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Liquid hydrogen refueling infrastructure to support a zero-emission U.S.–China container shipping corridor

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Summary

The International Maritime Organization (IMO) has set ambitious goals to reduce and eventually eliminate greenhouse gas (GHG) emissions from international shipping (Rutherford & Comer, 2018). Achieving these goals will require new fuels and propulsion technologies that produce low and even zero GHG emissions on a life-cycle basis, and fuel cells powered by liquid hydrogen (LH_2) are one such technology. While there are several current barriers to the use of hydrogen in container shipping, including storage challenges and fueling infrastructure for marine application, and higher costs relative to fossil fuels, focused research and development and policy interventions could lower these barriers over time (Comer, 2019).

In March 2020, the International Council on Clean Transportation (ICCT) examined the feasibility of powering a fleet of container ships servicing a shipping corridor between China and the United States with hydrogen fuel cells (Mao, Rutherford, Osipova, & Comer, 2020). Even though ships powered by hydrogen fuel cells are expected to have shorter ranges than ships powered by fossil fuels, by assessing energy demand and refueling needs, that study found that 43% of voyages along that corridor could be completed using hydrogen with no changes whatsoever. Moreover, adding just one refueling stop at ports somewhere along the route brought the voyage attainment rate to 99%. The study also identified Alaskan and Japanese ports, among others, as potential locations for hydrogen refueling, and suggested additional work to assess refueling infrastructure.

This follow-up study evaluates what refueling infrastructure would be needed, and at which ports, to enable the same 2015 container ship traffic that Mao et al. (2020) assessed to use LH_2 in combination with fuel cells along the same transpacific corridor. By analyzing 2015 operations, we found that ports would need to supply 730,000

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tonnes of LH_2 per year to fuel virtually all of the container ships on this corridor. That is about 1% of the hydrogen used in the industrial sector worldwide in 2019. After assigning each of the Pacific Rim ports to one of 25 refueling hubs based on geographic proximity, we found that hydrogen refueling infrastructure at five hubs in Northeast Asia and Alaska alone could provide fuel for more than 60% of the voyages that would require an additional refueling stop.

We also estimated basic infrastructure needs in terms of on-site fuel storage tanks and refueling vessel visits (Figure ES1). On-site storage tanks at ports accommodate stable weekly refueling demand, and refueling vessels are deployed for demand peaks. The San Pedro Bay hub would need to dedicate 13,000 square meters (m^2) of land, or approximately 1% of the Ports of Los Angeles and Long Beach's current area, for 39 on-site storage tanks, each with a capacity of 2,500 cubic meters (m^3). For months when demand peaks, 15 refueling vessel visits per week, each with a capacity of 2,500 m^3, would be needed to provide the additional supply. Other refueling hubs would need to invest in fewer on-site storage tanks and refueling vessel visits.

We also propose some initial considerations for the positioning of refueling infrastructure. First and foremost, infrastructure investments should be designed to allow the maximum number of ships to access hydrogen with minimum diversions for refueling. The Aleutian Islands ports could be particularly useful, as the refueling hub there could provide fuel for up to 171 additional voyages on this corridor, or about one-quarter of all voyages that need an additional stop for refueling. The Aleutians are the only top refueling hub without an existing major container port and have abundant renewable energy potential; they are thus an attractive target for future investment to expand renewable refueling supply.

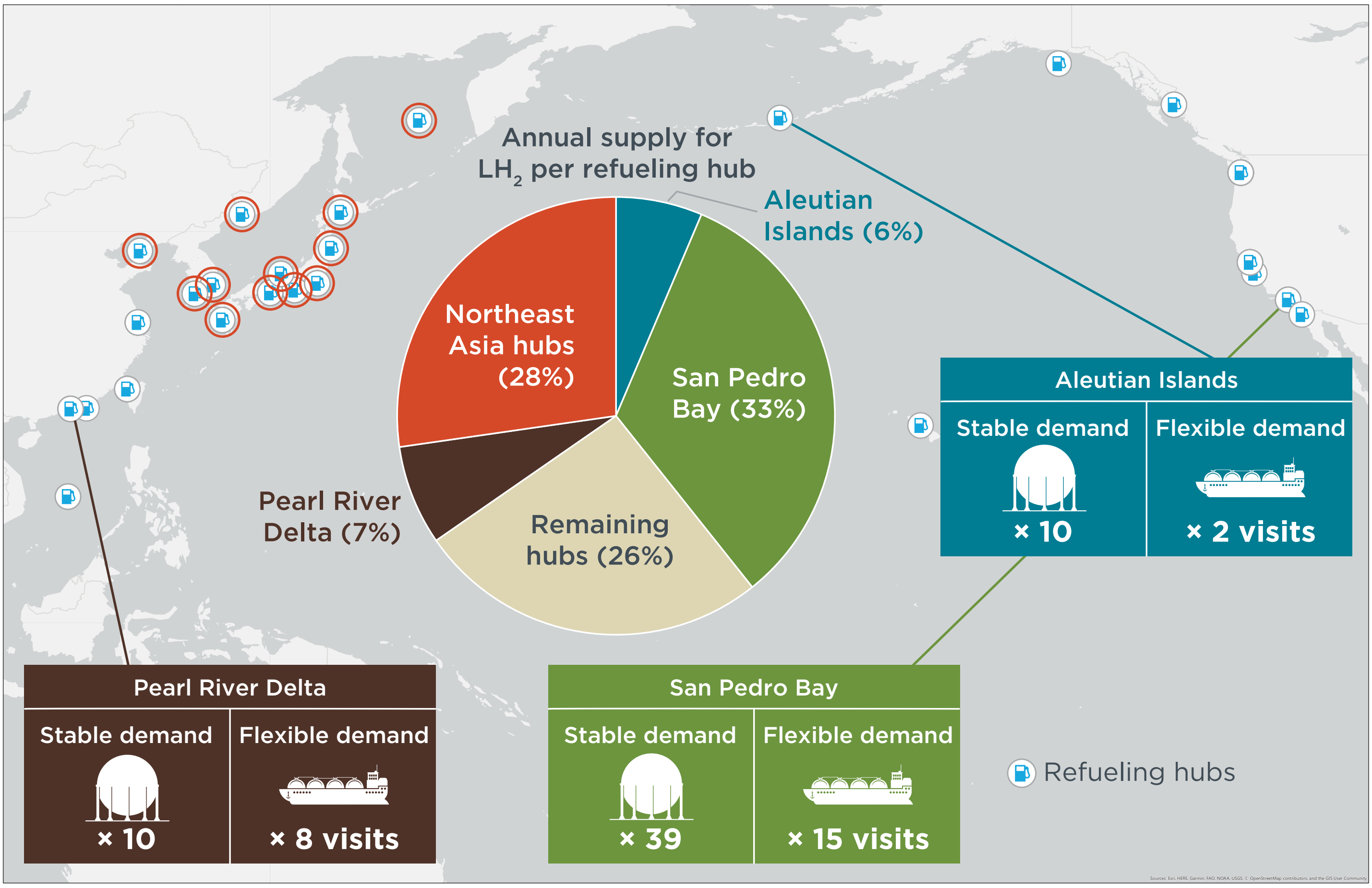

Figure ES1. Hydrogen demand and refueling infrastructure needed for transpacific container ships under the full deployment scenario

Background

In previous ICCT work, Mao et al. (2020) analyzed the potential use of LH_2 together with fuel cells to power transpacific container ships traveling between China's Pearl River Delta (PRD) and California's Ports of Los Angeles and Long Beach, also known as the San Pedro Bay (SPB) Ports. The PRD–SPB shipping corridor shown in Figure 1 is part of the transpacific container shipping lane, which moved 46% of the world's twenty-foot-equivalent unit (TEU) containers in 2015 (United Nations Conference on Trade and Development, 2016).

