Potential Availability of Alternative Fuel To Supply Maritime Activities in Pacific Northwest Ports

Kelcie Kraft, Sydney Harris, Kristi Moriarty, Emily Newes, and Billy Roberts

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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List of Acronyms

bioLNG	bio-based liquified natural gas
bpd	barrels per day
CCS	carbon capture and storage
CFP	Clean Fuels Program
CFS	Clean Fuel Standards
COP27	twenty-seventh Conference of the Parties
DOE	U.S. Department of Energy
DOS	U.S. Department of State
EOI	expression of interest
EPA	U.S. Environmental Protection Agency
FID	final investment decision
FOG	fats, oils, and greases
F/S	feasibility study
GHG	greenhouse gas
HEFA	hydro-processed esters and fatty acids
HFO	heavy fuel oil
IEA	International Energy Agency
IMO	International Maritime Organization
km	kilometer
LCFS	Low Carbon Fuel Standard
LNG	petroleum-based liquified natural gas
MDO	marine diesel oil
MESD	Maritime Energy & Sustainable Development Center of Excellence
MGO	marine gas oil
MMBtu	million British thermal units
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
MSW	municipal solid waste
NREL	National Renewable Energy Laboratory
NWSA	Northwest Seaport Alliance
ORNL	Oak Ridge National Laboratory
PNW	Pacific Northwest
PNNL	Pacific Northwest National Laboratory
ROK	Republic of Korea
SAF	sustainable aviation fuel
ULSD	ultra-low sulfur diesel
U.S.	United States
VLSFO-GE	very-low sulfur fuel oil gallon equivalents
ZESM	Zero-Emission Shipping Mission

Executive Summary

The international shipping sector represented 3% of global greenhouse gas emissions in 2023 (Office of Energy Efficiency & Renewable Energy 2024) and has been classified as a difficult-to-decarbonize industry (IRENA 2024). In an effort to drive decarbonization, the U.S. Department of Energy has partnered with Mission Innovation to co-lead the Zero-Emission Shipping Mission, which launched in 2021 (Office of Energy Efficiency & Renewable Energy 2021). In addition, the U.S. Department of State partnered with Norway to launch the Green Shipping Challenge in 2022 (Office of the Spokesperson 2022b). As part of the Zero-Emission Shipping Mission (ZESM) and Green Shipping Challenge, the United States is collaborating with the Republic of Korea (ROK) to develop a green shipping corridor (U.S. Mission Korea 2023).

The United States and ROK have conducted a pre-feasibility study as the first step in developing green shipping corridors connecting the countries. The ports included in the study are Seattle, Tacoma, and Everett in the U.S. Pacific Northwest (PNW) and Busan, Ulsan, and Masan in ROK. The National Renewable Energy Laboratory's role in the study was to analyze the availability and technical potential of alternative marine fuels in proximity to U.S. PNW ports.

The main findings show:

- Most (89.4%) of the existing alternative fuel capacity within the region is from renewable diesel (59.4%), biodiesel (18.2%), and sustainable aviation fuel (SAF) (11.8%) facilities, and is derived from lipids (canola, soybean, and distillers corn oils) and waste feedstocks such as waste fats, oils, and greases (FOG), woody residues, agricultural waste such as crop residues, and municipal solid waste.
- The largest growth in fuel capacity in the region by 2030 is projected to be in renewable diesel and hydrogen, though 85% of the renewable diesel capacity is anticipated to be produced at facilities using purpose-grown vegetable oils as part or all of their feedstock.
- The overall technical readiness of non-drop-in alternative fuel production and conversion technologies is more developed than alternative-fueled ships and associated fueling infrastructure (though methanol-fueled vessels are fully developed and in use throughout the world ("Methanol Fuelled Vessels on the Water and on the Way" 2024)). However, much of the fuel capacity in the region is comprised of drop-in fuels, making it technically possible to use existing infrastructure for transporting and bunkering to the existing fleet.

Data to inform regional alternative fuel quantity estimations were collected from an extensive review of databases, reports, announcements, and other publicly available resources. A maturity index and sector competition factor were applied to announced fuel projects to estimate the quantity of alternative fuel available to the maritime sector in the region by 2030. Demand data were collected from fuel bunkering logs covering the PNW seaports (State of Washington 2021). Both supply and demand data were converted to very-low sulfur fuel oil gallon equivalents (VLSFO-GE) for better comparison. Qualitative data were gathered through interviews with stakeholders, project developers, and industry experts.

Figure ES-1 shows the comparison of the anticipated fuel demand for the Ports of Seattle, Tacoma, and Everett and the estimated annual alternative fuel supply, both listed in VLSFO-GE.

Total alternative fuel capacity available to the maritime sector in the region is estimated to be 729.7 million VLSFO-GE per year by 2030, based on assumptions outlined in this report. This would be sufficient to cover the requirements of a green shipping corridor between the United States and ROK in the same period. However, it is possible that facilities listed in this report may not become operational with the capacity or timeline anticipated.

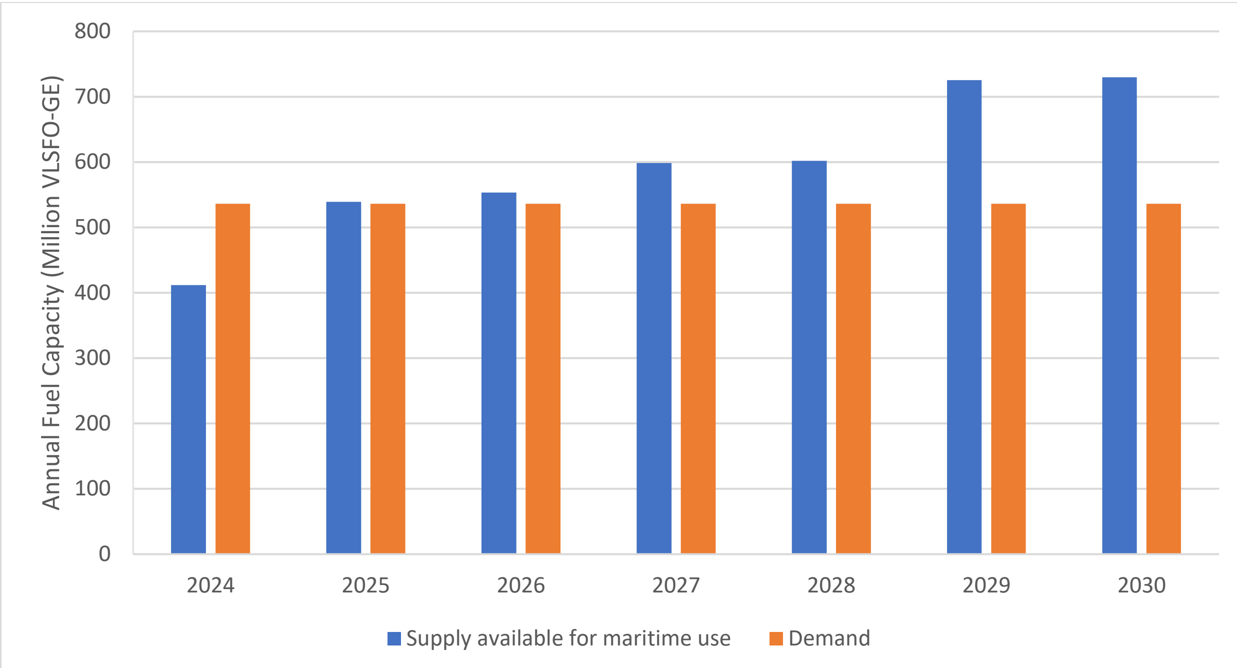

Figure ES-1. Comparison of alternative fuel supply available for maritime use within 1,000-km of the Port of Seattle and anticipated average annual fueling demand for the Ports of Seattle, Tacoma, and Everett from 2024 to 2030. The anticipated annual average fueling demand for the three ports is based off the average annual demand for the ports from 2007 to 2020 and lack of increasing fuel demand trends. Quantities listed in million very-low sulfur fuel oil gallon equivalents (VLSFO-GE) per year.

The findings from this report are being used to inform detailed feasibility studies for several U.S. PNW - ROK green shipping corridors. Updates from the U.S. PNW – ROK feasibility studies will continue to be published on Mission Innovation's green corridor tracking website (Zero Emission Shipping Mission, n.d.). In addition, this report has helped to inform further work on shipping decarbonization in the U.S. PNW, including the Pacific Northwest to Alaska Green Corridor focused on cruise vessels fueled by methanol (Port of Seattle, n.d.). Finally, this report provides a template for determining potential alternative fuel supply in future pre-feasibility studies for new green corridors.

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1 Introduction

Decarbonization of international shipping has the potential to reduce emissions on a global scale, as the industry contributed 3% of global greenhouse gas (GHG) emissions in 2023 (Office of Energy Efficiency & Renewable Energy 2024). Emissions from the sector increased by 5% between 2021 and 2022 and are expected to increase by 50% from 2018 levels by 2050 under a business-as-usual scenario (Office of the Spokesperson 2022a). In 2022, 99% of the total energy demand from ships was met with petroleum-based fuel (Connelly 2023). Additionally, shipping contributes to air pollution (nitrous oxides, sulfur oxides, carbon monoxide, hydrocarbons and particulate matter) that can have harmful health impacts (Gossling, Meyer-Habighorst, and Humpe 2021). The maritime industry is responsible for 9% of sulfur oxide and 18% of nitrous oxide emissions each year. Local air quality in coastal and port towns, affecting 12% of the population in the United States, can significantly suffer as a result ("Maritime Decarbonization," n.d.).

Despite these adverse environmental and health impacts, the shipping industry is relied on heavily to transport goods and passengers. 90% of global goods are transported by cargo ships (Bioenergy Technologies Office, n.d.). Therefore, it is vital to examine the use of alternative, low-carbon fuels to reduce shipping emissions and decarbonize the industry.

The interest in decarbonizing shipping routes is growing both internationally and domestically, including among private actors (Office of the Spokesperson 2022a). In 2023, the International Maritime Organization (IMO) announced a strategy to minimize emissions in the shipping sector, with a specific target to reach net-zero emissions by 2050 ("Revised GHG Reduction Strategy for Global Shipping Adopted" 2023). Prior to the IMO strategy, the Green Shipping Challenge, a decarbonization challenge created by the United States and Norway, was initiated in 2022. The challenge provides a framework to create green shipping corridors, which serve as low-emission shipping routes between partner nations (Office of the Spokesperson 2022a). Since initiation, 60 projects have been announced through the challenge, from both public and private actors, including the creation of the Zero-Emission Shipping Mission (ZESM) by Mission Innovation ("Green Shipping Challenge," n.d.). The ZESM aspires to showcase the commercial viability of switching to zero-emission ships and fuels ("Zero-Emission Shipping" n.d.). The United States – Republic of Korea (ROK) green corridor project was introduced at COP27 in collaboration with the ZESM and the Green Shipping Challenge (U.S. Mission Korea 2023).

