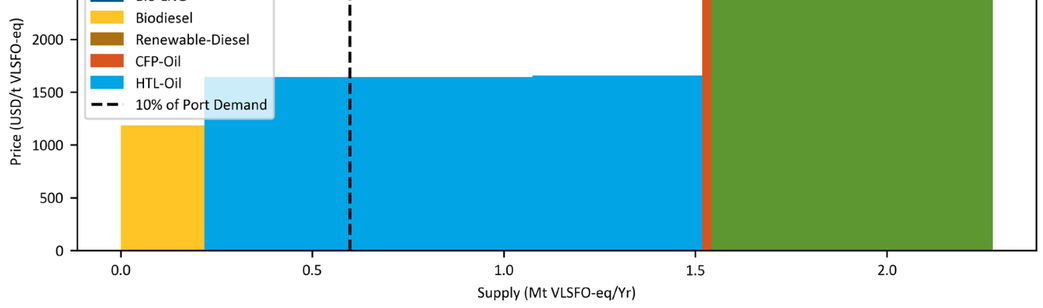


Figure B-24. Port of Zhoushan's potential biofuel production based on feedstock quantity and a maximum MFSP of $3,000/t VLSFO-eq. Dashed line represents 10% of current demand being met with alternative fuels. *Image by Nicholas Carlson, NLR*

Appendix C. Table of Biofuels Policy With Potential Maritime Applications

Table C-1 only includes policies with biofuels provisions; it excludes sweeping emission reduction or climate targets that do not have specific biofuel provisions.

Table C-1. Biofuels Policy With Potential Maritime Applications

Country	Policy	Provisions	Biofuels Covered	Maritime Applications
Argentina	Biofuels Law 27640—2021	Created Biofuels Special Committee Established biodiesel blend rate of 5% and bioethanol blend rate of 12%; only locally produced biofuels can meet mandates Exempted biofuels from taxes on carbon dioxide and liquid fuels Established company authorization process for biofuel production, storage, and distribution Bars fossil fuel companies from producing biofuels • If petroleum companies convert refineries to produce renewable diesel, must limit production capacity to avoid outcompeting smaller producers (USDA 2023a).	Ethanol, biodiesel, advanced biofuels (renewable diesel)	No
Argentina, Province of Cordoba	Law of Promotion, Development and Consumption of Biofuels and Bioenergy (Biofuels Law 10721)—2020	Created B100 mandate for provincial fleet Committed to receive support from the federal government for the creation of small biodiesel plants Implemented E85 and E100 for government fleets Opened gas stations that supply specific biofuel blends for government vehicles with the aim of providing higher percentage blends in 2024 (USDA 2023a)	Corn and soybean biodiesel	No
Argentina, Province of Santa Fe	Biofuels Law 14010	Encouraged biofuel usage across sectors, including maritime (USDA 2023a)	Soybean biodiesel	Yes
Brazil	National Biofuels Policy (RenovaBio)—2017	Established national carbon intensity targets; allocated among individual fuel distributors proportional to their shares in fossil fuel market Established certification process for biofuels production through energy-environmental scores Created Biofuel Decarbonization Credit (CBIO) issued by biofuel producers; fuel distributors meet above targets by purchasing CBIOs (equivalent to 1 ton CO2) (USDA 2023b)	Ethanol, biodiesel, biogas, advanced biofuels (renewable diesel, sustainable aviation fuel [SAF])	Yes
Brazil	BNDES RenovaBio—2021	Gave loans to biofuel producing companies to improve energy efficiency Reduced interest rates for those who reach the CO2 emission targets in RenovaBio (2017) (USDA 2023b)	Ethanol, biodiesel, biogas, advanced biofuels (bio-CNG, renewable diesel, SAF)	Yes
Brazil	Fuel of the Future (Resolution 7/2021)—2021	Designed to promote measures for expanding the use of sustainable fuels and the development of fuel technologies, covering land, water, and air transportation Created National Aviation Biofuel Program (ProBioQAV) subcommittee to oversee SAF introduction Intended to include broad range of stakeholders (e.g., government bodies and entities, airlines, airport operators, distributors of fossil fuels and biofuels, aircraft manufacturers, quality certification laboratories, universities, raw materials sector) Mandated the aviation sector to cut carbon intensity by 1% from 2027 (against a 2026 baseline), rising to 10% by 2037 (USDA 2023b)	Ethanol, biodiesel, biogas, advanced biofuels (renewable diesel, SAF)	Yes
Brazil	National Program for Production and Use of Biodiesel (PNPB)—2004	Required laws to introduce blending mandates, define the federal tax model for biodiesel, establish the conditions for the registration of producers and importers (USDA 2023b)	Biodiesel	Yes
Brazil	Law 11,097—2005	Mandated the blending of biodiesel with conventional diesel Progressively increased blend ratio; beginning at 2% (USDA 2023b), currently at 14% Hydrocarbon Processing, 2025)	Biodiesel	Yes
Brazil	Ordinance MME 252/2019; Ordinance MME 349/2019	Identifies priority projects in oil, natural gas, and biofuels to determine issuance of incentives Finances programs to reduce carbon intensity of biofuels	Ethanol, biodiesel, biogas, advanced biofuels	Primarily addresses road transport
Brazil	Social Fuel Seal—2005	Granted certification to smallholder farmers/producers to incentivize rural inclusion in biodiesel production (Silva et al. 2014)	Biodiesel	Yes
China	14th Five-Year Plan (FYP) for Bioeconomic Development—2022	Established national biotechnology framework Promotes: • Development of bioenergy, biofuels • Biomass combustion and blending standards • Development and manufacturing of equipment for bio-LNG, cellulosic ethanol, algae-based biofuels • Replacement of fossil fuels with advanced biofuels in municipal operations, transportation, and other critical areas • Collection of biomass raw materials, the production and use of organic fertilizers, and the scaling up of biofuel production • Use of biodiesel and bio jet fuel through pilot projects and demonstrations in suitable areas. Includes pilot projects for cellulosic ethanol, biodiesel, and biogas industries in urban and rural areas with concentrated organic waste (USDA 2023c)	Non-grain ethanol, cellulosic biofuels, biomass, bio-LNG, cellulosic ethanol, algae-based biofuels	Yes