A key limitation to hydrogen use in shipping is its low volumetric energy density, which means that ships can travel less distance for a given fuel tank size than when powered by heavy fuel oil (HFO). The PRD–SPB route is particularly challenging because it involves long distances at sea with few refueling opportunities; if hydrogen can work here, it is likely viable in many other corridors.

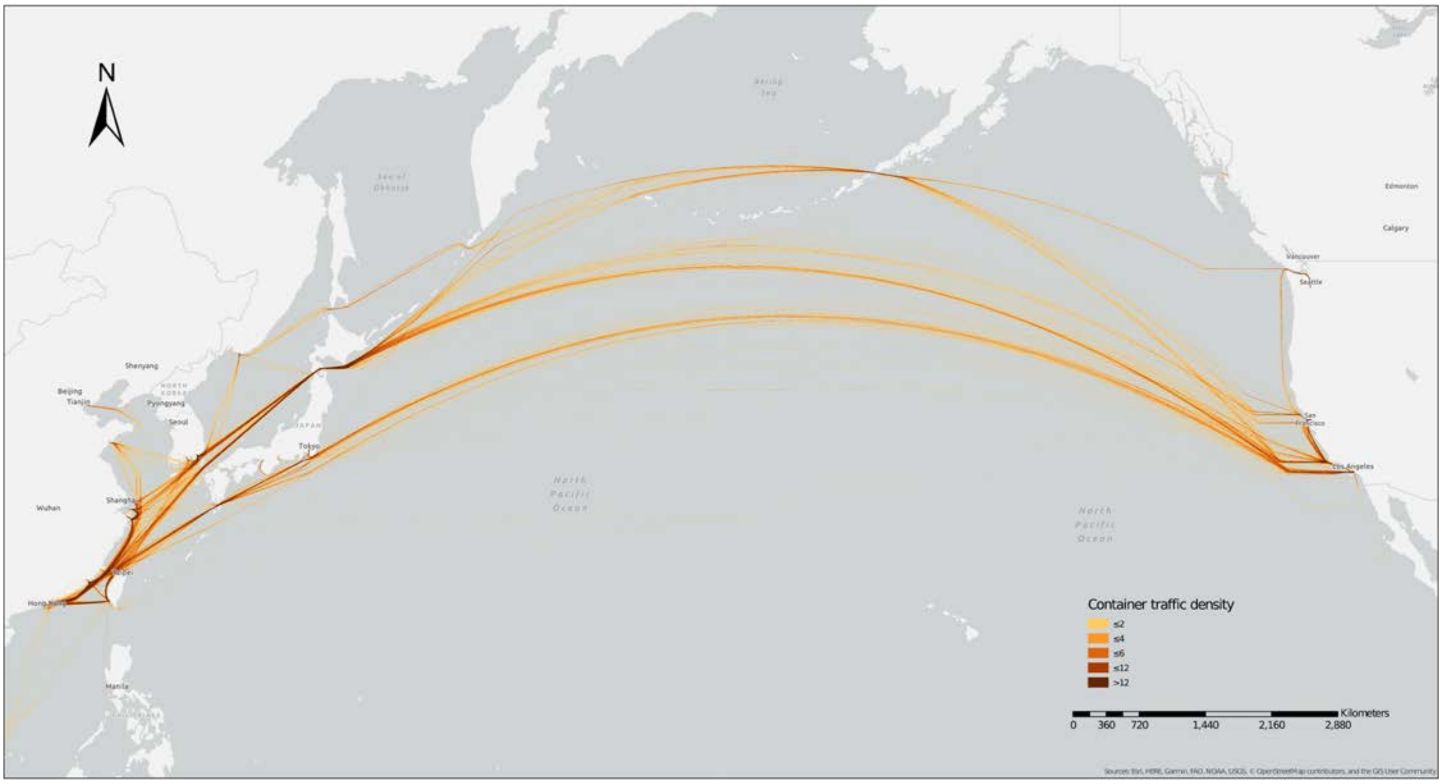

Figure 1. Ship traffic along PRD–SPB container shipping corridor in 2015

Mao et al. (2020) found that 43% of the container ship voyages in 2015 between PRD and SPB could hypothetically be powered by hydrogen instead of fossil fuels without any design or operational changes to the ship. Virtually all of the remaining voyages, 99%, could be completed by either replacing 5% of cargo space with additional LH_2 fuel storage or by adding one additional refueling stop along the route.

While compressed hydrogen fuel cells are being deployed in on-road vehicles, LH_2 is not yet a mature technology in the transportation sector, including marine applications (NCE Maritime CleanTech, 2019). As emphasized in Germany's newly released National Hydrogen Strategy, the adoption of hydrogen in the transport sector requires demand-oriented refueling infrastructure construction.[1] Mao et al. (2020) identified Alaskan and

1 A summary was retrieved on June 24, 2020 from: https://www.cleanenergywire.org/factsheets/germanys-national-hydrogen-strategy#:~:text=According%20to%20the%20strategy%2C%20%22only,to%20establish%20corresponding%20value%20chains.

Japanese ports, among others, as potential LH_2 refueling ports. This follow-up study expands on that work by assessing the amount of refueling demand along this corridor and the infrastructure that would be needed to meet that demand.

Specifically, this study considers the scenario in which 99% of voyages along the corridor are powered by hydrogen by adding one more refueling stop at a convenient port. The results reflect the full extent of opportunities for Pacific Rim ports to support LH_2 use along the U.S.–China container shipping corridor between PRD and SPB ports.

To account for uncertainties, we also modeled three additional scenarios where the fleet adoption of hydrogen and/or the number of ports with hydrogen infrastructure is more limited. Under those more limited scenarios, use is constrained by the size of ships, based on the assumption that smaller ships will adopt LH_2 first; and infrastructure is constrained by the size of the refueling port, as we assume ships will refuel at a larger-scale port as much as possible even though it means a longer detour.

All four scenarios are included in Table 1. S1 is the most restricted LH_2 deployment scenario, S2 and S3 are transitional stages, and S4 is full deployment.

Table 1. Scenario definitions

	LH_2 refueling ports	
Size of container ships using LH_2	**Limited[a]**	**Expanded**
Less than 8,000 TEUs	Most restricted (S1)	Transitional demand (S3)
All ships	Transitional supply (S2)	Full deployment (S4)

[a] The total number of refueling ports is limited so that ships refuel at a larger-scale port as much as possible, even though it means a longer detour than an alternative choice of a smaller-scale port.

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The rest of this paper is organized as follows. The next section describes how we identified possible LH_2 refueling ports and estimated both refueling demand and the associated need for infrastructure. Subsequently, we discuss the results, and then the conclusion identifies potential areas for further research.

Methodology

In the following sub-sections, we describe how refueling ports were identified for the 2015 container ship voyages along the PRD–SPB corridor that required an extra refueling stop when using LH_2 under the four scenarios. We then arrange the ports by proximity into refueling hubs, estimate LH_2 demand at those hubs, and translate that demand into needs for port-side refueling infrastructure.

Locating extra refueling stops

In Mao et al. (2020), all voyages were defined between an origin and destination consisting of one or more legs. All voyages began and ended at either a PRD or SPB port and burned HFO. Because LH_2 is less energy dense than fossil fuels, it will impose a range constraint compared to HFO. Unattained voyages here are defined as those where at least one of the legs of a voyage could not be completed by a ship using LH_2 due to range limitations.

We identified where ships could refuel based upon their existing routes and fuel tank capacity. To complete a given voyage using LH_2, a refueling port must be located so that the unattained leg can be broken into two shorter, attainable legs. As illustrated in Figure 2, we identified refueling ports using the following steps:

» Identified the origin and destination of an unattained leg (A and B in Figure 2).