The U.S. Pacific Northwest (PNW) is a central region for trade between the United States and ROK. The U.S. Department of State (DOS) is collaborating with the Northwest Seaport Alliance (NWSA), which is a partnership between the Ports of Seattle and Tacoma, for the United States – ROK green corridor project ("The Northwest Seaport Alliance Announces Partnership with Busan Port Authority to Further Decarbonization of Ports at United Nations Climate Conference" 2022). Specifically, ROK is one of the NWSA's main international trading partners ("Shipping: The Northwest Seaport Alliance" 2024). The Port of Seattle and the Port of Tacoma accommodate a variety of ships including roll-on/roll-off vessels, and the NWSA is one of the top five largest container gateways in the United States and over sees almost $75 billion in international trade through its ports ("The Northwest Seaport Alliance Bulkbreak Cargo Procedures" 2024; "Shipping: The Northwest Seaport Alliance" 2024). Both ports are home to naturally deep harbors that can serve the largest ships in use ("The Northwest Seaport Alliance

Cargo Operations: Terminals" 2024). The NWSA is also dedicated to emission reductions. The Alliance adopted the Northwest Ports Clean Air Strategy with the ultimate goal of phasing-out emissions from seaport-related activities, including from ocean-going vessels, by the year 2050 ("Northwest Ports Clean Air Strategy," n.d.). With the help of MMMCZCS and three U.S. national laboratories — the National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL), and Pacific Northwest National Laboratory (PNNL) —DOS and ROK hope to create green shipping corridors between the NWSA ports and ROK ports ("The Northwest Seaport Alliance Announces Partnership with Busan Port Authority to Further Decarbonization of Ports at United Nations Climate Conference" 2022).

To initiate the project, the United States and ROK developed an internal pre-feasibility report to acquire baseline data on the feasibility of establishing green shipping corridors between the U.S. PNW and ROK ("The Northwest Seaport Alliance Announces Partnership with Busan Port Authority to Further Decarbonization of Ports at United Nations Climate Conference" 2022). The report followed methodology designed by MMMCZCS for green shipping corridor initiation (Maersk Mc-Kinney Moller Center for Zero Carbon Shipping 2023). The pre-feasibility study compiled a variety of data including vessel types, route frequencies, and port readiness in an effort to determine which routes served as the best candidates to move forward with full feasibility studies. A key aspect of the pre-feasibility study was understanding the availability of low-emission alternative fuels in the two regions (ROK and the Pacific Northwest) and the technical potential to transport and bunker those fuels, as well as ensuring potential demand for alternative fuels could be satisfied. For the U.S. side, these analyses were completed by NREL, and this report provides a summary of those findings.

This report provides comprehensive analyses of the existing and potential alternative fuel capacity within the PNW region available to the maritime sector by the year 2030, as well as a brief assessment on the readiness of the transportation and bunkering infrastructure for those fuels and use in ship engines. The study focused on alternative fuel production projects within a 1,000-kilometer (km) radius of the Port of Seattle, specifically targeting methanol, ammonia, hydrogen, biofuels, and bio-based liquified natural gas (bioLNG).

In this report, we first present our methodology, including data collection, stakeholder interviews, and data analysis procedures. In the next section, we provide an estimate of alternative fuel capacity available to maritime use in the region, including a breakdown of alternative fuel capacity by year between 2024 and 2030. We then discuss the proposed facilities and possible barriers, including technical readiness, energy requirements, and social and political readiness. Next, we analyze fueling infrastructure considerations, fuel transport to port, and fuel sales and imports, respectively. Lastly, we compare the expected supply and demand of alternative fuels in the U.S. PNW region and provide concluding remarks.

This report is part of a larger project aimed at reducing emissions from the maritime shipping industry. Understanding the availability of alternative fuels in a specific region and assessing the readiness of the regional shipping sector to use alternative fuels is essential to reaching long-term goals established by the Green Shipping Challenge and ZESM ("Zero-Emission Shipping" n.d.; Office of the Spokesperson 2022b). The development of a pre-feasibility report for the PNW – ROK green shipping corridor was a critical first step to distinguishing the best possible candidate routes to move forward with feasibility studies ("Zero-Emission Shipping" n.d.). In addition, the results from this report have been used to inform work on a green corridor focused on cruise vessels between the U.S. PNW and Alaska (Zero Emission Shipping Mission, n.d.; Port of Seattle, n.d.) and can continue to be used to inform other work centered on alternative fuels and decarbonization of the maritime sector in the U.S. PNW region. Finally, this report provides a template for determining potential alternative fuel supply in future pre-feasibility studies for new green corridors.

2 Methodology

In this report, we used a systematic approach to data collection and analysis and assembled a comprehensive database of existing and proposed alternative fuel production in the vicinity of the Port of Seattle. The region of study included all areas within a 1,000-km radius of the Port of Seattle, as directed by MMMCZCS methodology (Maersk Mc-Kinney Moller Center for Zero Carbon Shipping 2023). The study area is shown in Figure 1. All existing facilities and proposed fuel production projects scheduled to come online by 2030 were included and the potential evolution of alternative fuel production in the Port of Seattle region was examined. In reality, these facilities may or may not come online as scheduled or with the anticipated capacity.

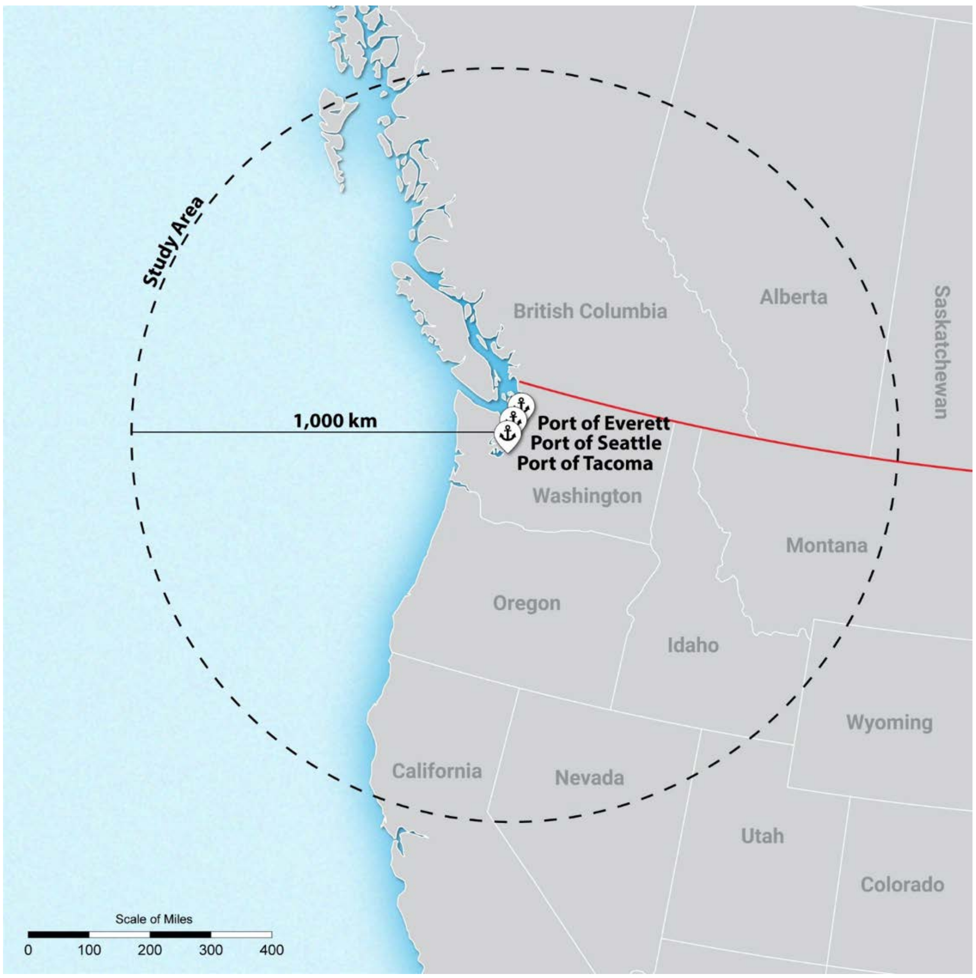

Figure 1. Map of the study area, a 1,000-km radius surrounding the Ports of Seattle, Tacoma, and Everett. The U.S. PNW is the leading region for international trade between the U.S. and ROK. A 1,000-km radius was used for the study area at the guidance of Maersk Mc-Kinney Moller Center for Zero Carbon Shipping.

The fuels of primary interest included green and blue methanol, ammonia, and hydrogen, and biofuels (biodiesel, renewable diesel, sustainable aviation fuel (SAF)[1], and bioLNG). Blue fuels

[1] SAF is included in the analysis because these facilities generally also produce renewable diesel and can ramp up production of one fuel compared to the other depending on market demand.

are traditionally made with petroleum feedstocks but have a component of carbon capture and storage to reduce emissions. Green and E-fuels fuels are made with renewable inputs, including renewable feedstocks or renewable electricity, and green carbon dioxide sources. Ethanol was not considered in this report. Biofuel projects considered in this report used lipid feedstocks such as canola, soybean, and distillers corn oil; algae; waste fats, oils, and greases (FOG); municipal solid waste (MSW); agriculture waste such as crop residues and manure; woody residues; and other waste like sewage sludge, raw landfill gas, commercial and residential organic waste, and pulp mill waste.

2.1 Data Collection

Secondary data were obtained through a review of documents, reports, and other publicly available resources relevant to the alternative fuel sector in the region. This included official documents from government bodies, public announcements regarding renewable energy projects, and other relevant publications.

Specifically, we used several publicly available databases to gather initial data on renewable fuel production facilities:

- *Biodiesel Magazine* Plants List for biodiesel plants ("U.S. Biodiesel Plants" 2023)
- U.S. Department of Energy (DOE) Integrated Biorefineries for general biofuel production facilities (BETO, n.d.)
- U.S. Environmental Protection Agency (EPA) List of Registered Biodiesel Fuels ("List of Registered Biodiesel Fuels," n.d.)
- Alberta Major Projects ("Alberta Major Projects," n.d.).

Each database was searched to obtain information on the location, fuel type, feedstock, production capacity, and operational status of renewable fuel production facilities within the region of study.

To supplement and update the information obtained from public databases, we conducted a search of online publications and press releases. These searches targeted announcements of new alternative fuel production projects in the study region. We consulted online publications including *Biodiesel Magazine*, *Advanced Biofuels USA*, and *Biofuels Digest*, among others. The searches encompassed all fuel categories of interest across all states and territories within the area of interest.

The data collected from these sources provided insights into the expected production capacities, types of fuels, and intended applications of the renewable fuel projects in the area.