Country	Policy	Provisions	Biofuels Covered	Maritime Applications
China	National Energy Administration Mandate—2024	Pilot project following FYP mandate Established policy frameworks to create demonstration projects to scale up biofuel usage Suggested introducing biodiesel into administrative or industrial clusters to develop biofuel supply chain Recommended testing B5, B24, and other qualified biodiesels on both inland waterways and sea routes (USDA 2023c)	Biodiesel	Yes
European Union	Renewable Energy Directives —2009, 2018, 2023	As of the most recent directive (REDII), member states must ensure that: • At least 29% of total transport fuel must be from renewables • 5.5% must be advanced biofuel • Proportion of biofuels from used cooking oil or animal fat-based feedstock in transport energy consumption is capped at 1.7% • Advanced biofuels and RFNBOs are double-counted • Advanced biofuels and RFNBOs receive multipliers of 1.2 in aviation and 1.5 in maritime transport. • Created sustainability criteria and quality standards for biofuels: • Defined and set limits on high indirect land use change (ILUC) biofuels • Allowed a 1% increase in the share of conventional biofuels used in the transport sector with a maximum share of 7%; calculated baseline using 2020 consumption. Mandates individual member nations to establish a 10-year National Energy and Climate Plan (European Council 2023) (European Commission, n.d.-b) (European Union 2023)	Ethanol, biodiesel, advanced biofuels (cellulosic ethanol, Fischer-Tropsch Diesel, renewable diesel, bio-methanol, bioethanol, algae-based biofuel), biogas	Yes
European Union	ReFuelEU—2023	Mandates blend of 2% sustainable aviation fuel in conventional jet fuel; proportion must be 20% by 2035 Applies to all airlines that operate in the region Eventually all aviation fuel must contain a minimum level of synthetic fuels manufactured with captured carbon. (European Commission n.d.)	SAF	Yes

Country	Policy	Provisions	Biofuels Covered	Maritime Applications
European Union	FuelEU Maritime Regulation	Passenger or cargo ships over 5,000 gross tonnage are required to reduce emissions starting with 2% by 2025, increasing to 80% of 1990 levels by 2050 Applies to 100% of fuel for ships within an EU member state, and 50% for nonmember state ships only arriving or departing Charges ships that fail to meet the requirement a penalty amount dependent on the difference in energy from compliant and noncompliant sources Beginning in 2030, ships will be required to use onshore power at certain EU member state's ports Biofuels from food or feed crops are calculated (V Group Limited n.d.) (European Commission 2021)	Biodiesel Bio-LNG HVO	Yes
Greece	Law 3054/2002	Mandates biofuel diesel blending of 7% and biofuel gasoline blending of 3.3% 0.2% of blended biofuels must meet the EU standard for advanced biofuels (ePURE 2024)	Biodiesel	Intended for road transport
Netherlands	Tradable renewable energy units (HBEs) system	Mandates that: • Fuel suppliers must ensure biofuels constitute 18.3% of energy for road transport. • Advanced biofuels must account for 7% of the share of biofuels by 2030. • Quantities must be reported to the Dutch Emissions Authority annually; penalties issued if sales quotas are unmet. Optional participation from maritime and aviation sectors by producing HBEs	Ethanol, biodiesel, advanced biofuels (cellulosic ethanol, Fischer-Tropsch Diesel, bio-methanol, bioethanol, renewable diesel, algae-based biofuel), biogas, catch crop-based biomass, food processing by-product-based biomass	Yes
Spain	Royal Decree 1085/2015—2015, modified in 2021	Established a maximum limit of 7.2% for biofuels produced from food and feed crops • Modified by Ministerial Order ITC/1342/2022; set the maximum limit for biofuels produced from food and feed crops at 3.5% in 2023, 3% in 2024, and 2.6% in 2025. Mandates a target of 0.2% for advanced biofuels; limits contribution produced from used cooking oil and animal fats to 1.7%, as defined by REDs I and II Requires: • Documentation and certification of raw materials in biofuel production • Reporting from fuel distributors and local authorities on energy sales, savings, emission reductions (IEA, n.d.-a).	Ethanol, biodiesel, advanced biofuels (cellulosic ethanol, Fischer-Tropsch Diesel, bio-methanol, bioethanol, renewable diesel algae-based biofuel), biogas	Yes