» Located potential port stops (C, D, and E in Figure 2) from a pool of Pacific seaports using the Marine Safety Information World Port Index.[2]

» Calculated the distances between the origin port and each port stop (AC, AD, and AE in Figure 2) and the distances between the destination and each port stop (BC, BD, and BE in Figure 2).[3]

» Selected candidate refueling ports in cases where the range of the vessel was sufficient to stop at the port, refuel, and then make it to the destination without needing to refuel again.

» The candidate ports were then further screened under different scenarios:

  » S1: Hydrogen powered ships with fewer than 8,000 TEUs would go to the larger port D to refuel even if it would introduce a longer detour, as the smaller port E does not have refueling infrastructure during the transitional S3 stage

  » S2: Hydrogen powered ships of all sizes would go to the larger port D to refuel even if it would introduce a longer detour, as the smaller port E does not have refueling infrastructure during the transitional S3 stage

  » S3: Hydrogen powered ships with fewer than 8,000 TEUs would transit smaller port E due to its shorter detour.

  » S4: Hydrogen powered ships of all sizes would transit smaller port E due to its shorter detour.

Once the appropriate refueling ports were identified and combined with refueling ports that ships have already visited, a network of LH_2 refueling ports was formed. We then arranged these ports into refueling hubs based on geographic proximity. For example, the Port of Vancouver and the Port of Tacoma are grouped as the Pacific Northwest refueling hub because they are close enough that a ship might plausibly refuel at either.

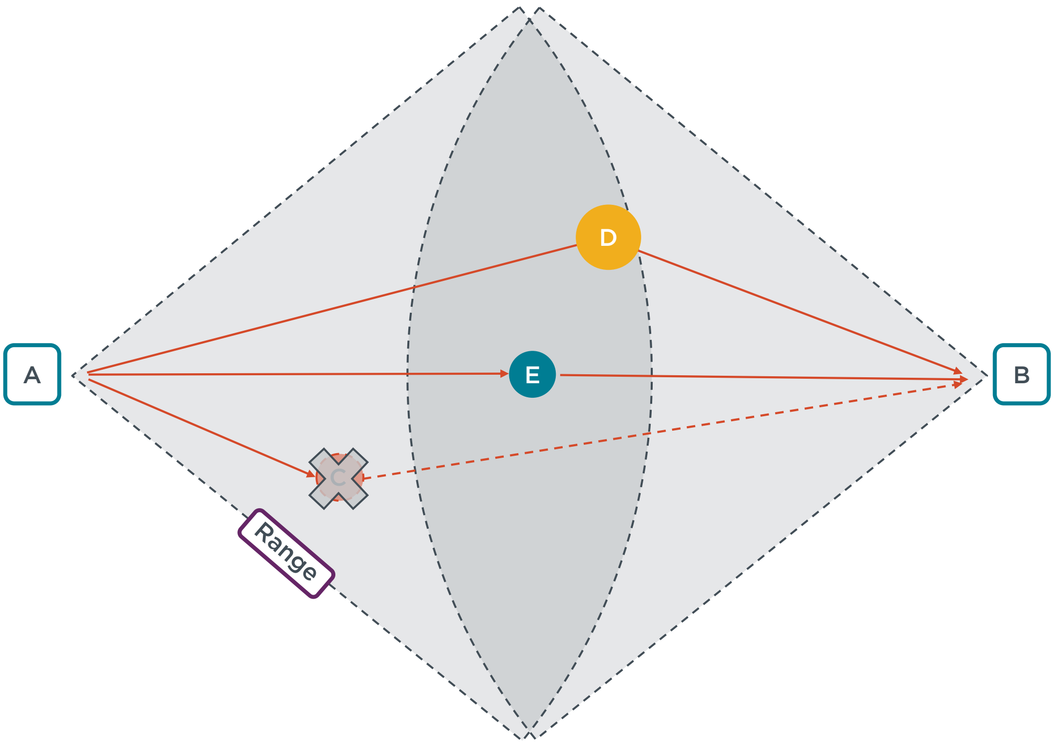

Figure 2. Diagram of refueling port identification

2 The National Geospatial-Intelligence Agency lists 3,700 ports and terminals in its World Port Index (WPI), which can be found at https://msi.nga.mil/Publications/WPI. We selected only Pacific ports for our analysis. Sizes of ports are determined by WPI using several factors such as area, facilities, and wharf space.

3 See Appendix A for further details on port-to-port distance calculations

Estimating LH_2 fuel supply needs at refueling hubs

LH_2 fuel supply needs at refueling hubs are estimated bottom-up from the needs at individual ports. For each port, refueling demand is assumed to be equal to the fuel use on the incoming legs with an additional fuel margin of 20% for safety considerations. That is, ships are assumed to "top up" their fuel tanks at each port they visit, with 20% more than it takes to cover the incoming trip. This approach, while an approximation, would allow an operator to maximize a ship's range on subsequent legs. An alternative, "forward looking" approach where a ship purchases just enough fuel at each port to operate the subsequent leg was considered but viewed as less representative of likely operations.

In Mao et al. (2020), fuel use on existing legs was estimated using ICCT's Systematic Assessment of Vessel Emissions (SAVE) model. In this study, we re-evaluated fuel use for legs that are segmented by additional refueling ports.

Estimating energy demand for the new legs

With the new refueling ports identified, we separated the formerly unattained legs into two legs linked together by a refueling port. Load factor, cruising speed, and engine power demand were assumed to remain the same as the original leg. For the new, now attainable legs, we estimated the energy it would take to complete them as follows:

Equation 1

$$E_{required_l} = P_l \times \frac{L_l}{v}$$

Where:

$E_{required_l}$	Energy required to complete leg *l*, in kilowatt hours (kWh)
P_l	Power output of the ship's main engine and auxiliary engine when traveling leg *l*, in kW; this is a direct output from ICCT's SAVE model (Mao et al., 2020)
L_l	Length of leg *l*, which is the port-to-port distance between the leg's origin and destination, in nautical miles (see Appendix A)
v	Average cruising speed of the ship traveling leg *l*, which is a direct output from ICCT's SAVE model (Mao et al., 2020)

Calculating the amount of LH_2 needed to refuel at each refueling hub

We grouped ports located near one another into refueling hubs. The full list of refueling ports and corresponding hubs is in Appendix B. For each refueling hub, we estimated the LH_2 refueling demands of incoming container ships by assuming that all ships replace the amount of LH_2 fuel they consumed on the previous leg. This was calculated using Equation 2:

Equation 2

$$BD_h = 1.2 \times \sum \frac{E_{required_{i,l,p}}}{ED_{LH2} \times \eta_{LH2}}$$

Where:

BD_h	LH_2 demand at refueling hub *h*, in tonnes
$E_{required_{i,l,p}}$	Energy required by ship *i* to complete the previous leg *l*, in kWh; leg *l* ends in port *p* which belongs to refueling hub *h*
ED_{LH2}	Energy density of liquid hydrogen (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 margin for safety reasons

We also estimated stable and peak demand at refueling hubs in order to determine infrastructure needs. For each refueling hub, we estimated weekly LH_2 refueling demand.

We then used the peak and average demand in the busiest month to assess stable and flexible refueling infrastructure need. More precisely:

» Stable demand is the *average* weekly LH_2 demand for the highest-demand month.

» Peak demand is the *highest* weekly LH_2 demand for the highest-demand month.

» Flexible demand is the difference between peak and stable demand.

A sample of the calculation used to identify stable and peak demand is shown in Table 2. Flexible demand requires infrastructure different than that necessary for stable demand.