Fuel demand data were acquired for the three Washington ports by extrapolating from a Washington State Department of Ecology oil transaction log covering all transactions from 2006 to 2021 (State of Washington 2021). The total number of gallons used per year was calculated for each fuel type at the Ports of Seattle, Tacoma, and Everett and then converted to very-low sulfur fuel oil gallon equivalents (VLSFO-GE) to determine the total demand per year of fuel in VLSFO-GE. The following equation was used for this conversion, along with the energy densities found in Table 1:

$$Gallons\ of\ fuel \times \frac{MMBtu\ of\ fuel}{gallons\ of\ fuel} \times \frac{gallons\ of\ VLSFO}{MMBtu\ of\ VLSFO} = VLSFO\ gallon\ equivalents$$

Table 1. Energy densities (million British thermal units (MMBtu)/gal) of current shipping fuels for conversion to very-low sulfur fuel oil gallon equivalents (VLSFO-GE). Converting quantities to a universal unit such as VLSFO-GE eases the comparison of supply and demand.

Fuel Type	Energy Density	Unit
Bunker oil/heavy fuel oil (HFO) (Aronietis et al. 2016)	0.1464	MMBtu/gal
Diesel / marine gas oil (MGO) (Aronietis et al. 2016)	0.1319	MMBtu/gal
Liquified natural gas (LNG)/LPG (U.S. Energy Information Administration 2024)	0.1104	MMBtu/gal
Very-low sulfur fuel oil (VLSFO) (U.S. Energy Information Administration 2024)	0.1387	MMBtu/gal

2.2 Stakeholder Interviews

Alongside the review of secondary data, we conducted a series of interviews with three stakeholders involved in renewable fuel production, distribution, and use. This included project developers and industry experts. These interviews provided additional insights and qualitative data regarding the current state and expected trajectory of renewable fuel projects in the region and their relation to the maritime industry.

2.3 Data Analysis

The data collected were designed to capture details of each alternative fuel project, including the location, types of feedstock, annual fuel production capacities as reported in the original announcements, planned fuel product type, conversion technologies, project timelines, stage of implementation, and existing or planned offtake agreements.

Since the quantities of fuel for both supply and demand were reported in varying units, based on original project announcements or logs, fuel capacities were converted to VLSFO-GE using each fuel's mass or volumetric energy density, which can be found in Table 2. By converting all quantities to a standard unit, the direct comparison of supply and demand of each fuel type is possible.

Table 2. Energy densities (MMBtu/ton) of alternative fuels for conversion to VLSFO-GE. Converting quantities to a universal unit such as VLSFO-GE eases the comparison of supply and demand. SAF is included in this analysis because it is often produced in the same facilities as renewable diesel, which can produce more of one fuel or the other depending on market demand.

Fuel Type	Energy Density	Unit
Biodiesel (U.S. Energy Information Administration 2024)	34.71979268	MMBtu/ton
Ammonia (Chatterjee, Kumar Parsapur, and Huang 2021)	15.993138	MMBtu/ton
Hydrogen (The Hydrogen Economy: 2004)	103.171243	MMBtu/ton
Methanol (Thomas 2020)	17.110938	MMBtu/ton
Renewable diesel (U.S. Energy Information Administration 2024)	36.87891847	MMBtu/ton
BioLNG (U.S. Energy Information Administration 2024; "LNG and Bio-LNG" 2023)	39.295481	MMBtu/ton
Sustainable aviation fuel (SAF) (Shahriar and Khanal 2022)	36.80247653	MMBtu/ton
VLSFO (U.S. Energy Information Administration 2024; "Very Low Sulphur Fuel Oil - Marine" 2019)	37.14260209	MMBtu/ton

A total proposed fuel capacity was calculated by summing the existing and announced fuel project capacities for all fuel types and all years. Projects producing more than one type of fuel without a publicly available breakdown of production capacity by fuel type were assigned a percentage of production of each fuel, which can be found in Table 3. This included one facility proposing to produce blue ammonia and blue methanol, and several facilities proposing to produce SAF and renewable diesel.

Table 3. Finished fuel breakdown for facilities producing more than one fuel. These allocation percentages were determined after meeting with industry experts and reading related project announcements.

Fuel 1/Fuel 2	Percent Fuel 1	Percent Fuel 2
Blue ammonia/blue methanol	60%	40%
SAF/renewable diesel	62%	38%

The allocation percentages were informed by interviews with industry experts (Dolan 2023; Ruth 2023) and information contained in similar project announcements (Yaku 2021).

A total fuel capacity available to the maritime sector was calculated by accounting for offtake agreements, a maturity index, and sector competition. Offtake agreements were accounted for on a percentage basis from zero to 100% of fuel capacity committed to an offtake agreement based on news releases and other supplementary information. The maturity index, found in Table 4, was applied as a percentage of total fuel capacity to each project stage. The maturity index indicates the percentage of total capacity in each category expected to come online by 2030. It was informed by conversations with industry experts (Wolcott and Brandt 2023; Dolan 2023; Ruth 2023; K. Brandt, personal communication, 2023). Projects that were operating at the time of writing or had completed construction were labeled as "operating". Projects that had passed the final investment decision (FID) and were awaiting construction or under construction were labeled as "FID". Projects that had passed their feasibility study (F/S) and were awaiting a final investment decision were labeled as "F/S". Projects that had not yet conducted a feasibility study were labeled as "initial". The intention of these assumptions is to account for the possibility that announced facilities may or may not be built.

Table 4. Maturity index for different development stages of proposed facilities. These percentages were determined after conducting interviews with industry experts.

Proposal Category	Maturity Index
Operating	100%
FID	90%
F/S	50%
Initial	20%

Not all potential fuel capacity will be used by the maritime sector. The sector competition factor was applied as a percentage of total fuel capacity to each fuel type and represents an estimate on the quantity of total fuel output that would be available for the maritime sector. These percentages can be found in Table 5. The biofuels competition factor was applied to biodiesel, renewable diesel, and bioLNG. The sector competition factors were informed by a prior green corridor analysis conducted by Maersk-Mc-Kinney-Moller ("The Chilean Green Corridors Network Pre-Feasibility Study 2022," n.d.), as well as consideration of local policy and conversations with industry experts (Dolan 2023; Ruth 2023). In particular, the Low Carbon Fuel Standard (LCFS) in California, the Oregon and Washington Clean Fuel Standards (CFS), the British Columbia LCFS, and the Canadian Clean Fuel Regulations, are currently serving as drivers pushing clean fuels into markets outside the marine sector. This is resulting in steep competition of fuels— particularly for renewable diesel and bioLNG— and is reflected in the sector competition factor.

Table 5. Sector competition factor by fuel type representing the percentage of each fuel assumed to be available to the maritime sector. These percentages were determined from industry expert interviews, a previous green corridor study, and analysis of relevant policies.

Fuel Type	Sector Competition Factor
Hydrogen	20%
Ammonia	50%
Methanol	90%
Biofuels	20%

Additionally, qualitative analysis was conducted to interpret the potential implications of the findings, especially in the context of establishing green shipping corridors between the U.S. PNW and ROK. Trends, opportunities, and challenges identified through the data were thoroughly evaluated.

3 Fuels

This section analyzes the existing and potential fuel quantities in the region as well as the quantities available for maritime use. The capacities presented in this section are independent of the technical readiness of the maritime sector to utilize the fuels, which is addressed in the Technical Readiness section of the report. As of April 2024, there are 31 existing and 26 planned alternative fuels facilities within the 1,000-km radius surrounding the Port of Seattle (Figure 1). The total fuel capacities summed by year online are shown in Table 6.

Table 6. Fuel capacity (million VLSFO-GE per year) within a 1,000-km radius of the Port of Seattle summed by fuel type and projected year online. Only facilities projected to be online by 2030 were included. Note that discrepancies between this table and Figure 2 are due to the inclusion of facilities with anticipated operational start dates in late 2024 in this table which are not included in Figure 2.

Fuel Type	2024	2025	2026	2027	2028	2029	2030
Biodiesel	208.9	208.9	208.9	208.9	208.9	208.9	255.8
Ammonia*	84.8	84.8	84.8	173.0	173.0	274.7	274.7
Hydrogen**	456.9	456.9	456.9	468.4	714.6	714.6	750.3
Methanol**	0.3	0.3	0.3	287.6	287.6	505.2	520.0
Renewable diesel	1,681.1	1,955.3	1,986.1	1,994.8	1,994.8	1,994.8	1,994.8
BioLNG	107.3	134.4	134.4	134.4	134.4	134.4	134.4
SAF	688.3	1,118.9	1,167.2	1,194.5	1,194.5	1,194.5	1,194.5
Total	3,227.6	3,959.5	4,038.5	4,461.6	4,707.8	5,027.1	5,124.5

* All ammonia capacity represented is blue ammonia

** Capacities represent both blue and green fuels

3.1 Existing Capacity

A chart showing existing fuel capacity (April 2024) by fuel type within the 1000-km radius region is presented in Figure 2. Note that discrepancies between Table 6 and Figure 2 are due to several facilities anticipated to become operational in the latter half of 2024 and are thus not yet represented in the existing capacity shown in Figure 2. The majority of existing capacity (59.4%) (as of April 2024) is dominated by renewable diesel, derived from vegetable oils (canola, soybean, and distillers corn oil), waste FOG, and MSW. Renewable diesel is considered a drop-in fuel for maritime applications; i.e. it can be used in existing maritime engines without major modifications (Bioenergy Technologies Office, n.d.). This is beneficial given it could be used nearly immediately for maritime applications in the region. There is relatively little existing production capacity for green or blue ammonia or methanol in the region (7.4%). These fuels are expected to play a critical role in sustainable marine shipping, and thus their absence from existing production is noteworthy and presents a significant challenge for green corridor projects.