Country	Policy	Provisions	Biofuels Covered	Maritime Applications
Spain	Recovery, Transformation and Resilience Plan (PRTR)— 2021	Facilitated regulatory reforms to streamline biofuel production; includes a system of guarantees of origin for biogas, mandatory penetration targets, and simplified administrative procedures Finances Biogas Roadmap (2022); allocated €150 million • Aims to multiply biogas production by 3.8 times by 2030 for transport, heating, and electricity • Supports R&D in biofuels to reduce emissions (European Commission, n.d.-c).	Biogas, cellulosic biofuel	No
Spain	Ministerial order TED/728/2024	Promotes RFNBO over biofuels Mandates that renewable energy must make up 29% of transportation fuel demand by 2023 Marine fuels from advanced biofuels have a multiplier of 1.2 times their energy content (Agencia Estatal Boletín Oficial del Estado 2024) (Instituto para la Diversificacion y Ahorro de la Energia 2024)	Advanced biofuels	Yes
India	National Policy on Biofuels—2018, 2022	Set a 20% blending mandate for ethanol; 5% blending mandate for biodiesel by 2030 Expanded the number of permissible feedstocks for different fuels Outlined the duties of government ministries to coordinate government actions Established guaranteed pricing, long-term ethanol contracts, and technical standards and codes (USDA 2024b) (IEA 2023b)	Ethanol, cellulosic ethanol, cellulosic butanol, biodiesel, advanced biofuels (algae-based biofuel, bio-CNG, biogas, SAF, pyrolysis oil, bio-hydrogen)	Yes
India	Make in India Initiative—2014	Promotes innovation in renewable energy; includes advanced biofuels generally Emphasizes production facilities in Special Economic Zones and Export Oriented Units (USDA 2024b)	Advanced biofuels	Yes
India	Roadmap for Ethanol Blending 2020–2025	Outlines annual plan to increase domestic ethanol production by: • Raising production capacity • Implementing phased rollouts of E10 and E20 fuel • Promoting production of E20 vehicles • Encouraging feedstock sustainability through low water consumption and non-food feedstocks (IEA, n.d.-b.)	Ethanol	No
India	Skill Council for Green Jobs—2015	Created industry-led council to lead vocational training, skills, and educational programs for renewable energy jobs Created occupational standards specifying skills needed for roles ("India's Skill Council for Green Jobs—Policies" n.d.)	Ethanol, biodiesel, biogas, biomass (Skill Council for Green Jobs, 2020.)	Yes
Panama	2011 Biofuels Law (Law 42 of 2011)	National biofuel incentives grant: • 10-year exemption from income taxes • Total exemption from entry fee costs • 10-year exemption from distribution or transmission rights for spot market operations (IEA, n.d.-d).	Renewable diesel, bioethanol, biodiesel, biogas	Yes
Panama	Blending mandates	Mandates 5% ethanol blending by April 2026 (Republic of Panama, 2024)	Ethanol	No
Singapore	Singapore Sustainable Air Hub Blueprint—2024	Aims to reduce aviation emissions from airport operations by 20% from 2019 by 2030; net-zero by 2050 Established a SAF blending mandate for 1% by 2026; to be increased to 3%–5% by 2030 (Neo 2024)	SAF	No
South Africa	Biofuels Industrial Strategy (BIS)—2007	Set a biofuels penetration target of 4.5% of the national fuel pool; 2% must come from first-generation biofuels (IEA 2023a)	Ethanol, biodiesel, biogas	Yes
South Africa	South African Biofuels Regulatory Framework of 2020	Guidelines to meet BIS targets: • Regulates feedstock production to avoid conflicts with food production • Set mandatory blending regulations • Subsidizes the development of the biofuel industry • Ensures a cost recovery mechanism for blended fuel manufacturers • Sets strict criteria for fuel subsidy eligibility • Provides subsidies for financial and technical support to biofuel manufacturers, projects, and farmers. Blending mandates updated regularly; most recent update in 2023 Low-sulfur-grade diesel can contain ≤5% biodiesel, with increasing percentages for higher blends such as B10 to B50 Bioethanol blending must be between 2% and 10% (IEA 2023d)	Non-food biomass, algae-based biofuels	Yes
United Arab Emirates	National Policy on Biofuels—2024	To meet Net Zero by 2050 Initiative; announcement to develop regulations to oversee biofuels distribution, trading, and production Calls for: • Increase in biodiesel production by 20% • Production of 700 million litres of SAF annually (Government of UAE 2025).	Biodiesel, SAF	Yes