Table 2. Sample calculation of stable and flexible LH_2 demand for a refueling hub

Month	Highest weekly demand (tonnes)	Average weekly[a] demand (tonnes)	Month	Highest weekly demand (tonnes)	Average weekly demand (tonnes)
January	260	60	July	490	200
February	360	80	August	190	40
March	800	260	September	240	110
April	280	160	October	340	130
May	260	110	November	240	90
June	520	430	December	240	110
Stable demand: 430 tonnes per week Peak demand: 800 tonnes per week Flexible demand: 370 tonnes per week					

[a] There are, on average, 4.4 weeks per month. This number is used to divide the month-specific demand, and it results in an average weekly demand.

Assessing refueling infrastructure need at refueling hubs

Pratt and Klebanoff (2016) compared LH_2 refueling to that of liquefied natural gas (LNG), which can be pumped into a receiving vessel through (1) a tank loaded on the chassis of a truck, known as truck-to-ship or TTS; (2) cargo tanks in a refueling vessel, known as ship-to-ship or STS; or (3) stationary storage tanks on the shore side or a pipeline, known as port-to-ship or PTS. A major difference across the three refueling pathways is the rate of fuel transfer. According to LNG bunkering guidelines set by the European Maritime Safety Agency (EMSA; 2018), the TTS pathway has a slower transfer rate that makes it less preferred by large fuel consumers like a container ship servicing transoceanic routes.

Although Pratt and Klebanoff (2016) evaluated feasibility for all possible LH_2 refueling options, including TTS, STS, and PTS, we chose to exclude TTS, as the slow rate of fuel transfer makes it impractical to refuel a typical container ship voyage in our study in the time it usually spends at port.[4] Meanwhile, PTS is sensible for long-term stable demand, and STS could offer operational flexibility to help meet flexible demand (EMSA, 2018).

Kawasaki Heavy Industries (KHI) Ltd. designed a pilot of stationary, land-based LH_2 storage tanks based on current space industry storage tanks. These are double-shell spherical tanks that have perlite vacuum thermal insulation and a capacity of about 2,500–3,000 m^3; KHI believes they could scale up to 50,000 m^3 (Kamiya, Nishimura, & Harada 2015). KHI also finished concept designs for small- and large-scale LH_2 refueling vessels. The capacity of small vessels is 2,500 m^3 and the capacity of the large vessels is 160,000 m^3. To be conservative, we assumed a spherical storage tank with a capacity of 2,500 m^3 to accommodate stable demand at refueling hubs, and that it can be refilled on a weekly basis. For flexible demand exceeding the local storage, we assumed that a refueling vessel with the same 2,500 m^3 capacity could be made available as needed.

4 According to EMSA (2018), the typical rate of fuel transfer for TTS is around 40- 60 m^3/h. For a typical container ship leg in our analysis, it would take at least four days to replenish the consumed fuel, which is not practical for container ship operations.

For simplicity, we also assumed zero boil-off rate for all refueling infrastructure.[5] A complete list of assumptions is presented in Table 3.

Table 3. Assumptions for LH_2 fuel storage infrastructure to meet stable and flexible demand

Fuel demand	Inputs		Assumption
Stable	Stationary storage tank	Tank structure	2,500 m^3 cryogenic spherical tank (Kamiya et al., 2015)
		Tank fill limit	90% of capacity (Stephens, Hanna, & Gong, 1993)
		Boil-off rate	0%
		Safety space needed between individual storage tanks	1.5 m (National Fire Protection Association, 2020)
Flexible	Refueling vessel	Vessel cargo tank capacity	2,500 m^3 cryogenic tank (Kamiya et al., 2015)
		Tank fill limit	90% of capacity (Stephens et al., 1993)
		Boil-off rate	0%

With the capacity of a storage tank and its fill limit assumed, we calculated the number of tanks needed by dividing stable demand by the unit capacity of a storage tank. The number of storage tanks needed is rounded up to the nearest integer. For each tank, we added a 0.75 m buffer area around the tank to make sure the 1.5 m shell-to-shell safety distance is maintained. As shown in Figure 3, each tank is assumed to occupy a square platform that separates it from the others; thus the surface area needed for one tank was determined by a square platform.

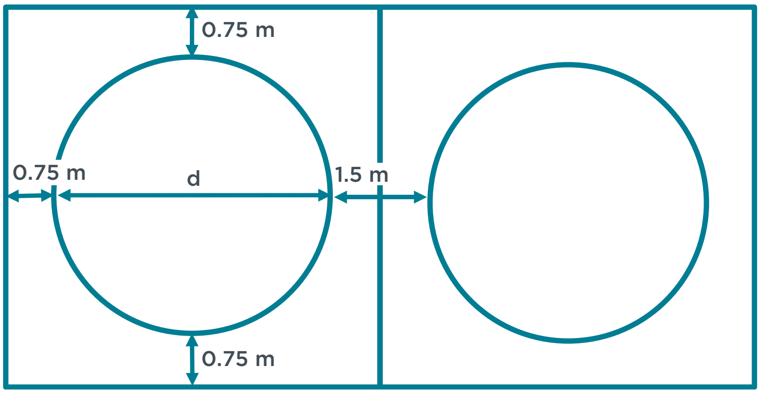

Figure 3. Hypothetical arrangement of multiple storage tanks sitting on platforms with safety distance

Similarly, with the capacity of a refueling vessel and its fill limit assumed, we calculated the number of refueling vessel visits needed at each refueling hub to meet flexible demand, which is the difference between peak and stable demand. In each case, the number of refueling vessel visits needed weekly is rounded up to the nearest integer.

Results

Refueling hubs along the PRD–SPB container corridor

Using the methodology above and 2015 voyages, we identified potential locations where ships could refuel with LH_2 for scenarios S1 to S4. In the most restricted scenario (S1), there are 30 new refueling ports; for the full deployment scenario (S4), there are 74 new

5 KHI indicated that their storage tanks and refueling vessels will have a boil-off rate of 0.18 %/day or less (Kamiya, Nishimura, & Harada, 2015). With weekly replenishing, the boil-off rate adds up to 1.3%/week, which is well within the range of uncertainty for this study.

locations with LH_2 refueling infrastructure. Combined with the ports that are already serving container ships, a network of refueling ports is formed, scattered across 25 refueling hubs based on geographical proximity. Figure 4 shows the distribution of 25 refueling hubs for the full deployment scenario (S4).[6]