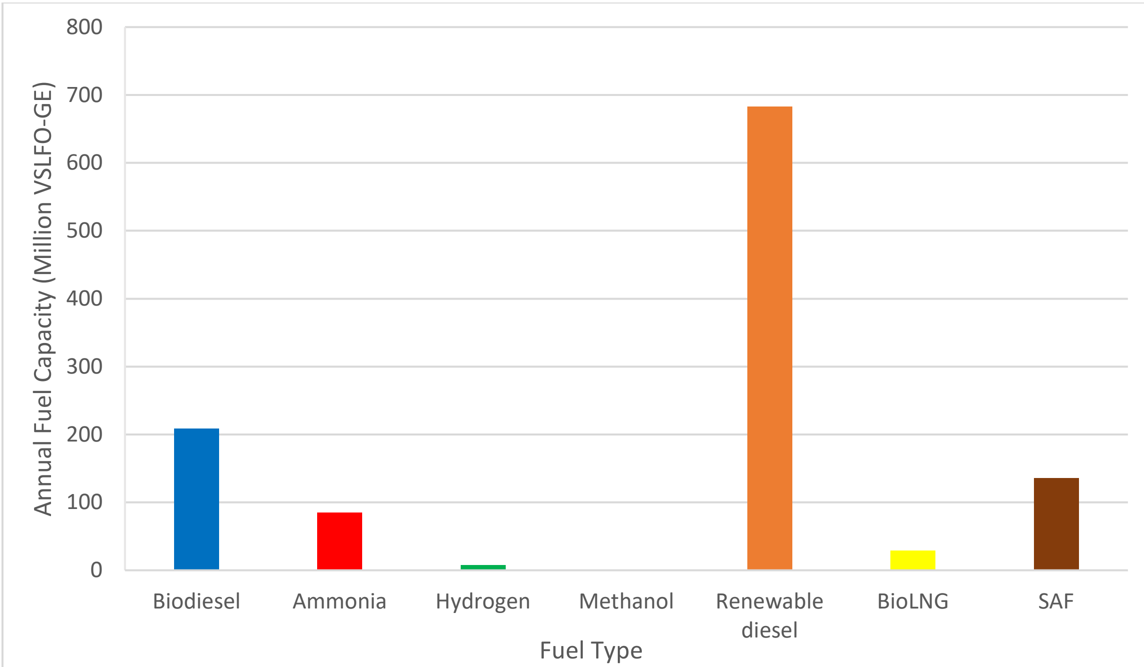

Figure 2. Existing fuel capacity (million VLSFO-GE per year) by fuel type as of April 2024 within a 1,000-km radius of the Port of Seattle. Majority (59.4%) of existing capacity is renewable diesel. Discrepancies between this figure and Table 6 are due to some projects having an anticipated operating start date falling in late 2024 and are thus not represented in the existing fuel capacity displayed in this figure.

3.2 Potential Capacity

All fuel types evaluated in this report are expected to increase in capacity between the start of 2024 and 2030. Most notably, renewable diesel production is projected to increase by approximately 1.6 billion VLSFO-GE per year by 2030 (403% increase). Similarly, production of SAF from MSW, crop and woody residues, and lipids is anticipated to increase by 1 billion VLSFO-GE per year by 2030 (781% increase), and production of biodiesel is expected to increase by nearly 47 million VLSO-GE per year (22% increase). However, without sufficient FOG supply, these biofuels will likely be produced using purpose-grown vegetable oils as their feedstock, significantly increasing their carbon intensity as compared to waste feedstock-derived fuels. This is representative of 85% of the anticipated supply of renewable diesel, SAF, and biodiesel in the region, making the need for identifying greater waste FOGs or similar feedstocks clear.

Production of methanol, from natural gas with carbon capture, water electrolysis, and pulp mill waste, is expected to increase by 520 million VLSFO-GE per year (191,488% increase). On a smaller scale, blue ammonia production, mostly produced from natural gas with carbon capture, is projected to increase by nearly 190 million VLSFO-GE per year (224% increase). Looking at hydrogen, there are currently not many announced projects. However, because hydrogen is very energy dense in terms of MMBtu/ton, when compared to other alternative fuels (see Table 2), it represents a large proportion of the capacity when discussed in terms of VLSFO-GE — increasing by approximately 740 million VLSFO-GE per year by 2030 (9,296% increase). In addition, the Pacific Northwest Hydrogen Hub was selected for negotiation as part of DOE’s “hydrogen hubs” program, which is expected to further increase hydrogen production within the region ("Biden-Harris Administration Announces Regional Clean Hydrogen Hubs to Drive Clean Manufacturing and Jobs" 2023).

As for bioLNG, there are many proposed projects within the study area, mainly focused on small-scale anaerobic digestion of agricultural waste. These small-scale projects are nearly all committed to off-take agreements with local utilities for commercial and residential heating ("The Renewable Natural Gas Opportunity," n.d.). There are very few large-scale bioLNG projects focused on fuel production in the region. For simplicity, the small-scale anaerobic digestion projects with existing utility off-take agreements were excluded from all analysis because they do not have the potential to be available to the maritime sector, and only larger scale bioLNG projects were included within our production capacity estimates. Bio-LNG can also be acquired by the purchase and retirement of Renewable Identification Numbers via the EPA's National Renewable Fuel Standard Programs, which would open up a much larger quantity of bioLNG to the area ("Renewable Identification Numbers (RINs) under the Renewable Fuel Standard Program" 2024). However, this study is focused on the production of fuels within the study area, and did not investigate this possibility. A chart showing total existing and proposed fuel production capacity in the region by year and fuel type is presented in Figure 3. Total existing and proposed fuel capacity in the area by 2030 is approximately 5.1 billion VLSFO-GE per year.

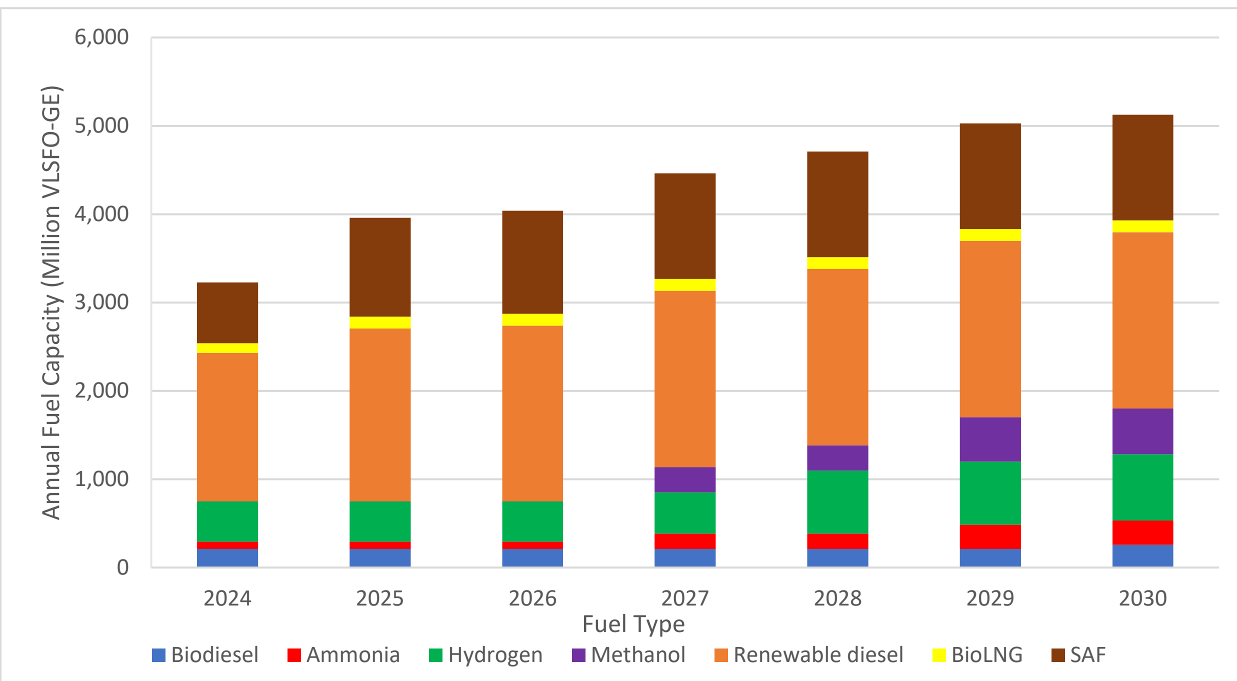

Figure 3. Total proposed fuel capacity (million VLSFO-GE per year) within a 1,000-km radius of the Port of Seattle by year and fuel type. Total proposed fuel capacity is the cumulative sum of quantities from all existing and announced projects with anticipated operating start dates between 2024 and 2030.

The largest proposed facilities include one renewable diesel (Lane 2022) and two combined renewable diesel and SAF facilities (Fallas 2022; Dubey 2019) all producing more than 694 million VLSFO-GE per year of fuel. Also included in the largest proposed facilities is a blue methanol and ammonia facility ("Northern Petrochemical Ammonia and Methanol Production Facility," n.d.) anticipated to produce 319 million VLSFO-GE per year and a blue methanol facility ("Launching a New Methanol Industry in BC," n.d.) proposed to produce nearly 215 million VLSFO-GE per year.

As noted in the Methodology section, an "available to maritime use" fuel capacity was produced using a series of limiting factors including any publicly announced offtake agreements, a project maturity index (Table 4), and a sector competition factor (Table 5). Most announced projects have made steps to be considered beyond the initial speculation stage. Many have secured land and permitting or completed feasibility studies. A chart showing total available fuel capacity by year and fuel type is presented in Figure 4. The capacity available for maritime use is much reduced from the total proposed capacity (Figure 3). Total fuel capacity available to maritime use in the region by 2030 is estimated to be 729.7 million VLSFO-GE per year, compared to 412 million VLSFO-GE in 2024. As noted, the combined available capacity of renewable diesel, SAF, and biodiesel would be reduced by 85% if facilities considering using purpose-grown vegetable oils as feedstocks are not included in the consideration.

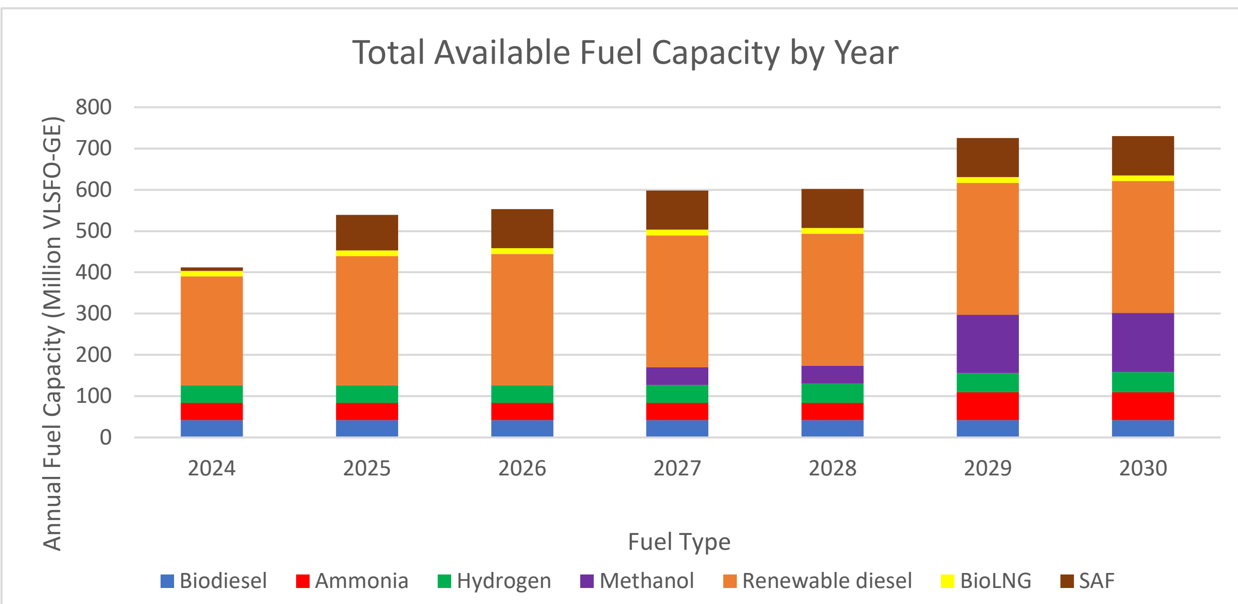

Figure 4. Total fuel capacity available to maritime activities (million VLSFO-GE per year) within a 1,000-km radius of the Port of Seattle by year and fuel type. The total fuel capacity available to maritime activities considers the offtake agreements, maturity indices (Table 4), and sector competition factors (Table 5) for each project and fuel type. Capacities are cumulative per year.

