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Scaling U.S. zero-emission shipping: Potential hydrogen demand at Aleutian Islands ports

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Summary

Interest is growing in the potential for "green" hydrogen generated from renewable electricity to help decarbonize maritime shipping. Green hydrogen can be produced with near-zero life cycle emissions, but due to its lower energy density than heavy fuel oil (HFO), it might require additional refueling stops on long voyages (Mao et al., 2020). Previous research (Georgeff et al., 2020) found that investments in liquid hydrogen (LH_2) bunkering infrastructure at five port clusters in Northeast Asia and Alaska could service more than 60% of the transpacific container voyages that would require an additional refueling stop. Two ports in Southwest Alaska, Dutch Harbor and the legacy Adak Naval Base, were identified as particularly well-situated for LH_2 refueling.

This study expands on that analysis by estimating the volume of fuel demand and potential market size, in U.S. dollars, for three scenarios for future LH_2 refueling in Alaska. We assess all transpacific ship operations in 2019 and include latent demand for LH_2 from the sizeable local fishing fleets in Dutch Harbor. We find a large potential demand for LH_2 ship fuel at Aleutian Islands ports that ranges from about 10,000 tonnes per year (market value estimated at $39 million assuming 2035 prices) from ships already visiting Dutch Harbor up to 260,000 tonnes (more than $1 billion) if oceangoing vessels divert to Alaska to refuel as part of a mature transpacific hydrogen network. An even larger potential market (up to $1.6 billion) could be captured if Alaska makes early, proactive investments in LH_2 bunkering infrastructure that lock in customers.

The results suggest the region is ripe for U.S. investment because the local fishing fleet in Dutch Harbor could generate an initial market for LH_2 that could be expanded over time to include larger oceangoing vessels. Developing hydrogen as a marine fuel could also bring additional benefits to the local community.

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Introduction and background

Global maritime shipping emitted about 1 gigatonne (Gt) of carbon dioxide (CO_2) in 2018 (Faber et al., 2020), or about as much as the German and Dutch economies combined (Crippa et al. 2019). Air pollution from shipping, which includes nitrogen and sulfur oxides (NO_x and SO_x) and fine particulate matter ($PM_{2.5}$), was linked to at least 64,000 premature deaths globally in 2020 (Sofiev, 2018). Recognizing the impact on climate change, in 2018, the International Maritime Organization (IMO) agreed to its Initial Greenhouse Gas Strategy (IMO, 2021). Under that strategy, international shipping will aim to reduce its carbon intensity by at least 40% by 2030, and absolute emissions by at least 50% by 2050, relative to a 2008 baseline.

This international call was answered by U.S. commitments. In 2021, U.S. Climate Envoy John Kerry committed the United States to help achieve 100% zero-emission international shipping by 2050 (Volcovici, 2021). The United States also signed the Clydebank Declaration (U.K. Department for Transport, 2022) and voiced support for the establishment of green shipping corridors to support the uptake of zero-emission marine fuels (Bankes-Hughes, 2022). Work is underway to develop one such corridor between the Port of Shanghai and the San Pedro Bay Ports in California (Richardson, 2022). Finally, the U.S. Bipartisan Infrastructure Law passed in 2021 earmarks $2.25 billion for port infrastructure projects, and these could support environmental objectives like port electrification and alternative fuel bunkering.

Deep decarbonization of shipping will require switching from fossil fuels like heavy fuel oil (HFO) and marine gas oil (MGO) to low- and zero-carbon fuels like hydrogen, methanol, ammonia, and electricity. These fuels can be generated from renewable electricity and carbon or nitrogen captured from the atmosphere, and expectations for renewable marine fuels are high (Ash & Scarbrough, 2019; Getting to Zero Coalition, 2020; Cerup-Simonsen, 2021). Still, research is needed to identify where demand for these fuels is likely to concentrate, to understand the kind of bunkering (fueling) infrastructure that is needed, and to estimate the costs and life-cycle emissions of these fuels. Such research could inform pilot projects and direct investments to priority technologies, vessels, and ports.

Previous work on liquid hydrogen (LH_2)

Starting in 2019, the International Council on Clean Transportation (ICCT) began investigating the potential for LH_2 to power transpacific container shipping. Because LH_2 contains about one-eighth the energy per unit volume of HFO onboard ships, powering them using LH_2 implies range and/or payload limitations. Still, Mao et al. (2020) found that 43% of transpacific container voyages could be fueled using LH_2 and fuel cells without any operational or ship design changes, and that 99% of voyages could be met either by adding one additional refueling stop or by replacing up to 5% of cargo capacity with fuel storage. Subsequently, Georgeff et al. (2020) estimated that container shipping could generate demand for over 730,000 tonnes of LH_2 per year at Pacific ports, one-third of which could be needed in the San Pedro Bay region (Figure 1).

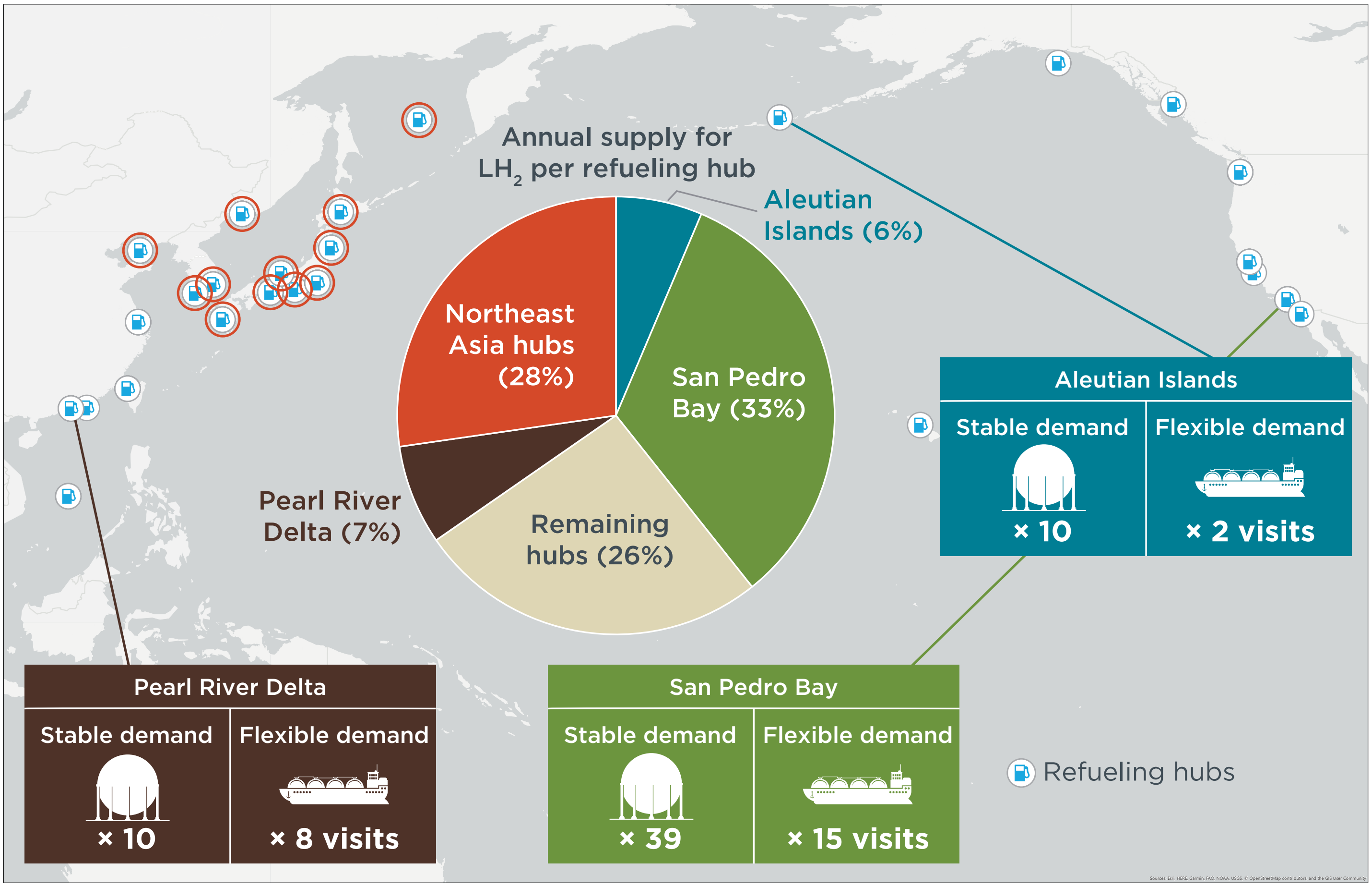

Figure 1. Maximum hydrogen demand and refueling infrastructure needed for transpacific container ships in Georgeff et al. (2020).