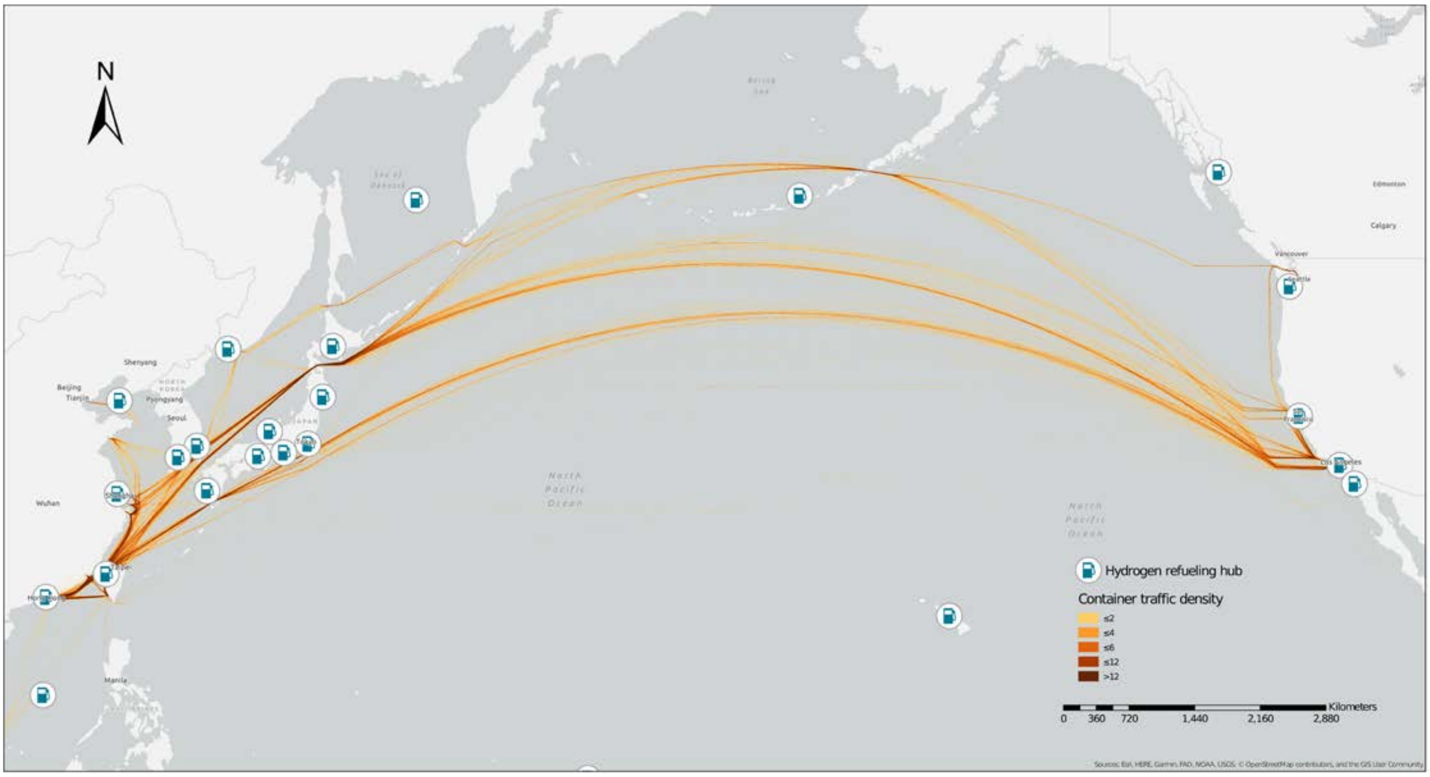

Figure 4. Refueling hubs along the PRD–SPB container shipping corridor in the full deployment scenario

Of the voyages enabled by refueling ports under the full deployment scenario (S4), 60% transit small-scale ports that we assumed were not available during the transitional stages. For scenarios S1 and S2, 60% of the voyages needing an additional refueling stop transit large-scale ports with a longer diversion.

Some LH_2 refueling ports are more useful than others. In particular, at full deployment (S4), the Port of Adak Naval Air Station and Dutch Harbor ports that make up the Aleutian Islands refueling hub could enable 171 additional voyages for hydrogen-powered ships, or about one quarter of all voyages requiring an additional refueling stop. If the Aleutian Islands hub cannot provide LH_2, then refueling demand could transfer to the Port of Hakodate and Kushiro in Japan. The Hokkaido hub there could provide fuel for most, 145 out of the 171, of those voyages, although ships would need to detour longer distances to refuel.

In total, the most restricted deployment scenario (S1) results in annual demand of 230,000 tonnes of LH_2. Under the full deployment scenario (S4), demand triples to around 730,000 tonnes annually. The latter is still only equivalent to 1% of global hydrogen use in the industrial sector in 2019.[7] Notably, more than 80% of the total demand for LH_2 is met by the top 10 refueling hubs across all scenarios.[8] Figure 5 shows the annual LH_2 demand for these 10 refueling hubs across all four scenarios. The San

6 The 25th hub, the miscellaneous hub, is not shown in this map. This is a catch-all category for ports that were rarely visited. Full details, including the full list of ports and corresponding hubs, are in Appendix B.

7 According to NCE Maritime CleanTech (2019), total hydrogen demand today is estimated at 67 million tons, or 61 million tonnes, although only 1% is in liquid form.

8 Results for all 25 refueling hubs are in Appendix C.

Pedro Bay refueling hub would supply the largest share of LH_2 since most voyages arriving there have a long preceding leg, which generates a large refueling demand. The next three of the top refueling hubs are all located in East Asia.

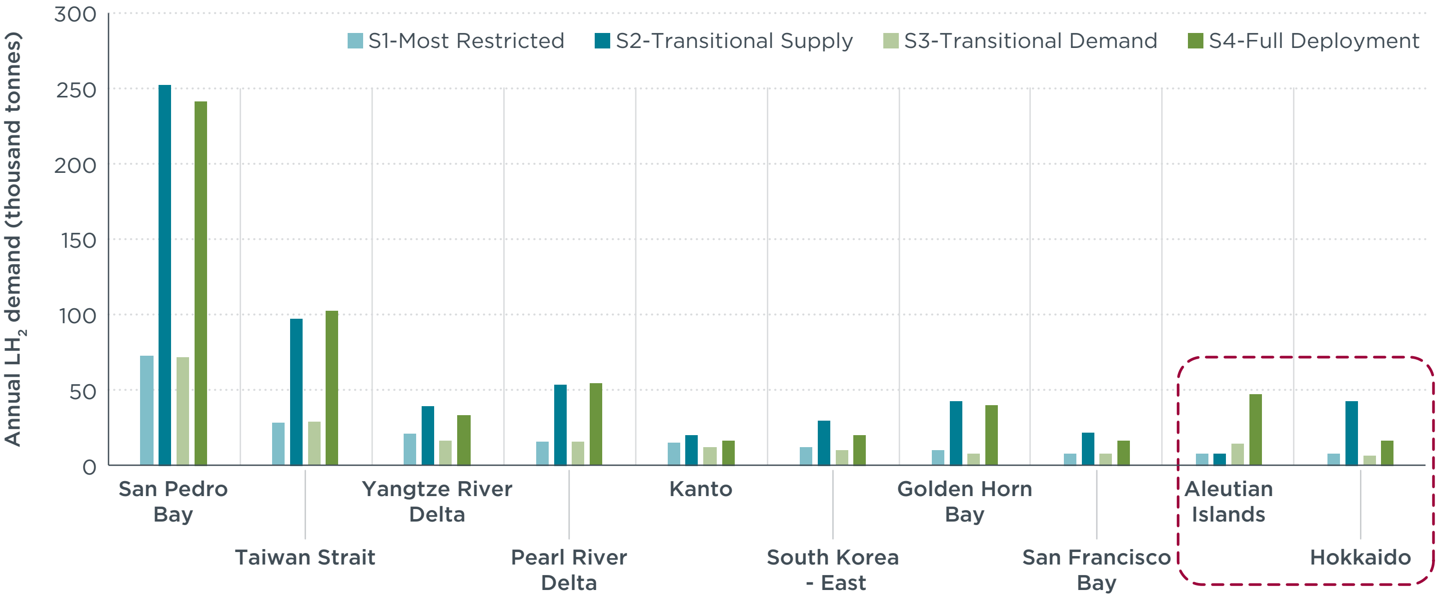

Figure 5. Top 10 refueling hubs by annual LH_2 demand and scenario

An overwhelming trend shown in Figure 5 is that results from the S3 and S4 scenarios (green bars) resemble those of the S1 and S2 scenarios (blue bars) for most hubs. Meanwhile, the difference between the S1 and S2 scenarios (blue vs. light blue bars) and the S3 and S4 scenarios (green vs. light green bars) are evident for all hubs. This suggests that refueling demand at most hubs is more sensitive to the level of fleet LH_2 adoption rather than number of refueling ports.