"Blue" projects —including ammonia, methanol, and hydrogen— are expected to be more common than "green" projects, likely due to the availability of natural gas in the region. Many of the proposed green projects, specifically for E-fuels, include the financing, siting, and construction of new renewable electricity projects to power the proposed fuel production, likely because all existing renewable electricity generation in the region is already committed to power users. This will add an additional layer of complexity to the green fuel projects proposed. On the other hand, blue fuel projects may be considered unsustainable in the long run, due to their petroleum-based feedstock, and continued reliance on an active natural gas industry. Figure 5 shows a map of the total existing and anticipated production capacities in the region. Figure 6 maps the anticipated fuel capacity available for the maritime sector within the region. The majority (63%) of fuel production within the study region is located within three main production hubs – coastal Washington; north of San Francisco, California; and Alberta's Industrial Heartland. A few smaller facilities exist outside of those clusters, including in northern Nevada, Oregon, eastern Washington, Montana, and British Columbia. The majority (97%) of existing and proposed methanol and ammonia production is located in Canada, whereas the United States has more renewable diesel, SAF, and biodiesel production.

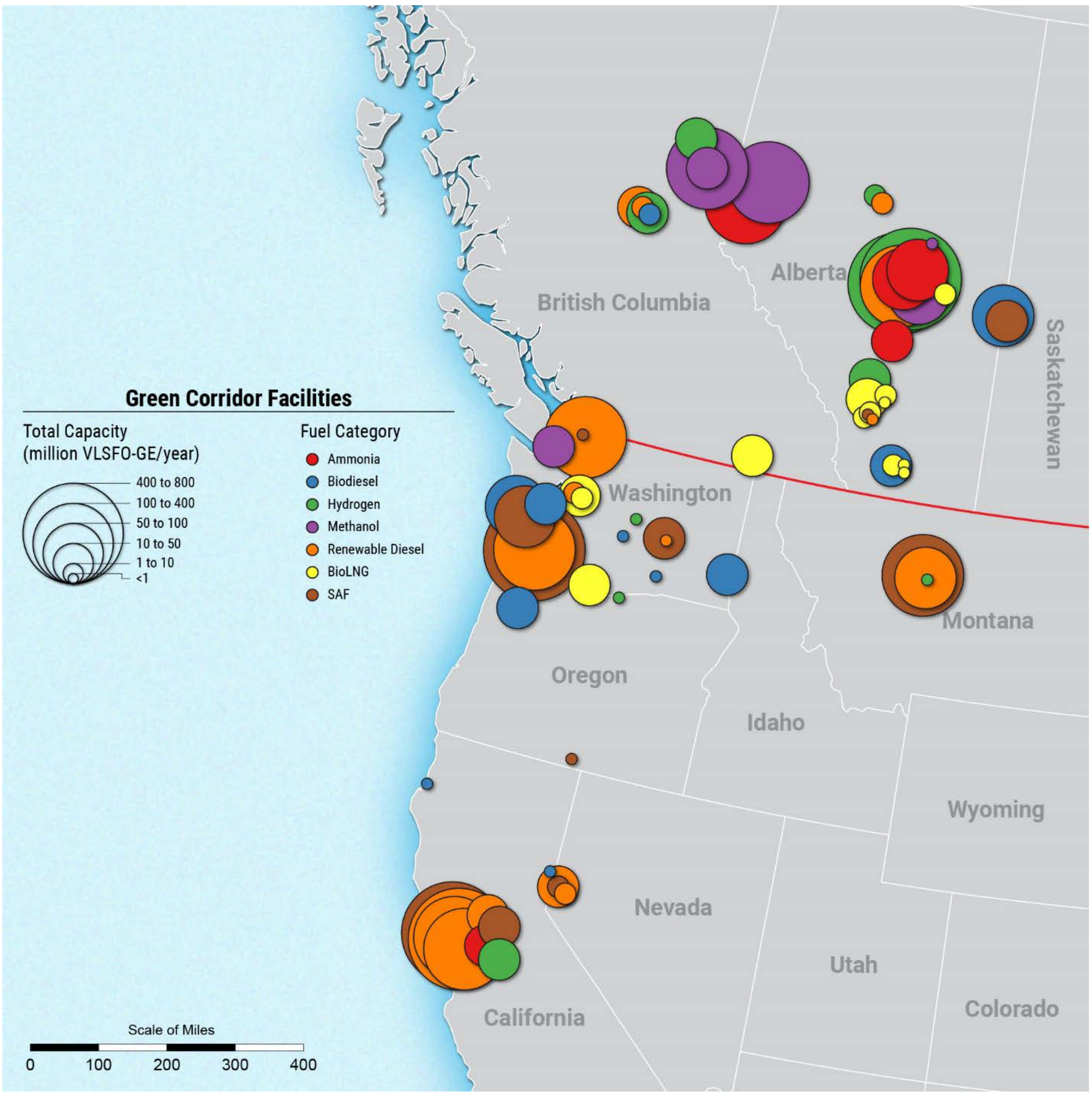

Figure 5. Map of existing and proposed fuel production facilities by fuel type and size within a 1,000-km radius of the Port of Seattle. All facilities shown have an anticipated operating start date by 2030. Total capacities shown are in million VLSFO-GE per year.

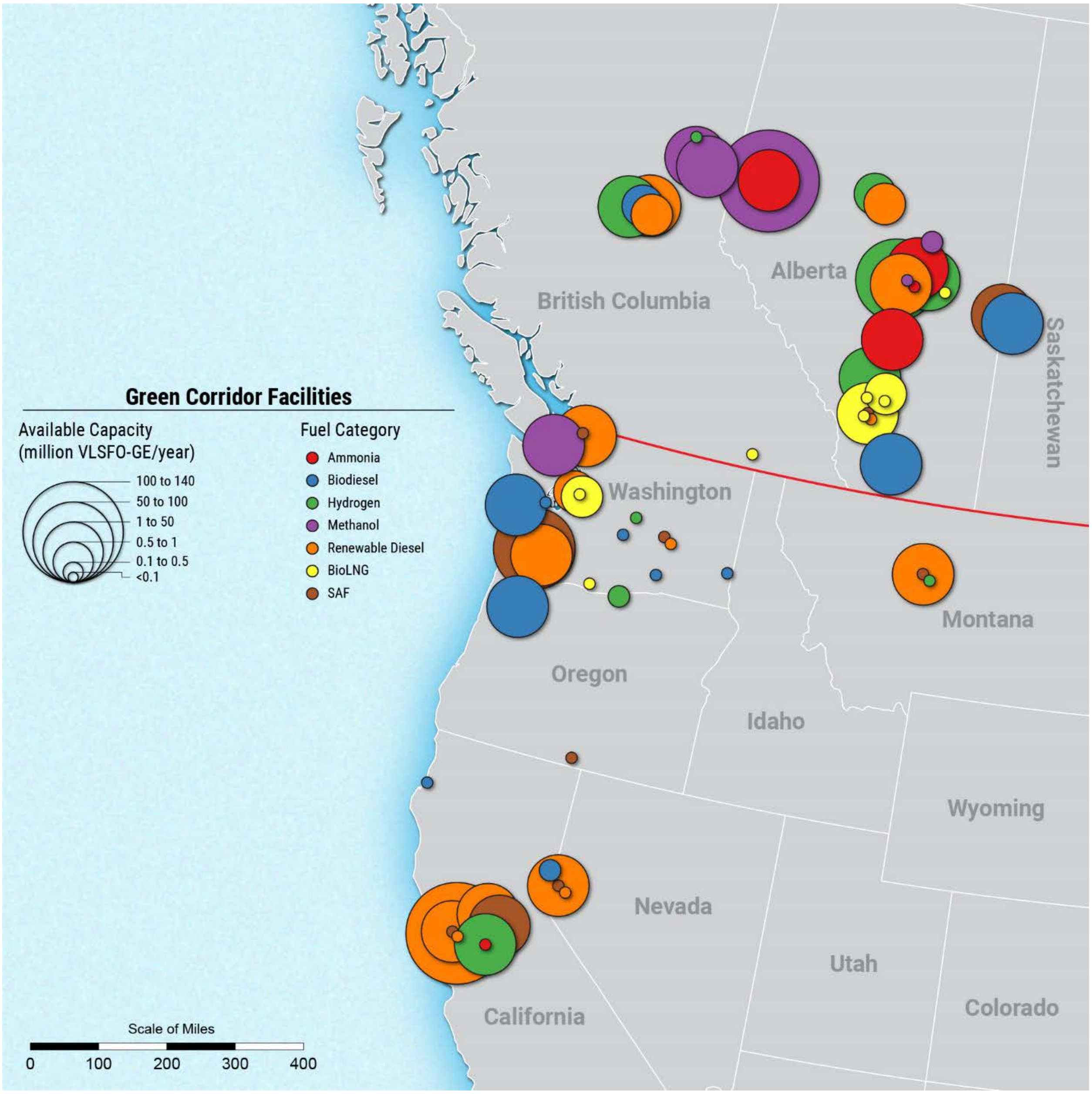

Figure 6. Map of fuel available for the maritime sector by fuel type and size within a 1,000-km radius of the Port of Seattle. All facilities shown have an anticipated operating start date by 2030. Available capacities account for offtake agreements, maturity indices (Table 4) for announced projects, and sector competition factors (Table 5) for each fuel type. Capacities are shown in million VLSFO-GE per year.

4 Proposed Facilities and Possible Barriers

Not all proposed fuel will be available for the maritime sector. In addition to limitations such as offtake agreements, technology maturity, and sector competition, there are also barriers to the fuel projects themselves and the use of alternative fuels within the sector.

4.1 Technical Readiness

This section analyzes the technical readiness of the maritime sector to use alternative fuels, independent of the fuel capacities which are presented in Section 3 of the report. Looking at fuel production, much of the existing and proposed capacity uses proven technologies. For example, nearly all SAF and renewable diesel projects plan to use hydro-processed esters and fatty acids (HEFA), an established and well proven conversion technology. Renewable diesel is considered a drop-in fuel that would only require tank cleaning and valve upgrading on bunker ships to be deployed. Biodiesel has already been blended and deployed in multiple biofuels trials, most commonly at a B30 (30% biodiesel) blend (CMA CGM 2022). However, the HEFA and biodiesel (transesterification) technologies are feedstock constrained. Without the development of new resources (e.g., algae), their production potential will be limited. This concern was confirmed in industry interviews.