Georgeff et al. (2020) additionally found that targeted investments in hydrogen fueling infrastructure at key ports could have large benefits, and that Aleutian Islands ports, namely Dutch Harbor and the legacy Adak Naval Base, are particularly well-situated to serve as an LH_2 refueling hub. Alaska has abundant potential to generate renewable energy that could be leveraged for renewable marine fuel production (U.S. Department of Energy, 2013).

However, previous studies did not consider the likely evolution of demand for marine LH_2 in Alaska, namely that the introduction of hydrogen-powered ships is likely to happen in stages. Deep-sea cargo ships, due to their long-range, high power demand, and often flexible operations that allow them to refuel at multiple ports, are less likely to be a source of early demand for hydrogen. In contrast, smaller coastal vessels serving shorter routes could provide early, predictable LH_2 demand at their home ports. To complicate things, though, methods to estimate fuel demand from fishing vessels, which dominate local fleets and traffic in the Aleutians, remain underdeveloped compared to oceangoing vessels. Finally, previous ICCT studies only assessed LH_2 refueling demand for container ships and omitted other transpacific ship types such as oil tankers and bulk carriers.

This paper investigates the role that Aleutian Islands ports could play in supporting a transpacific, hydrogen-based shipping corridor by estimating two potential types of demand for LH_2: (1) "latent demand" from the existing fleet that already calls on the Port of Dutch Harbor; and (2) demand from transpacific oceangoing vessels that would require an additional refueling stop if operated on LH_2. For the former case, we develop new methods to characterize the operations and fuel use from fishing vessels, which are poorly represented in existing activity-based models.

For the second case, we develop two scenarios to consider how LH_2 demand might evolve. One is a "mature network," medium-volume scenario where Aleutians ports compete with a large network of LH_2 refueling ports throughout the North Pacific. The other is a maximum "early mover" case where proactive investments in LH_2 bunkering infrastructure are made at Aleutians ports and two competing port clusters in the Kanto region of Japan and the Pacific Northwest of the United States. For all three scenarios, we then compare the modeled LH_2 demand to existing and potential Alaskan renewable energy supplies and assess the potential LH_2 market size in Alaska, in U.S. dollars.

Methods

We start with an overview of the scenarios investigated and then present how latent LH_2 demand from the existing Aleutian Islands fleet was modeled. Following that, we explain how demand was estimated for new refueling stops by oceangoing vessels. This section closes by outlining how the estimated demand was compared to local renewable energy supply and how market size was estimated.

Scenarios investigated

We developed three scenarios to span the full range of possible LH_2 demand at the ports (Table 1). Scenario 1 is "latent demand" only from fishing and cargo-carrying vessels that visited Dutch Harbor, Alaska in 2019, as defined by a geofence between N 51° and N 54° and W -165° to W -168°. Scenario 2, the "mature network" scenario, is a middle case scenario where Aleutian Islands ports (Dutch Harbor and Adak Naval Air Station) are one of 21 hubs that sell LH_2 to marine vessels. Scenario 3 is a maximum capture scenario wherein we assume that Aleutian Islands ports are one of three "early mover" port clusters that invest in hydrogen refueling infrastructure. For Scenarios 2 and 3, the latent demand identified in Scenario 1 was added to the diversion demand to generate the full refueling demand.

Table 1. Three scenarios considered in this study

Scenario	Scenario name	Ships analyzed	Number of refueling hubs	Hubs
1	**Latent demand**	Ships that stopped in Dutch Harbor in 2019	1	Aleutian Islands
2	**Mature network**	Scenario 1 ships + oceangoing vessels that divert for an additional fuel stop	21	Transitional supply scenario (S2) in Georgeff et al. (2020), minus North Russian ports
3	**Early mover**	Scenario 1 ships + oceangoing vessels that divert for an additional fuel stop	3	Aleutian Islands, Kanto region, U.S. Pacific Northwest

Estimating latent demand

Dutch Harbor is one of the United States' busiest fishing ports. In 2019, it brought in 763 million pounds of seafood (National Marine Fisheries Service, 2021) worth $190 million, the second most of any American port (City of Unalaska, Alaska, International Port of Dutch Harbor, n.d.-b). Accordingly, fishing vessels are expected to dominate existing fuel use at this port. Globally, however, fishing vessels account for only about 4% of shipping fuel consumption (Faber et al., 2020). Methods of estimating fuel use and emissions from fishing vessels do not currently account for different energy consumption characteristics for fishing activities (Faber et al., 2020), so we developed a new method to characterize their fuel use using Automatic Identification System (AIS) data and based on the type of fishing vessel.

To identify fishing vessels that bunkered in Dutch Harbor in 2019, we first geofenced ships' global AIS data around the Dutch Harbor region and identified the oceangoing fishing fleet active there in 2019 using the IHS ship database. Ships not found in the IHS database were instead matched with Global Fishing Watch (GFW) data, which uses a machine-learning algorithm to identify fishing vessels based on their traffic patterns.[1] Vessels matched to GFW data were assumed to be smaller local boats and were classified as the domestic fishing fleet active around the Dutch Harbor region in 2019.

Of the identified fishing vessels, some were active in the region but did not visit the port of Dutch Harbor in 2019. We wanted to identify the ships that typically fuel in Dutch Harbor, so we further filtered down the fleet to those that were present at least once in 2019 in Unalaska Bay, defined as between N 53.8° and N 53.95° and between W -166.66° and W -166.38° (Figure 2, blue box at lower right). We assume that the vessels meeting this criterion visited the port of Dutch Harbor and bunkered fuel there.

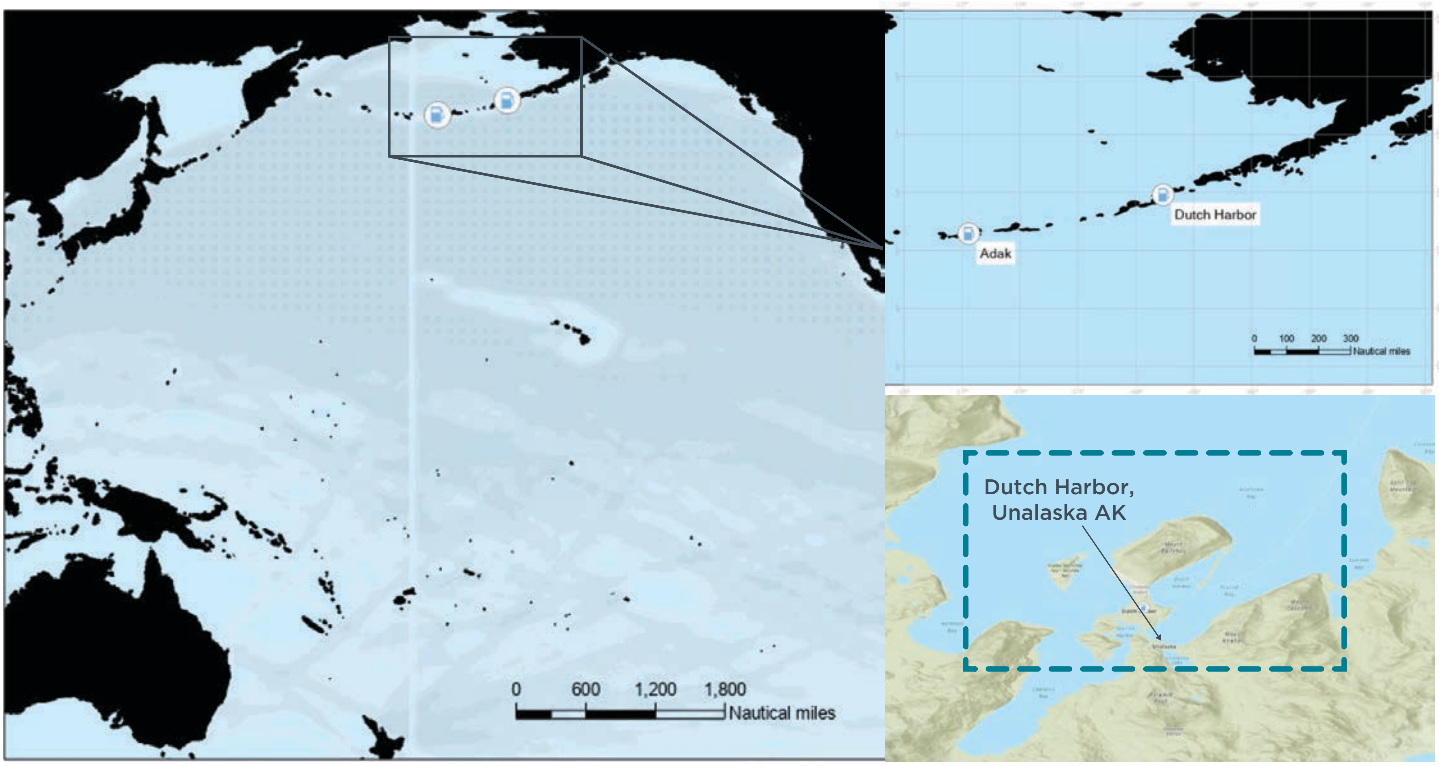

Figure 2. Study area of transpacific routes with inset of the Aleutian Islands, Dutch Harbor, Alaska.