However, for the Aleutian Islands and Hokkaido refueling hubs, both variables play a role, although in opposite ways. Geographically, both hubs are well situated to split PRD–SPB voyages and therefore attract LH_2 refueling demand. For scenarios with limited supply (blue bars), larger ports in Hokkaido meet more refueling demand. For scenarios with expanded supply (green bars), the Aleutian Islands strongly attract refueling traffic as those two smaller ports enable ships to detour less for refueling. At full deployment (S4), total annual demand for LH_2 at the Aleutian Islands hub is around 47,000 tonnes, or almost 6% of the total. To put this number into context, this is a 60-fold increase over the amount of LH_2 that would be expected based on 2015 business as usual traffic going to and from the Aleutian Islands, which is only about 780 tonnes LH_2.

Stable and flexible refueling demand

For stable LH_2 demand, we present results for the most restricted deployment scenario (S1) and full deployment scenario (S4) only in Figure 6. The full set of results is in Appendix D.

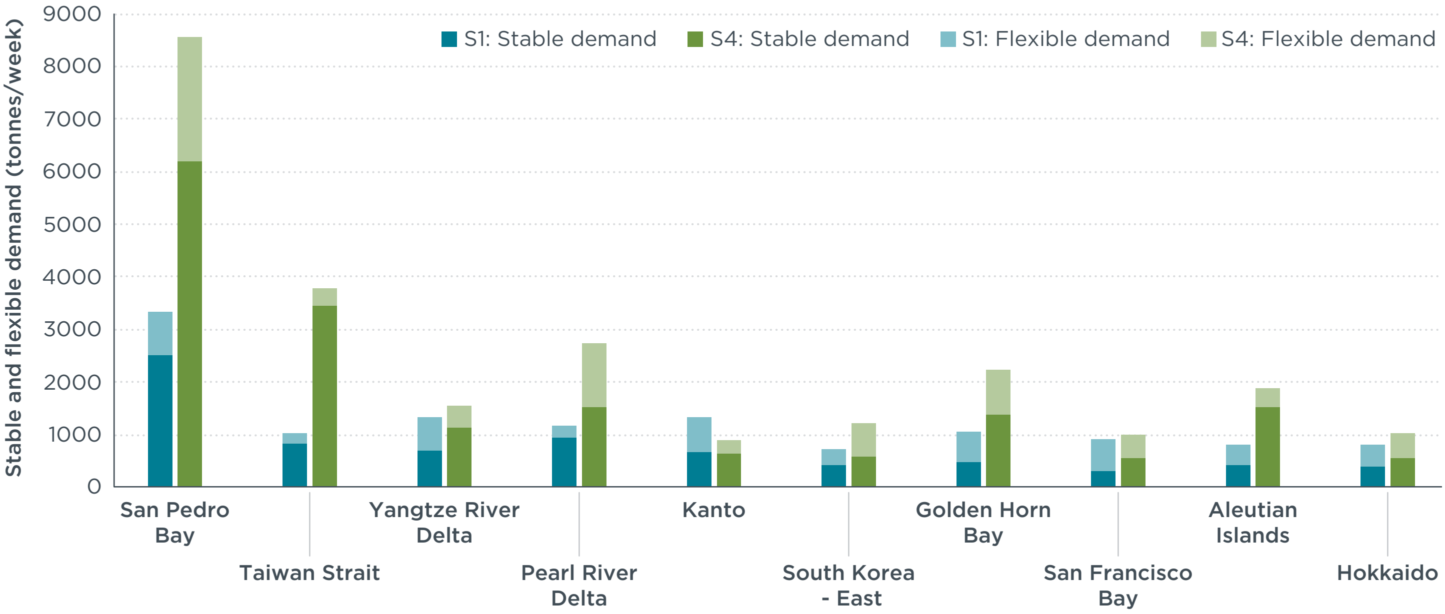

Figure 6. Stable and flexible demand of top 10 refueling hubs for S1 (blue bars) and S4 (green bars) scenarios, with lighter colored bars representing flexible demand.

As shown, stable demand (blue and green bars) follows the same pattern as annual demand (Figure 5), as it represents typical weekly incoming ship traffic. For flexible demand, however, there seems to be no overwhelming trend. The San Pedro Bay hub has high stable and flexible demand under the full deployment scenario (S4), as does the Pearl River Delta hub. The Taiwan Strait hub and Aleutian Islands hub have high stable demand but relatively low flexible demand for both scenarios. Under full deployment (S4), the absolute amount of flexible demand decreases for four refueling hubs—the Yangtze River Delta, Kanto, San Francisco Bay, and the Aleutian Islands.

LH_2 refueling infrastructure needs for the most restricted deployment scenario (S1) and full deployment scenario (S4) are shown in Figure 7. The full set of results is also in Appendix D. Stable demand is fulfilled by stationary storage tanks, so the need for storage tanks follows the same pattern as stable demand. The total area needed to position those tanks is proportional to the number of tanks needed. For the most restricted deployment scenario (S1), the average refueling port would need to invest in three storage tanks to meet the stable hydrogen demand, which would require about 1,000 m^2 of dedicated space, or about the size of an Olympic swimming pool. This demand almost doubles for the full deployment scenario (S4).