Driven in part by the 2020 IMO low-sulfur bunker fuel regulations, petroleum-based LNG is also already established as a marine fuel. As of January 2023, 185 ports worldwide had the capability to bunker LNG and another 50 were planned. Hundreds of ships are already operating on LNG, and LNG-fueled tonnage represented a significant percentage of the new build ship orderbook in 2022 (Ovcina Mandra 2023). Given bioLNG is a drop-in replacement for petroleum-based LNG, these vessels will be able to operate on bioLNG without modification. BioLNG can also be transported, stored, and bunkered in ports using existing petroleum-LNG infrastructure, and already nearly 70 ports offer bioLNG bunkering (Blenkey 2023).

Greater technical challenges emerge at the port and ship levels for fuels that are not drop-in replacements. For example, in late 2022, Energy Market Authority of Singapore launched an Expression of Interest (EOI) to build and operate a hydrogen and ammonia bunkering solution — the first EOI issued for ammonia bunkering. In April 2023, reports on safety and technical feasibility were reviewed from Vopak, the Maritime Energy & Sustainable Development Centre of Excellence (MESD), and A*STAR's Institute of High-Performance Computing. Reports highlighted the risks involved in handling ammonia as bunker fuel and determined more dispersion and release studies were needed to better understand the impact of a release under various environmental conditions. Further review and investigation enabled an ammonia bunkering pilot at the Port of Singapore in 2024 ("World's First Use of Ammonia as a Marine Fuel in a Dual-Fueled Ammonia-Powered Vessel in the Port of Singapore" 2024). Additionally, the Port of Rotterdam has announced that it will be ready for commercial bunkering of ammonia by 2027 (Macqueen 2024). At the ship level, the first ammonia-ready vessel in the world was completed and delivered in early 2022 ("World's First Ammonia Ready Vessel 'Krisi Future' Delivered" 2023). Since then, more projects are underway and ammonia-ready vessel orders have been placed.

Methanol use in the maritime sector is more advanced than ammonia, with multiple bunkering trials being performed and the first non-tanker vessel being bunkered ship-to-ship with methanol in January 2023 ("Methanol Bunkering Carried Out in the Port of Gothenburg" 2023). Multiple shipping companies have large orders placed for methanol ready ships, including A.P. Moller – Maersk (Maersk 2021), of which several are now in operation ("Maersk Names Second Vessel of Its Large Methanol-Enabled Fleet 'Astrid Maersk' in Yokohama, Japan" 2024). On February 4, 2023, the *Cajun Sun*, operated by Waterfront Shipping and Mitsui O.S.K. Lines, completed its 18-day journey from Louisiana, U.S.A to Antwerp Belgium. It became the first net-zero voyage fueled by bio-based methanol ("Methanex and MOL Complete First-Ever Net-Zero Voyage Fuelled by Bio-Methanol" 2023).

Looking at other fuels, hydrogen has the lowest technical readiness. A joint study by NREL and PNNL showed that hydrogen could play a role in the shipping industry, but challenges related to cost competitiveness, safety, and infrastructure remain (Tan et al. 2021). Conversations with industry experts indicate that ammonia appears to currently be the leading option for using hydrogen energy in the international shipping sector (Ruth 2023), while smaller vessels and ferries are already operational on hydrogen (Moore 2022).

4.2 Energy Requirements

Of the fuels considered, e-methanol, e-ammonia, and e-hydrogen require renewable electricity inputs to create a "green", or carbon-neutral fuel output. Globally, large scale projects to produce e-methanol, e-ammonia, or e-hydrogen are either closely coupled with large existing renewable electricity sources or are creating their own commercial-scale renewable electricity generation to support the fuel production. This adds another complex layer of financing, permitting, and construction to these e-fuel projects, which make up relatively little of the overall anticipated fuel capacity in the region of study.

A much greater amount (89%) of the anticipated capacity is comprised of blue fuels, mostly ammonia and methanol. The blue fuel projects in the area of study largely use natural gas as their feedstock and are combined with a carbon capture and storage system to make the resulting fuel low carbon.

The biofuels projects being considered use waste feedstocks such as waste FOG, MSW, woody residues, crop residues, sewage sludge, or purpose-grown energy crops such as canola. Waste feedstocks require relatively little energy input on the backend, primarily collection and transportation. Purposefully grown energy crops require higher levels of energy input when considering production, harvesting, processing, and transportation, significantly raising their carbon intensity as compared to fuels made from waste feedstocks.

4.3 Social and Political Readiness

As with any energy project, social acceptance and environmental justice must be considered. Many of the proposed projects are located at existing refineries or brownfield sites. For example, in Alberta, the fuels projects are located in dedicated industrial areas and existing brownfields. In the United States, most of the renewable diesel, SAF, and biodiesel projects are located at existing refineries that are either fully repurposing or adding alternative fuel capacity. Examples include the Cherry Point and Grays Harbor Refineries in Washington, the Phillips 66 Rodeo Renewed Refinery in California, and the Al-Pac Refinery in Alberta.

Even so, it will be important to invite community involvement and input within the planning and permitting process of these projects, addressing all facets of energy and environmental justice. This will likely be of particular importance for e-fuels projects that require the siting and use of large land areas for renewable electricity generation, and for refining facilities that have the potential to emit pollutants. The transportation of these fuels must also be considered early in the planning process and executed in a safe and equitable manner.

Involving communities early in the planning process can also be beneficial to project developers, as it can help to avoid costly delays. For example, the Ports of Seattle and Tacoma and the Northwest Seaport Alliance spent two years engaging with the local community to formulate its emission reduction plan. Concerns about accountability and transparency, cost, and undesirable and unequitable impacts on employees were common themes in community responses. The Ports then implemented new measures to increase transparency and worked with local organizations to ensure the community was satisfied with the plan before moving forward (Child 2021).

Additionally, as a part of its fiscal year 2024 grant application to the EPA's Clean Ports Program, the NWSA asked for $3.5 million allocated towards increasing community engagement and workforce development. With these funds, the NWSA and the Port of Seattle plan to have quarterly newsletter updates, update and increase awareness of their online progress portal, organize biannual community roundtables, support three to five community-led clean air projects per year, hold ten community meetings per year, and increase readership of the Ports' Zero Emission Technology Deployment Workforce Development Action Agenda. These actions are intended to increase awareness and understanding of the ports' efforts to reduce emissions and implement new technologies ("Accelerating Zero-Emission Technology Deployment at Puget Sound Ports Project Narrative" 2024).

Regarding readiness and acceptance within the industry, many shipping companies are choosing to delay investments due to uncertainty surrounding fuel availability, infrastructure upgrades, and safety. Many companies are concerned about aligning ship engines, fueling tanks, and bunkering systems for the same type of fuel at each port their ships access (Harahap et al. 2023).

Looking at policy within the region, permitting times for new facilities can be onerous, and process simplification will be necessary to speed up the approval and construction of proposed facilities. For example, under the [Washington] State Environmental Policy Act, all proposals determined likely to result in significant environmental impact must prepare an Environmental Impact Statement (EIS). Under legislation drafted in 2018 to address the amount of time required by this process, the Department of Ecology must submit a report on the average time it took to complete EISs in the previous two years. According to the most recent report, the average wait time for the completion of an EIS was 25 months, while the longest wait was 91 months (Cassal 2023). Permitting wait times of multiple years can end projects and could impact a port's ability to reach near-term benchmark goals for emissions reductions.

In addition, the political landscape in the region has evolved rather rapidly in recent years in relation to transportation fuels. In the United States, the EPA's Renewable Fuel Standard program and the Inflation Reduction Act both incentivize the use of alternative fuels through tax credits, blending mandates, and Renewable Volume Obligations. Individual states also have policies in place for transportation fuels. California has had an LCFS since 2011, with amendments approved in 2018. Oregon has had a CFS since 2016, and Washington implemented one at the beginning of 2023. British Columbia has had an LCFS since 2013, with amendments as recent as the beginning of 2023, and Canada just approved a federal clean fuels regulation that went into effect July 1, 2023. These regulations set limits for the carbon intensity of fuels bought, sold, and produced within their jurisdictions. However, no regulation to date has included maritime fuels within the mandatory carbon intensity reductions. Opt-in options exist in the United States and Canada for ocean-going vessels that may have an impact on shore power for ships, but not on the maritime sector at large.

The lack of coverage for maritime fuels in these regulations may result in increased competition in other sectors, reducing the quantity of renewable fuels going to the maritime sector. This will likely be the most pronounced with biofuels, namely renewable diesel, as there is high demand for renewable diesel in other qualifying transportation sectors ("Biofuels" 2023). In fact, the existing renewable diesel production capacity is already consumed mostly by the heavy-duty vehicle market, and there is more demand for renewable diesel than supply ("Alternative Fuels Data Center: Renewable Diesel," n.d.). Industry interviews confirmed that fuels, such as methanol and ammonia, that have relatively few uses in transportation sectors regulated under the CFSs, will be less impacted by competition created by the regulations, and thus may have greater overall supply available to the maritime sector, although supply-demand dynamics are highly uncertain (Dolan 2023; Ruth 2023).

Current trading prices in May 2024 for the Washington CFS credits are approximately $59.33 per metric ton and had an average trading price in 2023 of $91.23 per metric ton ("Monthly CFS Credit Transfer Report for May 2024" 2024). These prices are similar to Oregon's CFS, which is currently trading at $56.30 per metric ton in May 2024 and had an average trading price of $129.76 in 2023 ("Monthly CFP Credit Transfer Report for May 2024" 2024). California has a similar current trading price of $56 per metric ton in May 2024 but a lower average trading price in 2023 of only $75 per metric ton ("Monthly LCFS Credit Transfer Activity Report for May 2024" 2024). However, California's market has experienced much fluctuation, with prices reaching as high as $220 per metric ton in 2020 (State of California 2023). With initial prices in Washington trading competitively amongst the U.S. market, it may be a challenge to pull biofuels into the maritime industry within the state. However, it is possible that the jurisdictions mentioned will amend their standards to include maritime fuel in years to come. This would be a significant boon for bringing alternative fuels into the maritime sector.