Finally, we used a voyage identification method (Mao et al., 2021) to retrieve individual voyages of the identified fishing vessels. Some voyages originated from Dutch Harbor, while others ended at it. In order to avoid double counting, we assumed that only voyages that originated from Dutch Harbor bunkered there. To estimate fuel bunkered,

1 Data available at https://globalfishingwatch.org/datasets-and-code/.

we assumed that ships “top up” fuel consumed on an inbound voyage in order to leave the port with a full fuel tank for the subsequent voyage.

Estimating fuel consumption from fishing vessels is more complicated than for a cargo-carrying vessel. For the latter, an activity-based approach using high-resolution AIS data is used. Our Systematic Assessment of Vessel Emissions (SAVE) model (Olmer et al., 2017) takes this approach, as does the Fuel Use Statistics and Emissions (FUSE) model used in the Fourth IMO Greenhouse Study (Faber et al., 2020). Both SAVE and FUSE interpolate missing ship positions and activity assuming that ships move linearly between missing AIS signals, and this approach works well for cargo-carrying ships. But fishing vessels operate bimodally; they travel linearly between their home port and fishing grounds, and then more circularly within fishing grounds. To compound the problem, fishing vessels sometimes turn off their AIS transponders when actively fishing to avoid disclosing the location of preferred fishing grounds to competitors (Cutlip, 2016). This makes their AIS data less reliable.

AIS coverage is not the only issue. Unlike cargo vessels, which consume most of their fuel for propulsion, fishing vessels consume fuel across a variety of functions, including propulsion, hydraulic demand for fishing, and refrigeration loads. Additionally, although ship speed is a reliable indicator of the engine load and thus energy demand for cargo ships, it is less reliable for fishing vessels that incur a large dragging force when using fishing gear. It is for these reasons that we developed the new method to estimate fuel consumption from fishing vessels described below.

Estimation of fishing vessels’ fuel use

We started by considering the typology of the fishing fleet in the United States, which is multifaceted. Generally speaking, the vessels are classified by gear type, licenses held, or by participation in a catch share program. These classifications are not mutually exclusive (Comer, 2019). Fishing gear could generate significant drag during use and that makes fuel consumption sensitive to the type of gear used. As a result, we classified fishing vessels based only on fishing gear, as found in the vessels’ Federal Fisheries Permit (FFP).

The FFP authorizes a vessel owner to operate in the Gulf of Alaska (GOA) or Bering Sea and Aleutian Islands (BSAI) under the categories of catcher vessel, catcher/processor, mothership, tender vessel, or support vessel (Witherell et al., 2012). In addition to FFPs, individuals might be required to obtain other permits or to qualify for certain license programs, like the Individual Fishing Quotas (IFQ) fleet, American Fisheries Act (AFA) fleet, and the Amendment 80 fleet (Witherell et al., 2012). We consider the FFP dataset to be the most comprehensive available to characterize the Aleutian fishing fleet.

We used the ship names and ages in our AIS data to match the Dutch Harbor fishing fleet to the FFP data. In cases where a ship was renamed, its former name(s) were used for matching, instead. All 255 of the oceangoing fishing vessels in our AIS data were matched with the FFP data. Apart from FFP, the State of Alaska manages a permit program for commercial vessels that operate in state waters (Commercial Fishing Entry Certificate, or CFEC); we used the CFEC data to match an additional 33 domestic fishing vessels with this dataset. The CEFC data overlaps with the FFP data for ships that operate in both federal- and state-managed fisheries.

Of the 255 vessels analyzed, some were marked with multiple gear types because they target different fishing stock based on the season. For simplicity, we assigned one primary gear type to each fishing vessel, after considering the following questions in order:

1. If the vessel was marked as neither a “catcher vessel” nor a “catcher/processor” in the FFP record, it was considered a non-fishing support vessel.
2. Any remaining vessel marked under any “trawler” category in the FFP record was assumed to be a trawler primarily.
3. Any remaining vessel marked under any “hook and line” category in the FFP record was assumed to be a “hook and line” vessel.
4. Any remaining vessel marked under any “pot” category in the FFP record was assumed to be a “pot” fishing vessel.
5. Any remaining vessel marked under any “jig” category in the FFP record was assumed to be a “jig” fishing vessel.
6. For remaining vessels, we tried matching with the CEFC data, which assigns a primary gear type including trawler, longline, pot, jig, seine, gillnet, and troller.
7. All remaining vessels are categorized as “other” vessels.

Finally, all ships were grouped broadly into one of the three categories: non-fishing (1 and 7), active fishing (trawler, troller, and seine), and passive fishing (hook and line, pot, jig, and gillnet).

Fishing vessel activity is broadly differentiated between transit hours and fishing hours. When transiting, a fishing vessel acts like a cargo-carrying vessel, and the SAVE model reliably estimates fuel consumption. When actively fishing, though, a fishing vessel consumes energy to meet a wider variety of operations. A 2018 energy audit conducted on a fishing fleet in Alaska under The Fishing Vessel Energy Efficiency Project (FVEEP; Kemp, 2018) found that most fishing vessels consume energy across propulsion loads, hydraulic loads, DC/AC loads, and refrigeration loads while fishing. Depending on the gear type, propulsion accounts for between one-third and two-thirds of total energy consumption while actively fishing.

The likely speed ranges for active fishing vessels and passive fishing vessels during fishing voyages in this study were taken from the FVEEP report (Kemp, 2018) and information from an industry leader in fishing boat design (Jager, 2022). According to the GFW database, fishing vessels spend approximately 40% of operational hours fishing, so we used the median speed of a voyage as estimated via AIS to distinguish between fishing and transit by vessel category. Fishing voyages were defined by a median voyage speed of between 3 and 5 knots for an active fishing vessel and between 1 and 3 knots for a passive fishing vessel. All other voyages were classified as transit voyages.

For transit voyages, we estimated hourly fuel consumption directly from the SAVE model as described in Olmer et al. (2017), using the GFW vessel database. For fishing voyages, we adjusted the SAVE output as follows:

» For active fishing vessels, we applied an engine load override rule which assumes the ships operate at a constant 75% load during the fishing hours of the voyage (Coello et al., 2015). The portion of fishing hours (40%) is determined from the GFW database, which estimates the annual percentage of fishing activities for each fishing vessel. The fuel consumption of the remaining hours was estimated directly from SAVE using the propeller law (cubic relationship between speed and load factor).

» For passive fishing vessels, we increased the total energy consumption of fishing voyages by 50%, consistent with the energy audits described in Kemp (2018).

Prior to assessing the LH_2 demand from shipping vessels, we assessed the feasibility of repowering the fishing fleet with LH_2 fuel cells by evaluating what share of fishing voyages could be fueled with hydrogen without requiring vessel redesign or operational change.[2] We found that without any changes to ship design or operations, an estimated 92% of fishing voyages that bunkered in Dutch Harbor could be attained using LH_2 and doing so would replace about 62% of consumed bunker fuel. The remaining unattained voyages were those with long duration at sea.[3] This is discussed in further detail below.

The mass of LH_2 that would be needed to fuel fishing fleets at the port of Dutch Harbor is estimated using Equation 2 from Georgeff et al. (2020).

$$BD = 1.2 \times \sum \frac{E_{required_{i,v}}}{ED_{LH2} \times \eta_{LH2}}$$

Where:

BD: LH_2 demand at port of Dutch Harbor, in tonnes

$E_{required_{i,v}}$: Energy required by ship i to complete the voyage v originating from the port of Dutch Harbor, in kWh

ED_{LH2}: Energy density of LH_2, which is 33,300 kWh/tonne (Comer, 2019)

η_{LH2}: Efficiency of proton exchange membrane hydrogen fuel cells, which we assume to be 54% (Comer, 2019)

1.2: An assumed 20% fuel contingency for safety reasons

There were also a limited number of stops made by container and bulk carriers that contribute to latent demand in Dutch Harbor. Our SAVE model was used to estimate energy demand from those ships.