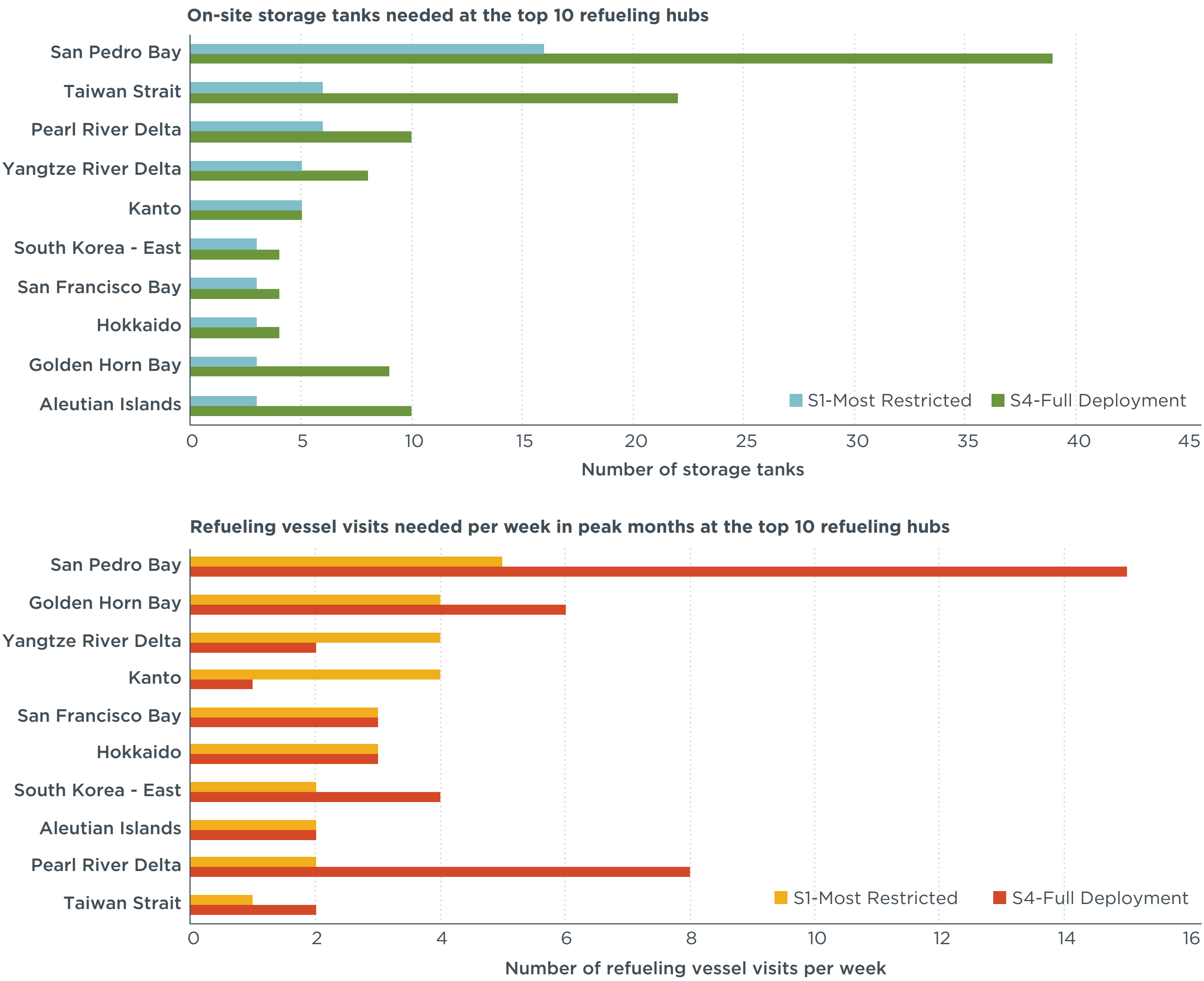

Figure 7. Infrastructure need for top 10 refueling hubs

Demand at the San Pedro Bay refueling hub is notably higher than at other hubs, at 16 and 39 storage tanks for S1 and S4, respectively. This requires dedicated space of 5,400 m^2 and 13,000 m^2, respectively.

While we show an increasing need for dedicated space to place storage tanks, conserving the need for land in even the most expanded scenario is still possible if tanks sizes scale up. For example, the Aleutian Islands hub needs three storage tanks (Figure 7a) under the S1 scenario, and this takes up space of the size of one Olympic swimming pool. That space can be repurposed to build one cylindrical tank big enough to hold the more than triple stable demand under the S4 scenario. A sample calculation is in Appendix E. With the same scale of cylindrical tank, the same amount of land for storage tanks at the San Pedro Bay hub could meet a tripled demand, full deployment scenario, as well.[9]

Flexible demand could be fulfilled by commissioning refueling vessels ad hoc. Similar to storage tanks, refueling vessel visits follow the same pattern as flexible demand. Shown

9 The land dedicated to storage tanks at the San Pedro Bay hub, if repurposed for cylindrical flat-bottom tanks with a capacity of 20,000 m^3, is enough to accommodate twice its LH_2 demand under the full deployment scenario.

in Figure 7b, a typical refueling hub would need to commission two refueling vessel visits per week to accommodate flexible demand for weeks with peak incoming ship traffic under the S1 scenario.[10] At full deployment (S4), the number of visits required nearly doubles. For some hubs, such as the Aleutian Islands, the need for ad hoc refueling vessel visits does not change over the scenarios; this suggests that a full deployment attracts not only more demand, but also a more stable refueling demand. The Kanto refueling hub even saw demand for refueling vessel visits fall in S4, although the overall annual demand of this hub remains mostly the same (Figure 5). This is also a good sign of consistent, stable demand.

Discussion and conclusions

Discussion

Having explored the location of potential refueling hubs and having estimated the likely demand for LH_2 refueling infrastructure for a zero-emission container shipping corridor between China and the United States, we find that this demand can be met for most refueling hubs if not all ships in the fleet adopt LH_2 fuel cells at once. Additionally, compared with the most restricted deployment scenario, full deployment would triple annual demand for LH_2.

Figure 8 illustrates annual demand for LH_2 by refueling hub under the full deployment scenario. We find that the San Pedro Bay hub would need to supply about 241,000 tonnes annually, or one-third of the 730,000 tonnes needed in total. Northeast Asian hubs collectively would need to supply 200,000 tonnes annually. The Aleutian Islands hub, located strategically on the corridor for range-limited ships, would need to provide almost 50,000 tonnes, or 6% of the total. That is almost as much as the Pearl River Delta hub which, due to the ability of ships to refuel in northern Chinese ports, would only supply around 54,000 tonnes.

10 This number is calculated as the average number of refueling vessel visits needed per week across all 25 refueling hubs.

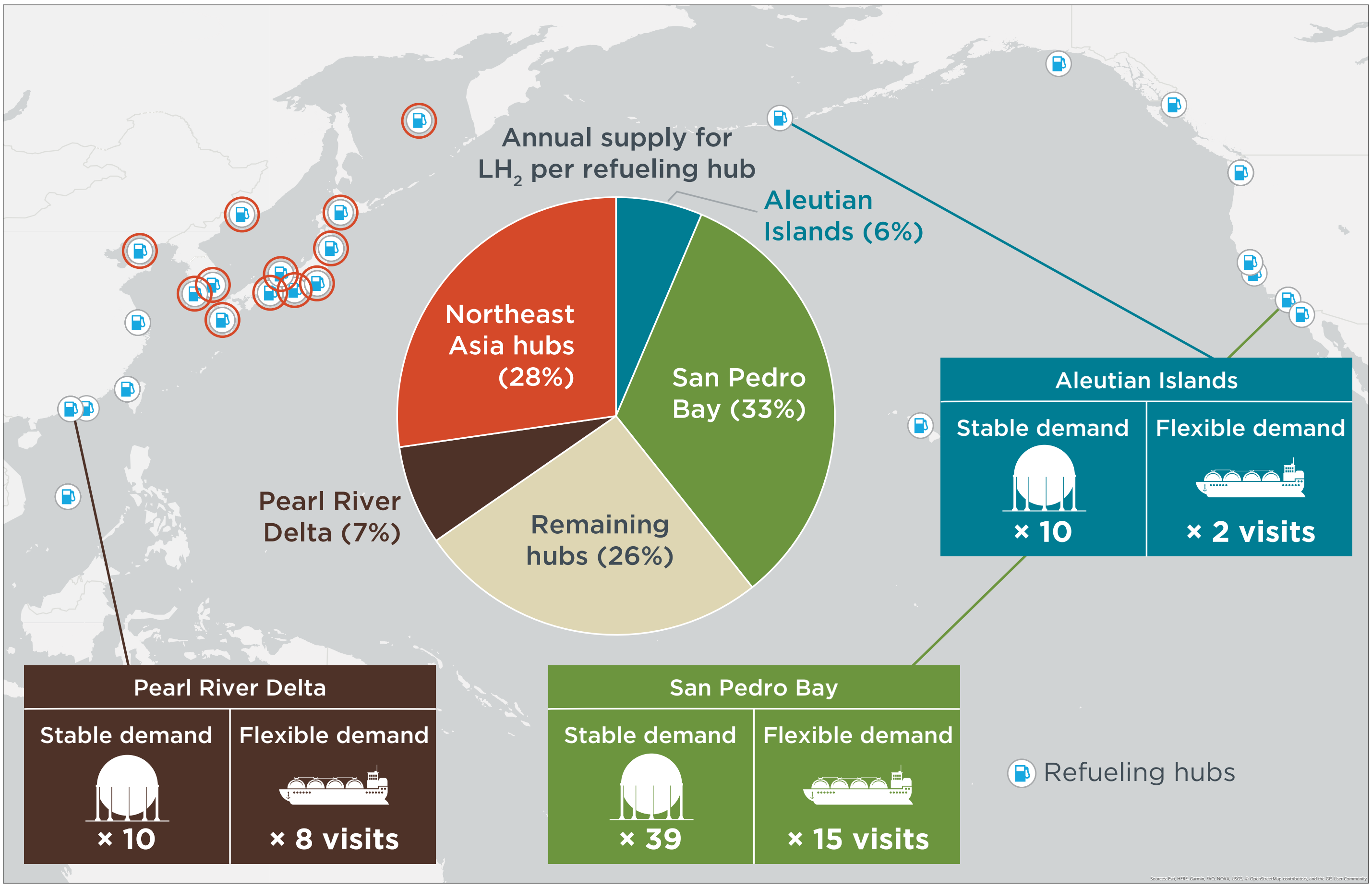

Figure 8. Hydrogen demand and refueling infrastructure needed for transpacific container ships under the full deployment scenario

The results suggest that strategic investments at key refueling hubs could enable hydrogen use for most transpacific container ships. In the full deployment scenario, hydrogen refueling infrastructure at just five hubs in Northeast Asia and Alaska could provide fuel for more than 60% of voyages that would require an additional refueling stop. Additional investments in smaller refueling hubs would reduce the extra distance traveled due to diversions.