5 Fueling Infrastructure Considerations

An entirely new fueling infrastructure at ports and terminals would need to be constructed to accommodate non-drop-in fuels, such as methanol and ammonia. Even for drop-in fuels, challenges remain. Large (25,000 to 59,999 gross tonnage) and very large (≥60,000 gross tonnage) ships including bulk carriers, tankers, and container ships are responsible for transporting roughly 85% of global fuel, goods, and commodities, which accounts for approximately 70% of marine fuel use (Hsieh and Felby 2017). Container ships generally have a useful life of at least 15 years, although it is more common for them to operate for 20-30 years ("How Old Is an Elderly Ship?," n.d.). These ships use two-stroke diesel engines with fuel processing and heating systems. They are equipped with extensive fuel storage systems; according to the International Energy Agency (IEA), large ocean-going ships have fuel storage capacities ranging from 10,000 to 14,000 metric tons (67,000 to 93,000 barrels), capable of propelling the ship for up to 70 days. In addition, they are designed with several tanks, enabling them to operate on more than one fuel type (Hsieh and Felby 2017). Given their fuel tank capacity and consequently long range, larger ships are capable of crossing an ocean and returning on a single refueling, and they usually choose to refuel at locations where prices are favorable.

Ports themselves typically do not store or dispense fuel. Instead, ships place orders with maritime fuel suppliers operating at ports to meet their fuel requirements. Ships in ports, or the surrounding area are typically refueled by bunker barges, which receive fuel from these privately operated marine terminals. Because of the potential variations in viscosity, ships do not mix fuels from different sources in a single tank, as it could overload fuel filters and reduce fuel flow. Bunker barges are equipped with flexible pipes for receiving fuel from a marine terminal and separate pipes to deliver fuel to the vessels. They also contain valves, manifolds, pumps, leak detection, and containment equipment. Bunker barges are designed with multiple tank and fuel systems, enabling them to deliver different types of marine fuels, though currently all of them are liquid at ambient pressure and temperature.

The rate of fuel delivery depends on the ship's refueling system, typically ranging from 500 to 700 metric tons per hour and up to 1,000 metric tons per hour, with refueling times of 9 to 12 hours (Hsieh and Felby 2017). In smaller ports, typical bunker barge capacities range from 500 to 1,000 metric tons, whereas larger ports can accommodate bunker barges with capacities of 3,000 to 5,000 metric tons. Centerline Logistics, an organization with operations throughout the United States, reports bunker barge capacities ranging from 1,492 to 13,432 metric tons (Centerline Logistics, n.d.). Its ships are typically designed with 12 tanks, arranged in pairs, with 10 tanks carrying HFO and 2 tanks carrying either MGO or marine diesel oil (MDO).

Liquid biofuels are not expected to pose significant challenges for existing bunker barges. However, it would be necessary to clean the ship's fueling systems when switching to biofuels, as is done with any fuel switching—a process that incurs costs ranging from $250,000 to $500,000 for a bunker barge with a capacity of 2,850 to 7,150 metric tons. Currently, bunker barges typically house tanks less than 3,000 cubic meters in size. Industry concerns for adopting new liquid fuels include pour point, precipitation, waxing, oxidation, shelf life, and the need for potential adjustments such as heating, centrifuge recalibration, and purification system adjustment. An additional consideration would be updating the fuel transition clause in charter parties for insurance purposes.

The use of packing, non-mechanical sealing throughout the bunker barge is an important consideration. Flax or graphite sealants, taken from a spool and cut into rings, are attached to connections throughout the bunker barge. Although this sealing mechanism is suitable for heavy fuel oils, lighter fuels such as MGO and biofuels would require the replacement of non-mechanical seals with mechanical seals. Research funded by DOE has identified the compatibility of various elastomer materials with different types of biofuels (Kass et al. 2016; 2011).

Fueling with other fuels such as methanol, ammonia, or hydrogen is likely to require greater infrastructure modifications. Because methanol does not need to be stored at extreme temperature or pressure, it will be easier to accommodate in the industry than ammonia and hydrogen; as noted, successful ship-to-ship bunkering of methanol has already been demonstrated. Methanol bunkering is available or planned at 29 ports worldwide (Gordon 2024). In addition to methanol-ready ships, methanol-ready bunker barges will also need to be considered, and these purchases are reflected in ship order books (Dolan 2023). There has been successful barge-to-ship and non-tanker ship-to-ship methanol transfers at the Ports of Rotterdam and Gothenburg, respectively ("Methanol as a Marine Fuel," n.d.).

As noted, ammonia has greater storage requirements, including extreme temperature and/or pressure to properly contain the fuel in a liquid state. This will require tanks to be located in the center of ships, as with bioLNG, which necessitates newly built ships and bunker barges. The heightened storage and fueling infrastructure requirements are part of the reason that ammonia-readiness lags behind methanol (Dolan 2023). However, the Port of Singapore safely demonstrated its pilot ammonia bunkering facility in 2023, and a floating ammonia bunkering terminal designed by Azane Fuel Solutions in Norway has received an approval in principle rating from the classification society DNV (Connelly 2023).

Liquification of hydrogen is a mature technology but liquid hydrogen storage at ports is in the early stages of development. The world's first liquid hydrogen bunkering in Glasgow is operational in a pre-commercial stage (Connelly 2023). Thermal and vacuum insultation as well as flexible unloading technologies are in the early process of being designed and tested at international ports. Further research is necessary to move liquid hydrogen infrastructure from early demonstrations to ready-to-use commercialization (Shu-Ling Chen et al. 2023).

6 Fuel Transport to Port

Currently, renewable diesel is the one fungible fuel with substantial market share on the U.S. West Coast. In 2022, petroleum distillate production in the United States was at its lowest level since 2002 due to increasing renewable diesel consumption (Troderman 2023). Because renewable diesel meets the same American Society for Testing and Materials (ASTM) specification as petroleum diesel, it can be seamlessly blended, transported, and co-processed with petroleum diesel. This means it could use existing infrastructure for transportation, including pipelines, terminals, and fueling stations ("Energy Everywhere: Renewable Diesel" 2023). The first pipeline transport of renewable diesel occurred in France in 2022, reducing GHG emissions by 92% as compared to conventional transport by tanker trucks (Neste Corp. 2022). In the Unites States, Kinder Morgan, Inc. has created two renewable diesel hubs in California. Its Southern California hub has been delivering 20,000 barrels per day (bpd) of renewable diesel coming into the Port of Los Angeles via tanker ship to San Diego and other inland areas via its SFPP pipeline (formerly Santa Fe Pacific Pipeline) system since February 2023. Since April 2023, the Northern California hub has provided 21,000 bpd of renewable diesel via the SFPP northern pipeline system from the San Francisco Bay area to inland terminals ("Kinder Morgan Announces Commercial In-Service of Southern and Northern California Renewable Diesel Hub Projects" 2023).

Non-fungible biofuels, such as biodiesel, produced at stand-alone facilities are still commonly moved by rail for large volumes or truck for small volumes. As volumes increase, barge transport becomes more common (Moriarty, Milbrandt, and Tao 2021). Once the fuel is at the port, blending of biofuels such as renewable diesel and biodiesel with HFO, MDO, or MGO is anticipated. Marine terminals are considered the logical locations for blending, because they possess the necessary equipment and expertise. Alternatively, blending fuels into a bunker barge tank is also a possibility. However, it is generally recommended ships do not blend fuels from different suppliers onboard. Shipping companies can collaborate with their bunkering companies to determine the necessary modifications to accommodate biofuel blends at various concentrations.

Ammonia is currently the second most traded chemical in the world, with approximately 20 million tons transported by sea each year. Extensive transportation infrastructure exists for ammonia, including ports, ships, large storage tanks, and pipelines. As noted, ammonia will likely be used as the energy carrier for countries seeking green hydrogen as well, also using existing systems of transportation ("Green Ammonia Revolutionizes the Transport of Hydrogen," n.d.). Because of the heightened requirements for the storage of pure ammonia, truck and rail are significantly less suitable. Currently, the most common (and thus safest and easiest means) of large-scale, land-based transportation of ammonia is pipeline (Ruth 2023). The United States already has approximately 3,000 miles of ammonia pipeline in service within the Corn Belt to deliver ammonia fertilizer, and Alberta has extensive existing ammonia pipeline infrastructure as well as a small length of hydrogen pipeline. As the use of ammonia develops as a maritime fuel, dedicated infrastructure to transport ammonia from refineries to ports will need to be developed.

Similar to biodiesel, methanol is most commonly transported via barge, tank truck, or unpressurized rail tank car ("Methanol (CH3OH) Handling Design, Loading, and Installation," n.d.). Methanex, the world's largest methanol producer and supplier, uses rail to supply 40% of its North American customers ("2023 Sustainability Report Methanol: Improving Everyday Life" 2023).

Hydrogen can be transported in its liquid or gaseous forms or using other compounds such as ammonia or methanol (Shu-Ling Chen et al. 2023). Hydrogen is currently transported using pipelines or in cryogenic liquid tanks or gaseous tube trailers on trucks depending on the scale of operation and consistency with which hydrogen is delivered. Barges equipped to transport hydrogen are being developed for large-scale operations as ports are critical for hydrogen transport (Shu-Ling Chen et al. 2023; "Hydrogen Delivery," n.d.). Additionally, at the site of use there are other infrastructure needs such as compression storage, dispensers, and contaminant detectors ("Hydrogen Delivery," n.d.). As demand for all these fuels increases at the ports, more sophisticated, economical, and sustainable delivery infrastructure will continue to develop. Until then, existing infrastructure— mainly rail and truck— will continue to be used.

A further consideration, not explored in depth in this report, is how the price of these alternative fuels compares to that of conventional fuels. Blending of low-carbon fuels —i.e. renewable diesel, methanol, and ammonia—with their conventional counterparts may be an option to ease any large disparities in price, or to achieve certain carbon-intensity targets (Dolan 2023).

7 Fuel Sales and Imports

There are numerous methods by which ship owners can purchase fuel. Most commonly, the purchase method is decided by the type of ship and service it is providing. Charter or tramp service is dominated by bulk carriers and passenger ships. Tramp cargo ships typically have no fixed route, travelling wherever suitable cargo is available and needed. Because of their irregular fueling schedule at different ports, tramp cargo servicers most often purchase fuel through spot requests. These are one-time purchases based on the going fuel price at the port they are in. Spot purchases make up 30%-40% percent of global bunker demand (Ship & Bunker News Team 2019; Hsieh and Felby 2017).

In contrast to tramp, liner service comprises large and very large ships dominated by bulk carriers, tankers, and container ships. These ships make regular, scheduled stops along a fixed route and are mostly utilized in intercontinental or deep-sea shipping. They account for 60%-70% percent of global bunker demand. Because of their high fuel demands and fixed routes, liners set contracts with marine fuel suppliers to provide fuel at fixed locations (Hsieh and Felby 2017). These contractual negotiations are much more complex than spot purchases, and fuel purchasers and sellers use a variety of means to achieve the most beneficial price. Methods such as hedging, futures contracts, options contracts, and swap contracts can be used to purchase fuel. Many of these contracts are traded on international exchanges. The price in the contracts can be fixed, where a buyer agrees to purchase a certain amount of marine fuel over a certain period at a specific price, or floating— where the price is tied to a market index such as the Platt. The choice of purchase method for any liner depends on several factors including the company's risk tolerance and fuel requirements as well as market conditions (Hemnani 2018). The liners may also, as a part of their payment, embark on strategic alliances with the ports in which they are refueling, thereby ensuring that other activities for the liner are conducted in the port. Strategic alliances increase stability and optimization of routes by securing priority berths and schedules for liners and allow for more collaboration and communication between ports and ship companies on topics such as technology sharing. These agreements allow ports and carriers to benefit from economies of scale (Ghorbani et al. 2022).