Estimating diverted demand

The following approach was used to identify transpacific voyages that might stop to refuel in Alaska. Following the methodology in Mao et al. (2020), we first identified transpacific ship voyages in the Northern Hemisphere from our SAVE model in 2019, as defined by voyages that crossed the international date line (change in longitude from 180 degrees east to 180 degrees west, or vice versa) and operated only at latitudes above the equator. We then used ICCT's SAVE model to identify when ships were at berth prior to the crossing, and those points were defined as the origin. When the ship left the port, we tracked it until it came to berth at a new point. That became the destination for that leg and the origin for the next leg.[4]

We used the SAVE model to estimate the energy needed for each existing transpacific leg in 2019. We then calculated the onboard space needed to store that amount of energy with LH_2 and compared it to available space for an LH_2 fuel system using

2 See Mao et al. (2020) for methods used to estimate the "attainment" rate of hydrogen-fueled vessels. This metric indicates the share of existing voyages that could be operated on LH_2 and fuel cells without requiring additional refueling stops or sacrificing cargo space in order to store more fuel.

3 On average, the unattained voyages lasted 256 hours at sea, whereas the attained voyages lasted 46 hours at sea.

4 In the two diverted-demand scenarios, a leg is the distance between two stopping points, and a voyage is a moniker that denotes legs that at some point cross the international date line. For all scenarios, legs and voyages can be used interchangeably.

methods from Comer (2019), itself based on statistical relationships between engine size and power established in Minnehan and Pratt (2017). If the space needed for the LH_2 of the leg was less than the available fuel space onboard the ship, that leg was defined as attainable, and a refueling stop was deemed unnecessary.

For unattained legs, we considered two scenarios for refueling. Both assume LH_2 refueling infrastructure in the Aleutian Islands hub of Alaska (Dutch Harbor and Adak Naval Air Station) previously identified in Mao et al. (2020) as a natural halfway location for ships that require an additional LH_2 stop. Where they differ is in how many other ports are also potential refueling hubs.

For Scenario 2 (mature network), we assumed that all Northern Pacific ports labeled as "large scale" in the World Port Index have LH_2 bunkering infrastructure and are therefore also able to serve as refueling ports for ships.[5] For Scenario 3 (early mover), we assumed that only three port clusters proactively invest in LH_2 refueling infrastructure – the Aleutians, the Kanto region in Japan, and the "Pacific Northwest" hub as defined in Georgeff et al. (2020).[6] Between these ports, unattained legs selected a refueling port based on diversion distance, in other words, whichever refueling port required the shortest distance to divert was selected. Container ships that fail to attain their transpacific legs selected refueling locations based upon their maximum range on LH_2 and Pacific ports identified in the World Port Index (National Geospatial-Intelligence Agency, 2019).[7]

Care was taken to avoid overly long diversions that would delay goods movement and substantial loss of revenue for carriers. Diversion times were calculated by dividing the extra distance traveled by the speed over ground for each ship. Unreasonably long diversions were omitted, with the hourly threshold varying by ship type. For container ships, which engage in "liner services" with fixed or less-flexible schedules, a maximum 2-day diversion limit was set. According to a 2019 Liner Schedule Reliability ranking published by eeSea, the average delay time in 2019 was 1.6 days.[8] For other ship types that engaged in services with more flexible schedules, we identified and discarded outliers where diversion times fell above (were worse than) the third quartile of all diverted times.

Once a refueling hub was identified for each unattained leg in a given scenario, we estimated fuel demand at each corresponding hub. Following the methodology in Georgeff et al. (2020), we estimated the LH_2 refueling demands of incoming transpacific ships by assuming that all ships "top up" their fuel tanks to replace the amount of LH_2 fuel consumed on the previous leg.

The LH_2 bunkering demand modeled above under each scenario was used to estimate the potential market size, in U.S. dollars, for Aleutian Islands ports. Zhou and Searle (2022) used a discounted cash flow analysis to estimate the minimum selling price of

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5 This approach corresponds to the transitional supply scenario, or S2, in Georgeff et al. (2020).

6 Aleutian Island ports are included in this scenario because of previous research showing their strategic location for LH_2 refueling. The other two port clusters were selected in part due to their professed interest in LH_2 bunkering. The Kanto region, which contains ports in Tokyo, Yokohama, and Kawasaki, is exploring "green" hydrogen production to be used as a marine fuel for coastal shipping (Suda, 2021). In the Pacific Northwest, American ports such as Seattle and Tacoma and the Canadian ports of Victoria and Vancouver plan to incorporate hydrogen in maritime bunkering (U.S. Department of Energy, 2020; Zen and the Art of Clean Energy Solutions, 2019).

7 Our methods for calculating ship range are introduced in Mao et al. (2020). Ship range is estimated based upon the mass of fuel a ship can carry (tonnes), its average operating speed in a year (knots), and the total fuel consumption of its engines (tonnes/hour).

8 See here: https://www.hellenicshippingnews.com/eesea-unveils-2019-liner-schedule-reliability-rankings/

LH_2 by taking into account renewable electricity costs, capital and operational costs, liquefaction energy use, and transport costs for green hydrogen produced in 356 distinct U.S. regions from the National Renewable Energy Laboratory (2021). Solar and wind electricity were analyzed for each region, with the minimum cost selected in each case. Because Alaska was not included in that study, we assumed here that capacity factors for wind and solar in Alaska are comparable to the U.S. average; accordingly, the U.S. average price of $4.06 per kilogram (2020 dollars) was used to estimate the total market value in 2035.

Estimating renewable energy needed

We summed the total annual LH_2 demand for the Aleutian Islands hub in each scenario and compared that to existing and potential renewable electricity production in Alaska. We calculated the amount of electricity (kWh) needed to produce the LH_2 required at the Aleutians ports using the following equation:

$$RE_S = \sum BD_{l,H} \times \mathrm{EC}$$

RE_s = Required energy in MWh per scenario (s)

$BD_{l,H}$ = Energy demand per leg (l), per hub (H) in tonnes

EC = Electricity consumption for electrolysis of LH_2, 59.5 MWh/tonne assuming a lower heating value of 120 MJ/kg for LH_2 and an overall efficiency ratio of 56% (Zhou et al., 2022).

Estimates of the existing renewable power supply are provided by Electricity Data Browser – Net Generation for Electric Power (U.S. Energy Information Administration, n.d.). Estimates of the potential onshore wind, offshore wind, and tidal energy supplies are summarized in von Krauland et al. (2021), Doubrawa et al. (2017), and Kilcher et al. (2021), respectively.

Results

After summarizing the latent demand modeled for ships already visiting Dutch Harbor, we present the demand modeled for the additional two scenarios, mature network and early mover, that integrate refueling demand from transpacific ships requiring an additional fuel stop. These correspond to the most likely and maximum capture demand scenarios, respectively. Finally, we present the results of our estimated market size in U.S. dollars and compare it to local and statewide renewable energy supply in Alaska.

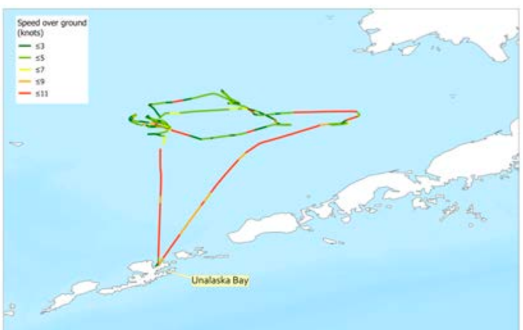
Local fishing fleet characterization

Table 2 details key characteristics of fishing vessels that bunkered in Dutch Harbor in 2019, including the number of vessels and voyages, the average ship length, and the range of voyage lengths. For voyage length, the interquartile range is shown in order to minimize outliers. In general, the oceangoing fleet was dominated by trawlers; passive fishing vessels were more common in the domestic fleet.