Country	Policy	Provisions	Biofuels Covered	Maritime Applications
United States	Renewable Fuel Standards (RFS)—Annual	EPA enforced Set annual renewable volume obligations; must achieve minimum life cycle emission reductions relative to 2005 petroleum fuel baseline Established trading system for renewable identification numbers (RINs); purchased or obtained by blending fuels; parties must submit annual reports (US EPA 2024)	Ethanol, biodiesel, advanced biofuels (cellulosic biofuels, algae-based biofuel, biogas, biomass-based diesel, renewable diesel)	No
United States	Inflation Reduction Act —2022	Committed $812 million toward biofuels Extended existing/created new tax credits toward biodiesel, renewable diesel, alternative fuels; second-generation biofuels New credits for SAF production and sale (e.g., SAF Grand Challenge) (Sadler, Rosas, and Clark-Sutton 2024)	Ethanol, advanced biofuels (renewable diesel, SAF, bio-CNG, algae-based biofuels, pyrolysis oil, bio-hydrogen), biodiesel, cellulosic biofuels	No
United States, California, Oregon, Washington	State Low Carbon Fuel Credits (LCFS); CA—2011	In CA, LCFS • Aims for 20% carbon reduction by 2030 from a 2010 baseline by setting declining annual target • Dictates at least 3% of the aggregate amount of bulk transportation fuel purchased by the state government must be from very-low-carbon transportation fuel sources. 13 states are considering/developing LCFS (NM, MN, IL, MI, NY, VT, MA, NE, OH, PA, NJ, HI, CO)	Ethanol, biodiesel, biogas, renewable diesel	Yes

Appendix D. United States Exports and Imports of Select Marine Fuels

Table D-1. United States Exports and Imports of Select Marine Fuels

Fuel Type	Exports ($)	Exports (Qty)	Imports ($)	Imports (Qty)
VLSFO Input (Distilled Fuel Oil <500 ppm Sulfur – 2024)	Not available	452,002 (EIA n.d.-b)	Not available	51,575 annual-thousand barrels (EIA 2024a; U.S. Imports from All Countries n.d.)
VLSFO Input (Residual Fuel Oil – 2024)	Not available	51,614 annual-thousand barrels (EIA n.d.-d)	Not available	2,954 annual-thousand barrels (EIA 2024a)
RD	Not available	The US has not exported RD in significant quantities through 2024 (EIA n.d.-c).	Not available	12,305 annual-thousand barrels (EIA 2024d)
Biodiesel (Mar 2024-Feb 2025)	$784M (OEC n.d.)	4,399 annual thousand barrels (EIA n.d.-a)	$1.42B (OEC n.d.)	9,992 annual thousand barrels (EIA n.d.-e)
LNG/RNG (2024)	$47,331,668,730 (WITS World Bank 2022b)	7,708,814 million cubic feet (EIA 2024b)	$1,004,379,480 (WITS World Bank 2023d)	3,144,546 million cubic feet (EIA 2024c)
Ammonia (2023)	355,957,710 (WITS World Bank 2023b)	1,152,450,000 kg (WITS World Bank 2023b)	1,345,887,040 (WITS World Bank 2023c)	2,090,180,000 kg (WITS World Bank 2023c)
Methanol (2023)	$923,385,340 (WITS World Bank 2023a)	3,533,820,000 kg (WITS World Bank 2023a)	$705,955,540 (WITS World Bank 2022a)	1,907,150,000 kg (WITS World Bank 2022a)

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The National Laboratory of the Rockies is a national laboratory of the U.S. Department of Energy, Office of Critical Minerals and Energy Innovation, operated under Contract No. DE-AC36-08GO28308.

NLR/TP-6A20-92537 • October 2026