The terms of bunker contracts can vary significantly. Long-term contracts can span months or years. Suppliers typically will not sign contracts for greater than 6 months, but some container liners buy on contracts up to 10 years. In that case, the price is renewed every 6 months with all other contract terms remaining the same. The price is typically determined based on the market conditions at the time the contract is negotiated and is often based on the Platt index (Hemnani 2018).

Alternative fuels currently compose such a small fraction of the current market (less than 1% (Kesieme et al. 2019)) that many of these strategies, such as fuel hedging and futures or option contracts, may only be relevant to a minor extent (Hsieh and Felby 2017). Currently, there have been several memorandums of understanding and other preliminary agreements signed between liner companies and alternative fuel producers. However, there are relatively few fuel supply contacts existing for alternative fuels. A recent contact signed between Wallenius Wilhelmsen and ExxonMobil for the supply of a B30 biofuel blend is one of few such publicly covered contracts ("Wallenius Wilhelmsen, ExxonMobil Team up for Sustainable Bio Bunker Fuel Supply Deal" 2023). As the industry matures, more contracts are expected to be penned. Because of the risk assumed by alternative fuel producers developing these projects, many of the initial contracts for alternative fuels may need to be for longer terms than the current standard for petroleum-based fuels.

It is also an option that companies in the United States would import alternative fuels for marine use, while production takes place elsewhere. Average annual renewable diesel imports in the United States from 2018 to 2022 were 6.5 million barrels per year. Biodiesel was 4.74 million barrels per year ("U.S. Imports by Country of Origin" 2023). In 2021, the United States was the largest global importer of ammonia, importing 2.53 million metric tons ("Alcohols; Saturated Monohydric, Methanol (Methyl Alcohol) Imports by Country in 2021," n.d.), and a top three importer of methanol, importing 2.84 million metric tons ("Alcohols; Saturated Monohydric, Methanol (Methyl Alcohol) Imports by Country in 2021," n.d.). However, the markets for ammonia and methanol have largely been based in agriculture and chemicals respectively, with no products going into transportation fuels thus far. In addition, the United States has imported 6.79 million barrels per year of residual fuel oil on average from 2018-2022 ("U.S. Imports by Country of Origin" 2023), and in 2021 the United States imported 100 million barrels of ultra-low-sulfur diesel (ULSD) ("Diesel Fuel Explained: Where Our Diesel Comes From" 2022). Looking within country, biofuels or other alternative marine fuels could be imported into the U.S. PNW region through the purchase and retirement of RINs in the EPA's Renewable Fuels Standard Program, or through the Washington State CFS program, though, as noted, the maritime sector is not currently an obligated party that must comply with these policies ("Renewable Identification Numbers (RINs) under the Renewable Fuel Standard Program" 2024). The United States has also historically exported all the above products as well. This could be the case for future alternative fuels as well if global markets or policy incentives are stronger outside of the United States.

IMO regulations have greatly influenced U.S. fuel sales over the past few years. The IMO sulfur restrictions passed in 2020 created an increase in demand in the diesel market, mainly due to an increase in demand for ULSD in the maritime sector following the effects of the 2020 pandemic. However, the latest IMO announcement on GHG reduction and associated Carbon Intensity Indicator, will likely have the opposite effect, as fuels with lower carbon intensities, such as green methanol and renewable diesel, take over the industry (Kingston 2023).

8 Comparison of Expected Supply vs Demand

Average annual demand from 2007 to 2020 at the Ports of Seattle, Tacoma, and Everett, Washington, was approximately 536 million VLSFO-GE per year. Fuel demand has not increased significantly from 2007 to 2020 at the Ports of Seattle, Tacoma, and Everett; fuel demand from 2014 to 2020 was lower than demand from 2007 to 2013. Given the lack of increase in demand, we assume fuel demand will remain similar to the 14-year average in the years to come. With an expected fuel demand of 536 million VLSFO-GE per year, the estimated alternative fuel production available for the maritime sector of 729.7 million VLSFO-GE per year could more than cover future demand at these three ports by 2030. Supply and demand quantities by year from 2024 to 2030 are displayed in Figure 7. This shows there would be sufficient supply of alternative fuel for maritime use to meet demand by the end of 2025, given no project delays. The availability of these fuels to meet demand does not account for transportation or infrastructure readiness, discussed previously. Given the lack of existing infrastructure, it is unlikely that many of these fuels will make it to the ports of interest by 2025. In addition, this supply represents a mix of fuels that may be more or less desirable to individual shipping companies; there will not be a great enough quantity of any one fuel in the region to meet overall demand.

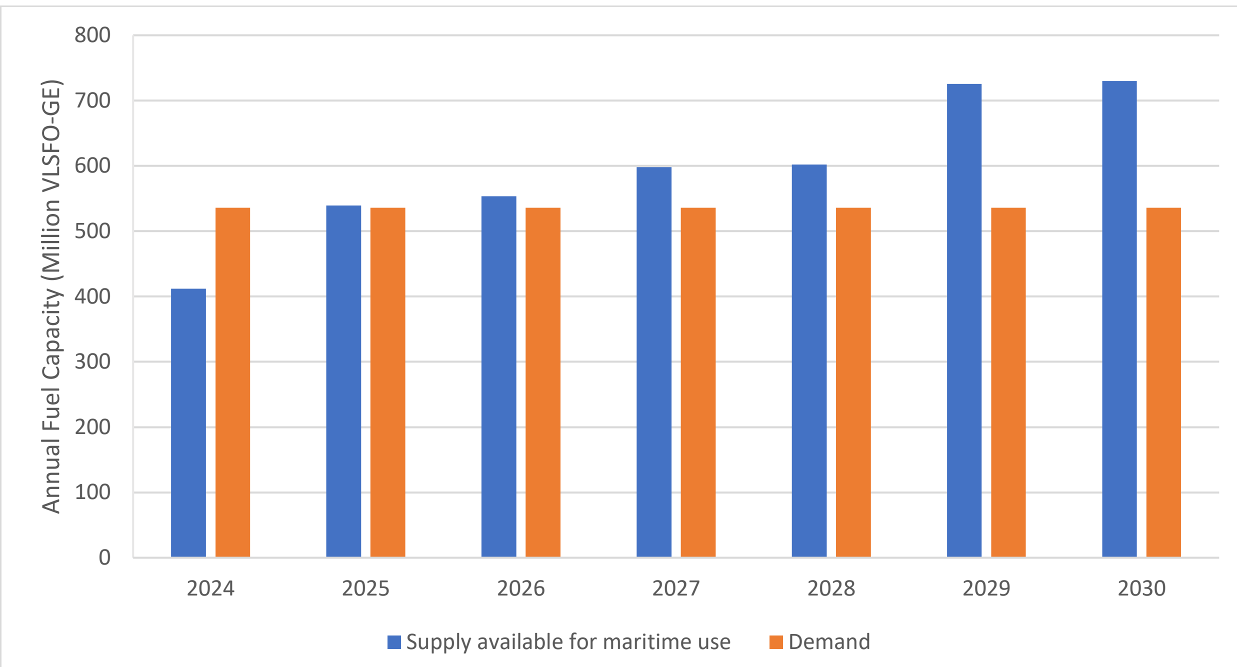

Figure 7. Comparison of alternative fuel supply available for maritime use within 1,000-km of the Port of Seattle and anticipated average annual fueling demand for the Ports of Seattle, Tacoma, and Everett from 2024 to 2030. The anticipated annual average fueling demand for the three ports is based off the average annual demand for the ports from 2007 to 2020 and lack of increasing fuel demand trends. Quantities listed in million VLSFO-GE per year.

Renewable diesel (43.8%) has the highest anticipated capacity of fuel available for the maritime sector by 2030, followed by methanol (19.7%), SAF (13.0%), ammonia (9.3%), hydrogen (6.6%), and biodiesel (5.7%). BioLNG (1.9%) has the lowest anticipated capacity available for the maritime sector by 2030. The estimate of 729.7 million VLSFO-GE per year reflects a conservative estimate – as stringent indices were used and offtake agreements were accounted for separately from sector competition. In addition, it is possible more fuel projects are announced and become operational as the economics become more favorable with various legislation or decreasing spread with the price of conventional fuels. The percentage of fuel that is available to the maritime sector between now and 2030 may also increase if changes to LCFSs and CFSs are made to include the maritime industry. This would be favorable to green corridor projects, as it could reduce the price or increase the quantity of various fuels of interest to the corridors.

9 Conclusions

The development of green shipping corridors between the U.S. PNW and ROK depends on understanding the supply of alternative fuels in comparison to anticipated demand as well as the social, political, and technical readiness of these fuels in the U.S. PNW. Through compiling publicly available information about projected production of alternative fuels in the region and analyzing sector competition and other potential economic barriers, this report provides information to be used in future ZESM feasibility studies for potential U.S. PNW – ROK green corridors.

The potential exists for sufficient supply of alternative fuels to the maritime sector in the region to meet the fuel demands of the three U.S. ports considered in the pre-feasibility study – Seattle, Tacoma, and Everett, Washington. Most of the projected alternative fuel production available for maritime use in the region is anticipated to be from renewable diesel and methanol. Because renewable diesel is a drop-in fuel, there is a possibility to use existing infrastructure. While methanol requires more modifications to transportation, bunkering, and ship infrastructure, progress has been made at the global scale for bunkering methanol. It is likely that methanol will play an important role in the potential implementation of U.S. PNW – ROK green shipping corridors, and its use is being investigated in greater depth in three green corridor feasibility studies resulting from the pre-feasibility analyses. Increased production capacity of green ammonia and hydrogen as well as the technical development of ship engines, bunkering, and fueling infrastructure compatible with these fuels could increase the potential use of these alternative fuels in the U.S PNW region. Favorable political and economic factors such as inclusion of maritime fuels into CFS programs could also impact the future supply and use of alternative fuels at U.S. PNW ports. Based in part on the findings of this report, three U.S. PNW – ROK shipping corridors have been selected for continued progress and in-depth feasibility studies. Future research on the transportation and deployment of these fuels, as well as on the economics of fuel production in the region would be beneficial. Further investigation into the proportion of fuel projects that reach operation will help to inform future analyses in this field. Finally, an in-depth exploration of the factors impacting competition for these fuels amongst sectors, including policies and willingness to pay, will play a critical role in understanding deployment of these fuels in the future.

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