Table 2. Characteristics of fishing vessels that bunkered in Dutch Harbor in 2019

Navigational region	Broad type	Fishing type	Number of unique vessels	Average ship length (m)	Number of voyages originated from Dutch Harbor	Interquartile range of voyage length (km)
Oceangoing	Active fishing	Trawler	127	42.5	1871	257 – 769
	Passive fishing	Hook and line	55	33.3	410	32.0 – 635
		Pot	44	32.3	296	11.0 – 307
	Support vessels	—	11	70.3	41	38.9 – 1730
	Other	—	18	41.0	150	18.5 – 796
Domestic	Active fishing	Trawler	4	24.6	20	491 – 2,652
	Passive fishing	Hook and line	13	19.3	103	81.5 – 443
	Other	—	59	32.5	335	274 – 1,208

By mapping out these vessels' individual routes, two traffic patterns emerged: one when ships actively fished in their fishing grounds and the second when they transited to and from those grounds, either to access those grounds or to transport fished cargo to a nearby port. The maps in Figure 3 are examples of fishing trips made by a trawler (a), a hook and line vessel (b), a pot vessel (c) and a non-fishing support vessel (d).



a. Trawler (active fishing)

b. Hook and line vessel (passive fishing)

c. Pot vessel (passive fishing)

d. Support vessel (transit trip)

Figure 3. Sample routes of the fishing fleet that bunkered in Dutch Harbor in 2019.

As shown in Table 2, the oceangoing fleet was more numerous, larger in size, and had more voyages than the domestic fleet. Although the voyage lengths varied, the majority (85% and 71% for oceangoing and domestic vessels, respectively) were less than 925 km (500 nautical miles, or nm). Voyage lengths are influenced by the type of fish caught, timing of the voyage (whether it is fishing season or not), and the particular purpose of the voyage; however, the relationship between these variables and whether the voyage can be attained using LH_2 is complex.

The relationship between fishing voyage length and its suitability for powering with LH_2 is shown in Figure 4. Although 90% of fishing voyages are less than 1,850 km (1,000 nm) in length, voyages of that distance or shorter are responsible for only about 60% of total fuel use because longer voyages consume disproportionately more fuel. Moreover, we found that a fishing vessel's attainment rate, or its share of voyages that could be met using existing LH_2 fuel storage volumes, is sensitive to voyage length. At the maximum observed distance of 6,000 km (3,260 nm) an estimated 62% of overall fishing vessel fuel use could be replaced with LH_2. We use this figure as an indicator of latent demand, while recognizing that this approach is conservative because operational changes (additional refueling stops) or technical changes (increased fuel tank volume) might allow more voyages to be attained.

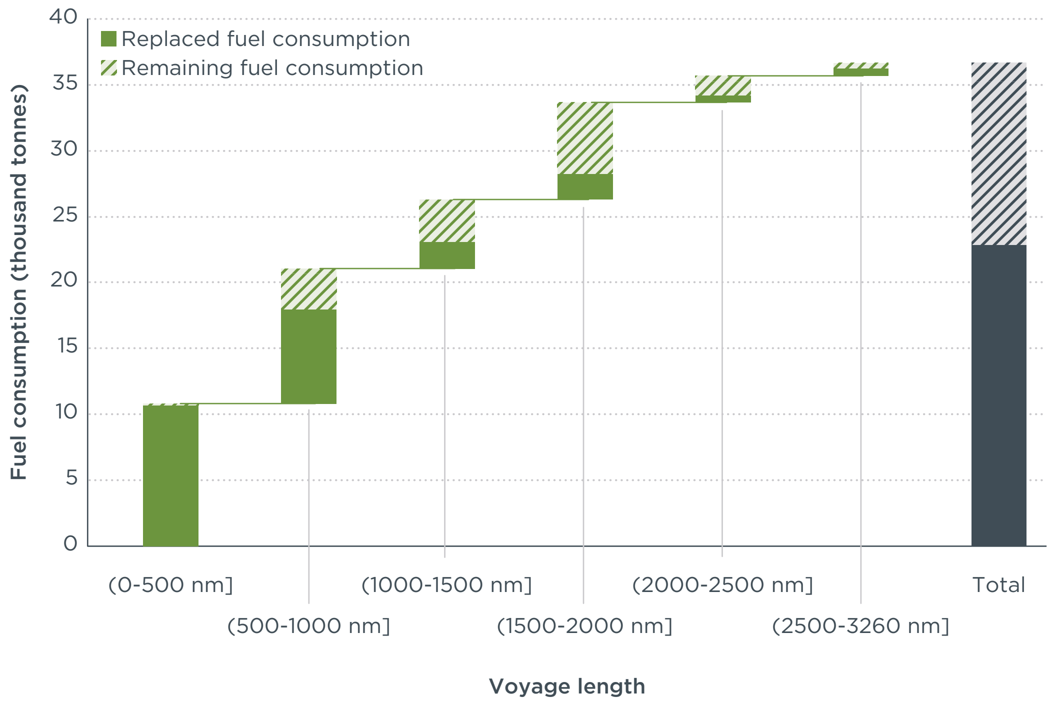


Figure 4. Cumulative fuel consumption, replaceable and not replaceable by LH_2, by voyage length for fishing vessels in the Aleutian Islands.

Predicted LH_2 refueling demand

Figure 5 summarizes the expected LH_2 demand under the latent demand scenario (Scenario 1). Following the adjustment for the higher energy demand of fishing vessels, we estimated that the existing Aleutian Islands fleet bunkers 37,000 tonnes of marine fuel (either HFO or distillate) in Dutch Harbor, or roughly 27% higher than estimated by SAVE. Taking out the share of fuel consumed on longer fishing voyages that cannot be easily shifted to LH_2 (which is 38%), leaves demand for 7,640 tonnes of LH_2 on an energy-equivalent basis (lower heating value). Visits from oceangoing vessels, namely container ships, would demand an additional 2,265 tonnes of LH_2. Total latent demand is thus about 9,900 tonnes per year, the majority (77%) of it from fishing vessels.

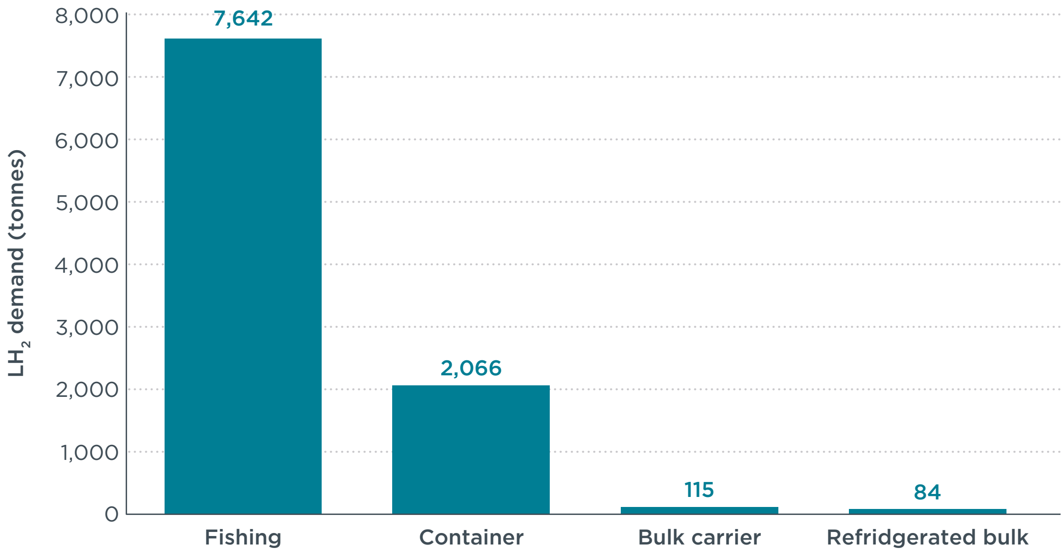


Figure 5. LH$_2$ demand by ship type, Scenario 1 (latent demand).

Figure 6 displays estimated diverted refueling demand under Scenario 2, the "mature network scenario, wherein a wide variety of ports build LH$_2$ refueling infrastructure. While the San Pedro Bay Ports (Port of Los Angeles and Port of Long Beach) capture a large fraction of container ship demand, the Aleutian Islands ports capture more total demand, almost a quarter of a million tonnes, from a diverse set of ships including containers, bulk carriers, vehicle carriers, and oil tankers. Pacific Northwest ports come in third at 138,000 tonnes, about two-thirds to fuel container ships. Aleutian Islands ports stand out in that almost 40% of their refueling demand would come from bulk carriers, not container ships.

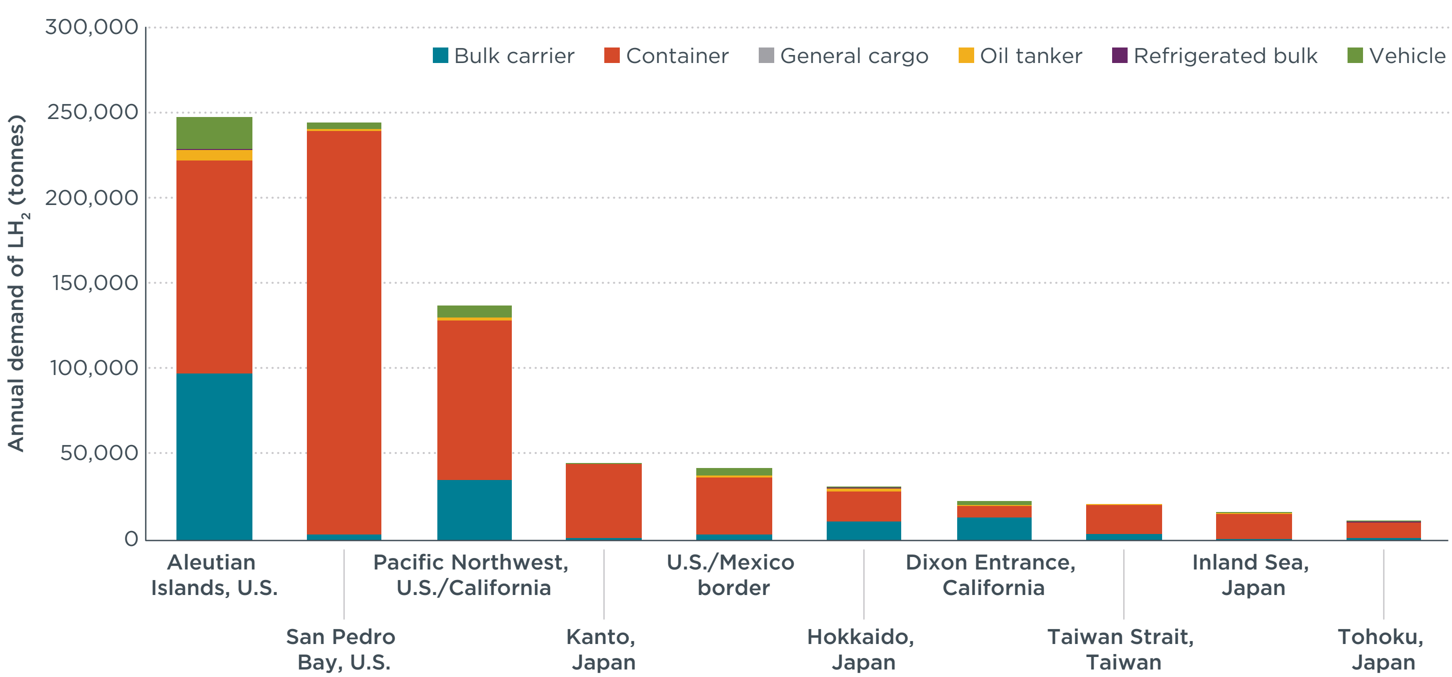


Figure 6. Diverted LH$_2$ refueling demand by ship type and port, Scenario 2 (mature network).

Figure 7 summarizes refueling demand under Scenario 3, the “early mover” scenario. In this case, more than 370,000 tonnes of LH_2 demand is estimated for the Aleutian Islands, or about 38 times that of the latent demand scenario. Aleutian Islands and Pacific Northwest ports capture a significant share of refueling traffic because of the lack of alternative ports and longer diversion distances to reach the Kanto ports in Japan. This reinforces the value of Aleutian Islands ports to transpacific refueling, particularly for bulk carriers.

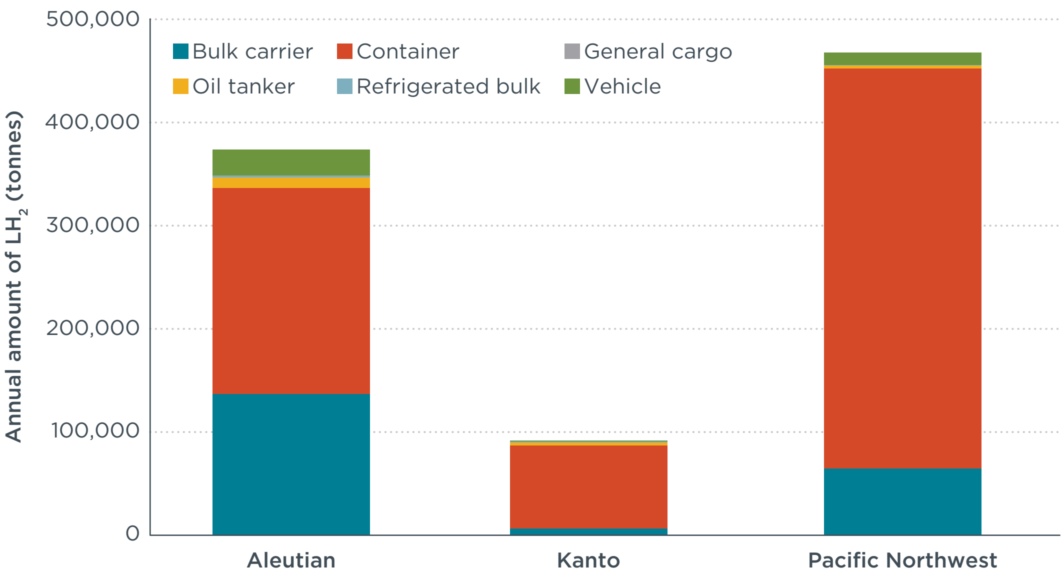


Figure 7. LH_2 refueling demand by ship type and region, Scenario 3 (early mover).

In terms of refueling demand by ship type at the Aleutian Islands, container ships are responsible for more than half (53%), and bulk carriers account for most of the remaining demand (37%). Both containers and bulk carriers often transit the Aleutian Islands between the Pacific Northwest and East Asia. Less demand is seen from vehicle carriers (7%) and oil tankers (3%), and refrigerated and general cargo carriers account for less than 1% each. The relatively larger modeled LH_2 demand from “tramp” services like bulk carriers, which operate on more flexible schedules over a larger number of ports than “liner” vessels like containers, at Aleutian Islands ports holds implications for refueling infrastructure that are discussed below.

Figure 8 summarizes the results of all three scenarios solely for the Aleutian Islands. Attracting diverted oceangoing vessels as part of a mature LH_2 refueling network (Scenario 2) would increase total demand to 260,000 tonnes of LH_2 per year, or 26 times the latent demand (Scenario 1). Early mover investments under Scenario 3 would increase the potential market captured almost fortyfold above latent demand. By comparing diversion demand across Scenarios 2 and 3, we can ballpark the value of early investments in LH_2 bunkering infrastructure in the Aleutian Islands. This comparison highlights that early action could potentially secure a customer base for LH_2 refueling in Alaska about 50% larger than if it builds LH_2 infrastructure in tandem with other competing hubs. Still, other factors like economies of scale of fuel production would also influence which ports ships choose to refuel at.

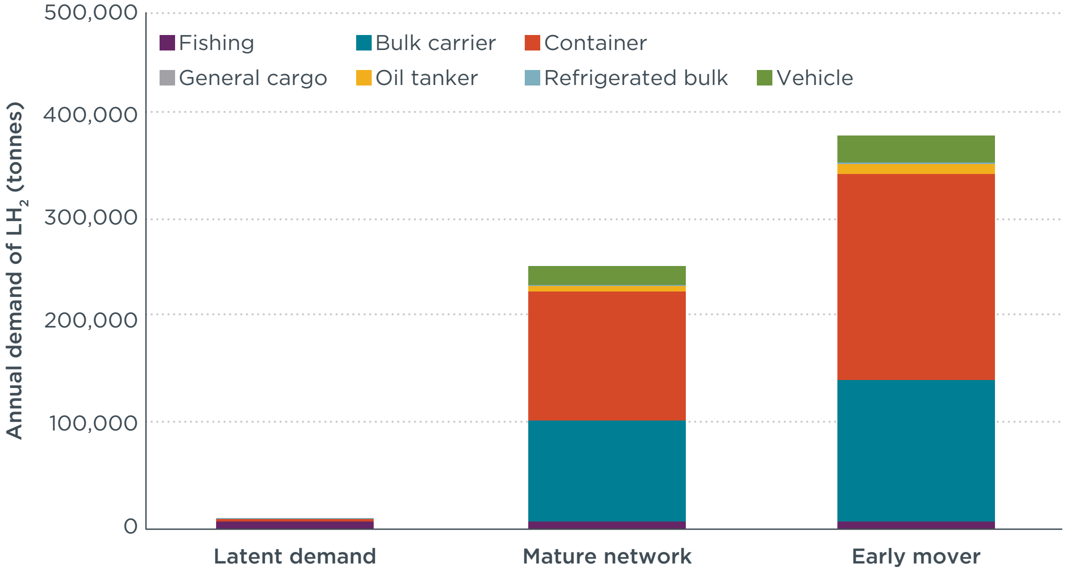


Figure 8. Potential LH_2 demand in the Aleutian Islands by scenario and ship type.

Several tests were conducted to investigate the unique value of LH_2 bunkering infrastructure in the Aleutians. First, the number of redirected fueling legs was identified by port for the mature network scenario. As shown in Figure 9, the Aleutians had by far the largest number of additional refueling visits, almost 1,500. The figure also shows a typical rerouted ship and voyage, namely, a 76,000 deadweight tonne bulk carrier that traveled an extra 2 days in order to fuel about 100 tonnes of LH_2 in the Aleutians.

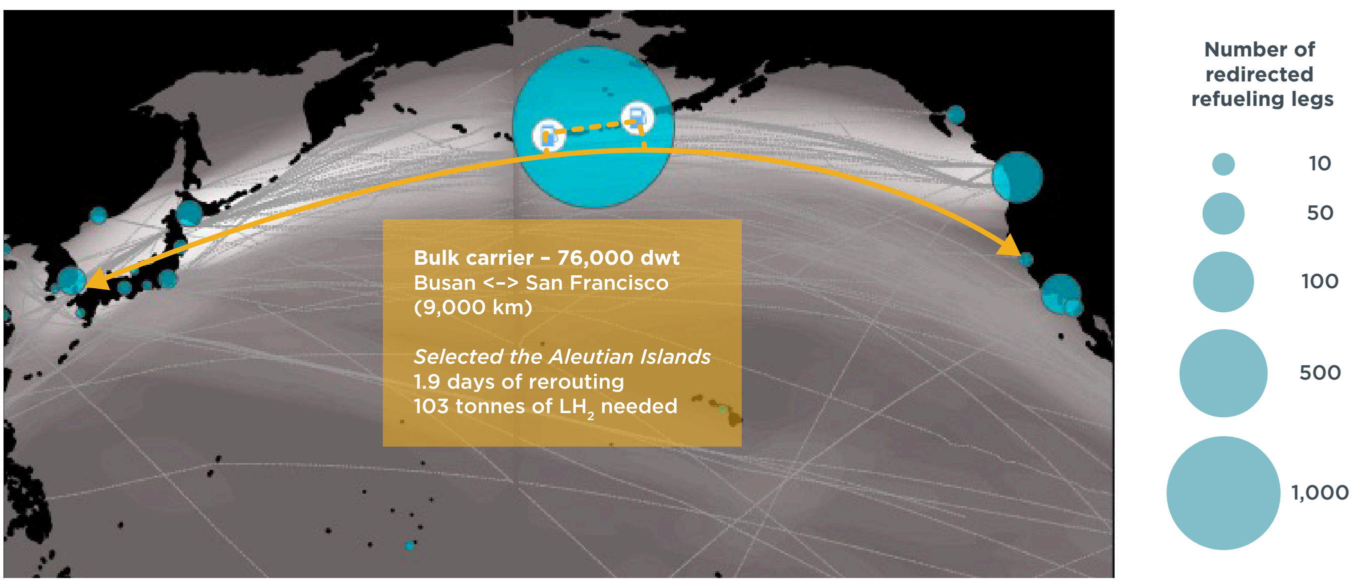


Figure 9. Diverted cargo ship traffic to key points under the mature network scenario.

Second, a sensitivity analysis was conducted to see where LH_2-powered ships would choose to refuel if the Aleutian Islands were not available. That was estimated by eliminating the Aleutian Islands as a refueling option in modeling for Scenarios 2 and 3. The results are summarized in Table 3. In Scenario 2 (mature network) with the Aleutian Islands absent as a refueling hub, ships could choose any of the transpacific hubs outlined in Table B1 of Georgeff et al. (2020). The Pacific Northwest added 288 additional refueling stops, 15% of the original 1,445 Aleutian Islands refueling stops. We also found that 401 voyages, or 21% of expected Aleutian fuel stops and about 9% of all unfulfilled transpacific voyages, were unable to be completed without refueling in the Aleutian Islands.

Table 3. Sensitivity analysis with no Aleutian Islands bunkering

Scenario	Number of refueling stops at Aleutian Islands ports	Percentage of Aleutian Islands refueling stops absorbed by		Percentage of Aleutian Islands refueling stops unfulfilled
		PNW ports	Other ports	
(2) Mature network	1,445	15%	65%	21%
(3) Early mover	2,743	45%	19%	35%

In the early mover scenario, with the Aleutian Islands absent as a refueling hub, ships were given the option to select the Pacific Northwest or Kanto region. The Pacific Northwest captured an additional 1,242 refueling stops, 45% of the original Aleutian Islands refueling stops. Kanto Region added 533 stops, 19% of the original Aleutian stops. 968 legs could not be attained using either Pacific Northwest or Kanto Region ports as an alternative. Those legs make up 35% of the 2,743 legs that were able to cross the Pacific using all three refueling hubs. This suggests that LH_2 bunkering infrastructure in the Aleutians might be particularly valuable before other ports invest.

Potential LH_2 market size

Table 4 lists estimates of the economic value of LH_2 refueling that would be generated across the three scenarios. Assuming an average green hydrogen cost of $4.06 per kilogram in 2035 generates an annual market of $40 million and $1.04 billion for Scenarios 1 and 2, respectively. Scenario 3 is a $1.55 billion LH_2 market.

Table 4. Potential LH_2 refueling market value (assuming 2035 prices)

Scenario number	Scenario name	LH_2 demand (tonnes)	Total market value (million)[a]
1	**Latent demand**	9,910	$40.2
2	**Mature network**	256,000	$1,040
3	**Early mover**	382,000	$1,550

a Assumes a cost of $4.06 US/kg of green hydrogen in 2035, based upon a U.S. average production cost via a discounted cash flow analysis.

Table 5 compares the calculated energy demand from LH_2 ship refueling to existing Alaskan renewable energy supplies. As shown, the State of Alaska generated about 1,700 gigawatt hours (GWh) of renewable electricity in 2020, more than 90% of it from hydropower. Generating enough green hydrogen to meet the latent demand at Aleutians ports would require about one-third of current renewable electricity production, while generating LH_2 to fuel diverted oceangoing vessels under the mature network scenario would require a significant ramping up of statewide renewable energy to almost nine times current production. The early mover scenario would require even larger increases in renewable electricity production, on the order of 13 times current production.

Table 5. Renewable energy supply needed by scenario and current Alaskan production (EIA, 2022)

Scenario number	Scenario name	Annual demand of LH_2 (tonnes)	Annual electricity demand (TWh)[a]	2020 Alaska renewable electricity production (TWh)	Share of existing renewable electricity supply
1	**Latent demand**	9,910	0.589	1.731	0.34
2	**Mature network**	256,000	15.2		8.80
3	**Early mover**	382,000	22.8		13.1

[a] Assuming that 59.5 kWh of electricity is needed to produce one kilogram of green hydrogen.

These numbers are large, but modest compared to the immense potential for renewable energy in Alaska. Table 6 compares Alaska's statewide potential renewable electricity for wind (onshore and offshore) and tidal power to shipping LH_2 demand under the mature network scenario. Alaska's on and offshore wind potential could fulfill that demand about 2,500 and 800 times over, respectively. Tidal power, at an estimated 1,100 TWh per year, could fulfill that demand 72 times over.

Table 6. Potential renewable energy supply in Alaska compared to the mature network scenario

Resource	Potential production (TWh/year)	Mature network scenario demand (TWh/year)	Share of existing renewable electricity supply	Source
Wind, onshore	37,800 (2018)	15	0.00040	von Krauland et al. (2021)
Wind, offshore	12,100		0.0013	Doubrawa et al. (2017)
Tidal power (all)	1,100		0.014	Kilcher et al. (2021)

In addition to wind and tidal power, local renewable energy such as hydropower and geothermal energy (Chena Power, 2020; TDX Power, 2013) could conceivably produce a share of latent LH_2 demand with co-benefits for local communities.[9] Currently, electric power for residents of both Adak and Unalaska, where Dutch Harbor is located, is provided by diesel-electric generators that consume 3.5 million gallons of diesel fuel and emit 39,000 tons of CO_2 per year (Richter, 2021). Along with the cost of transporting the fuel to this remote location, this contributes to the high cost of living in the Aleutians. Thus, efforts are underway to leverage renewable power to reduce dependence on fossil fuels.

Discussion

This analysis suggests that there might be a significant and diversified market for marine hydrogen at Aleutian Islands ports that could not only support the electrification of fleets via fuel cells, but also provide multiple benefits for local communities. Notably, we find that fishing vessels that bunker at Dutch Harbor have higher energy use to meet hydraulic and refrigeration loads than previously estimated. A refined duty cycle that

9 In Unalaska, there is a push to harness geothermal near the Makushin volcano, 14 miles away, and the project implies a potential geothermal capacity of 15 MW to 25 MW. The geothermal potential on the island of Adak was investigated in the 1970s by the U.S. Navy, but no definitive plans have been made about how to tap into the resource. Geothermal energy can provide uninterrupted power to generate hydrogen with high load factors for electrolyzers, in contrast to more variable wind and solar resources. This should reduce the cost of the hydrogen generated.

captured the full range of fuel used by fishing vessels increased their estimated fuel use by 27% above baseline SAVE values. For most fishing voyages longer than 1,850 km (1,000 nm), though, it would likely be difficult to fuel with LH_2 without operational or design changes; excluding these vessels constrains the latent LH_2 fishing demand to about 60% of the current fishing fuel demand at Dutch Harbor.

Additionally, in contrast to larger ports in California (San Pedro Bay Ports) and Japan (Tokyo Bay) that are dominated by container ships, bulk carriers are expected to account for almost 40% of new LH_2 refueling demand in the Aleutians, and container ships are expected to be just over half of demand. This matters because liner services like containers operate via a set schedule over a predictable set of ports, whereas bulk carriers operate "tramp" service that is flexible both geographically (i.e., which ports they stop at) and overall schedule.

This mix of ship types could influence how investments in LH_2 infrastructure at Aleutian Islands ports scale over time. If adopted as a marine fuel, hydrogen would phase in over time, first in newbuild ships and later via retrofits of existing ships. Among non-fishing vessels, containers are likely to adopt hydrogen early and can utilize bunkering infrastructure at select ports through liner services. Once LH_2 infrastructure is scaled up using predictable liner demand, it might then subsequently support a population of tramp ships like bulk carriers that operate more flexibly and will therefore require LH_2 bunkering infrastructure at a more diffuse set of ports. Policy might therefore prioritize LH_2 investments at ports with both potential liner and tramp refueling like the Aleutian Islands and the Pacific Northwest.

Lastly, related to ship size and port investments, many of the diverted ships considered in this analysis would be larger than what can currently be accommodated in the Aleutian Islands in terms of allowable draught, or depth below the surface of the water. Table 7 compares the average draught of ships that might divert to Dutch Harbor and Adak, respectively, to the maximum draught that various terminals can accommodate.

Table 7. Share of ships that selected the Aleutian Islands as a refueling hub that can be accommodated currently

<table>
<tr><th rowspan="2">Port</th><th rowspan="2">Terminal name</th><th rowspan="2">Maximum draught (m)</th><th>Scenario 2</th><th>Scenario 3</th><th rowspan="2">Source</th></tr>
<tr><th colspan="2">Percentage of diverted deep sea ships that can be accommodated</th></tr>
<tr><td rowspan="4">Dutch Harbor</td><td>United States Coast Guard Dock</td><td rowspan="2">12.2</td><td rowspan="2">33%</td><td rowspan="2">37%</td><td rowspan="4">City of Unalaska, Alaska, Interntional Port of Dutch Harbor (n.d.-a)</td></tr>
<tr><td>Unalaska Marine Center</td></tr>
<tr><td>Spit Dock</td><td rowspan="2">7.6</td><td rowspan="2">1%</td><td rowspan="2">1%</td></tr>
<tr><td>Light Cargo Dock</td></tr>
<tr><td>Adak</td><td>Port of Adak</td><td>7.6</td><td>1%</td><td>1%</td><td>Physical and Operational Characteristics for PPOR Map 07 of the Aleutian Subarea (2014)</td></tr>
</table>

As shown, only two terminals at Dutch Harbor can accommodate a substantial fraction of diverted ships, and even then, only about one-third of overall traffic. Moreover, the Port of Adak, with a maximum draught of only 7.6 m, is not currently suitable for refueling almost any transpacific vessels. Investments to upgrade these ports would therefore be needed to accommodate ships with larger draughts and/or to purchase LH_2 barges capable of ship-to-ship bunkering that would eliminate the need to refuel at the terminal.

Conclusion and policy implications

This study corroborates previous research which found that hydrogen-powered ships could generate substantial demand for LH_2 at Aleutian Islands ports. Here we estimate a latent demand of about 10,000 tonnes of LH_2 from ships already calling Dutch Harbor, the majority of it (77%) linked to fishing vessels. We find potential future demand of up to 260,000 tonnes LH_2 per year, equivalent to a market of more than $1 billion per year assuming 2035 prices, as part of a mature network of hydrogen hubs that sell fuel to transpacific oceangoing vessels. An even larger market, $1.6 billion per year, could theoretically be captured if early, proactive investments in LH_2 bunkering allows Alaskan ports to lock in customers.

Powering fishing vessels in particular could generate an initial market for LH_2 that could be expanded to oceangoing vessels. The results also highlight that existing models underestimate energy use from fishing vessels by about one-quarter because they neglect substantial hydraulic and refrigeration loads. Further, detailed AIS analysis showed that fishing fuel use is bimodal; although fuel use is dominated by propulsion on transit voyages, hydraulic and refrigeration loads are important during and after active fishing. This refined understanding might help design future zero-emission fishing vessels and engines.

This work holds certain policy implications. First, there is a strong case for federal funding to help jumpstart hydrogen bunkering at Aleutian ports, given their strategic location. The favorable geography, significant latent demand, and untapped renewable energy potential in Alaska combine to make this a unique opportunity for investment. That could take place through federal programs like the $2.25 billion set aside for port infrastructure under the Bipartisan Infrastructure Law passed by Congress in 2021. Work to generate and bunker renewable hydrogen could start small, with a focus on fishing vessels with lower power demand and shorter voyages, and then build outward to achieve economies of scale for oceangoing vessels. Demonstration projects to develop and mature fuel cell technology suitable for fishing vessels are also recommended. Funding for those projects could come from programs like the Diesel Emissions Reduction Act or the Marine Highways Program.

Active investment in LH_2 refueling infrastructure at Aleutian Island ports could reduce GHG emissions, cut the reliance of local communities on fossil fuel imports, and support local economic development. The strategic location of its ports, combined with a local fishing fleet to support early hydrogen demand, makes Aleutian Island ports of uniquely high value for LH_2 refueling. But investments will be needed to upgrade ports to accommodate larger vessels, to develop refueling infrastructure including onshore storage and bunker vessels (Georgeff et al., 2020), and to ramp up on-site LH_2 production or build infrastructure (terminals or pipelines) to transport renewable hydrogen produced elsewhere.

Second, given the combination of both latent (largely fishing vessel) and diverted demand, early investment should focus on supporting and maturing latent demand, followed by a gradual expansion to support diverted liner demand first and tramp service second. Scaling up in this manner could leverage near-term, predictable demand now while scaling up infrastructure and technologies to potentially capture large future markets from deep-sea ships. While the implied refueling demand is large relative to Alaska's current renewable energy demand, it is modest compared to the statewide potential. Proper planning will be needed to foster LH_2 refueling demand in a strategic way, and potential marine refueling should be integrated into Alaska's renewable energy strategy to ensure that the marine demand is satisfied without compromising other sectors' needs.

Developing hydrogen fueling infrastructure at Aleutians ports could provide both environmental and social benefits. For example, increasing vessel traffic via LH_2 refueling could help reduce transport costs for rural communities that struggle with a high cost of living today. However, some resistance to a new fuel like hydrogen might be expected, particularly if government regulations to drive uptake are put in place before there has been more informal outreach, education, and early stage partnerships with local stakeholders to achieve acceptance of hydrogen within fishing fleets.

More research would be needed to understand the exact sequence of steps required to successfully implement LH_2 bunkering at Aleutian Islands ports. Important areas of focus include identifying which specific hydrogen and fuel cell technologies require maturation and which specific projects would best demonstrate that fishing vessels can be repowered with fuel cells. Work is also needed to identify the kinds of refueling infrastructure (port side storage, bunkering barges, etc.) that would be suitable for the Aleutian Islands ports or if, alternatively, a purpose-built hub with proximity to local renewable energy resources would be best. Additional research focusing on renewable power supply that considers the accessibility and cost of local wind, geothermal, tidal, and solar resources would also be valuable.

Finally, due to the challenges of storing cryogenic hydrogen for extended periods of time, it is possible that LH_2 might be suitable for local use but a hydrogen carrier like methanol or ammonia would be needed for at least some transpacific voyages. Research into other zero-emission or near-zero-emission means of powering fleets is therefore recommended, as future refueling patterns would need to be reanalyzed to take into account the longer ranges provided by those fuels, which would obviate the need for some refueling stops in Alaska.

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