The Aleutian Islands refueling hub in Alaska stands out in many respects. The hub has only two small-scale ports, at Dutch Harbor and Adak Naval Air Station. In a full deployment scenario along the PRD–SPB corridor, it is an advantageous choice for refueling and enables 171 additional voyages for LH_2 ships, or one quarter of voyages that would require an additional refueling stop. This results in annual LH_2 demand at this hub five times higher than the most restricted deployment scenario. These Alaskan ports have abundant renewable energy resources that could be used to produce renewable hydrogen. Both Dutch Harbor and Adak Naval Air Station are rich in geothermal resources and Adak Naval Air Station is home to strong and consistent winds. Taken together, this shows the potential benefit of early investment in producing “green” LH_2 at the Aleutian Islands hub and making it available for hydrogen-powered ships.

Still, further studies are needed to better understand the opportunities. Refueling infrastructure is a complicated topic involving the whole supply chain from how the fuel is sourced, to how it is transported, and finally to how stored and then supplied to a receiving vessel. Such detailed assessment is needed to assess the true feasibility of “green” hydrogen at ports like the Aleutian Islands. The positioning of refueling ports that use LH_2 that is fully “green” on a life-cycle basis along a shipping corridor is another complicated topic by itself. Aside from the ships' range constraints, the availability of affordable LH_2 produced by local renewable energy is another key consideration which needs further analysis.

Regarding storage, current LH_2 tanks are used mostly by the space industry and are spherical. This shape is preferred because it minimizes evaporation (Kamiya et al., 2015). Tanks can take other shapes, too, if evaporation can be controlled. The common stationary storage tanks used in LNG terminals usually take the shape of a flat-bottom cylinder with a slightly domed cover. Similarly, KHI (Kamiya et al., 2015) has envisioned a future LH_2 tank with the same shape capable of storing 50,000 m^3 LH_2. We used uniformly sized and shaped LH_2 tanks in this analysis to compare between refueling hubs and across different scenarios. We also demonstrated a case where the initial land investment for stationary storage tanks can be conserved in the future to accommodate higher LH_2 demand by using a larger spherical tank in Appendix E. But it will be the port's decision to choose between expanding the land area, building larger and/or different shaped tanks, or a combination of both.

The number of LNG refueling vessels is increasing quickly (EMSA, 2018), and these are a flexible way to provide fuel to large LNG users. LH_2 refueling vessels could serve the same role. It is outside the scope of this analysis to identify how the LH_2 loaded onto those vessels would be supplied, but it could be an offshore hydrogen power plant located close by that has marine access. For inland production, a pipeline may be needed to supply LH_2 to a port. Similar to stationary storage tanks, we used a smaller LH_2 refueling vessel in this analysis to quantify flexible demand across hubs. Much larger LH_2 refueling vessels are on the horizon, though. Moss Maritime, in cooperation with Equinor, Wilhelmsen, Viking Cruises, and DNV-GL, has developed a design for a LH_2 refueling vessel with a cargo capacity of 9,000 m^3 (NCE Maritime CleanTech, 2019). The exact approach taken by each port will depend on the flexible demand and the cost and availability of commissioning or owning such vessels.

Future work

The methodology we established in this study can be applied to other zero-carbon fuels, other ship classes, and other shipping corridors, and that might be helpful in identifying low-emission technologies and fuels, and ship segments, that could become early adopters of zero-emission solutions.

Meanwhile, this analysis paints a positive picture of the future potential for Pacific Rim ports to enter the LH_2 refueling market and form a distributed refueling network for container ships. While our analysis has laid some groundwork for the spacing of refueling hubs, the cost of supplying renewable LH_2 at those potential refueling hubs needs to be studied to provide more insight into where the early refueling infrastructure investments are needed.

We assumed that all ships would want to refuel to a full tank at each port of call before setting sail again. This is a reasonable assumption if the goal is to maximize a ship's range for safety and economic reasons. This does not mean that these ships do not have other choices about how and where to refuel. Also, our modeling tried to conserve the current traffic pattern as much as possible. Still, in the future, ships could modify their routes to their benefit. The cost of fuel will also be an important factor for route planning, if not a deciding one.

Liquid ammonia as a hydrogen carrier and marine fuel is also attracting significant interest. Liquid ammonia has higher volumetric energy density than LH_2 and is easier to store, transport, and refuel. Still, risks remain because it is toxic and potentially releases excess nitrogen and nitrous oxide (NO_x and N_2O) emissions when burned (de Vries, 2019). Ammonia is also heavier than hydrogen per unit energy when used as bunker fuel. This means that for shipping segments that are weight carriers, like bulk carriers, oil tankers, and others, using liquid ammonia as fuel might impose its own range constraint.

Given the uncertainty of future marine fuels, the likelihood is that different types of ships will adopt different types of zero-carbon fuel to their benefit. Still, with a select few directions for zero-carbon shipping, future focused studies that outline the greenest path forward are critical. In Mao et al. (2020), we showed the initial promising results of replacing HFO with liquid hydrogen. With this analysis, we added another level of confidence by identifying a decentralized refueling port network. While cost was not considered, our results suggest that the amount of infrastructure investment that could support this transition would not be prohibitively large. Further analysis to better understand the ports at which early investment would most contribute to making a sizeable amount of liquid hydrogen relatively cheap will offer a clearer roadmap toward a zero-emission PRD–SPB shipping corridor.

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Appendix A. Port-to-port distance calculations

Port-to-port distance is calculated as the great circle distance between two ports multiplied by an adjustment factor to take into account circuitous routing. Each port is identified with a set of coordinates in the World Port Index dataset. While the great circle distance between two ports is calculated, the great circle distance is the shortest distance between two points on earth, and is shorter than the distance ships need to travel.

To obtain more accurate port-to-port distances, we used real-world Automatic Identification System (AIS) ship traffic data from exactEarth between ports for which the actual navigational distance between two ports can be retrieved from the Systematic Assessment of Vessel Emissions (SAVE) model. Because each voyage is different, the distances of multiple voyages between the same pair of ports were averaged. We constructed a summary table of the actual port-to-port distance versus its great circle distance for reference.

As shown in Table A1, the longer the distance legs, the lower the difference between actual port-to-port distance and great circle distance. As a result, for port pairs that do not have available port-to-port distance from AIS ship tracks, we calculated the great circle distance, categorized it into one of the four adjustment ratio groups in Table A1, and adjusted the distance accordingly.

Table A1. Port-to-port distance adjustment ratio

Great circle distance range (nm)	Adjustment ratio
< 400	1.41
400 – 1,000	1.35
1,000– 5,000	1.14
> 5,000	1.08

Appendix B. Ports and associated port hubs

Table B1 shows how we grouped individual ports into refueling hubs (**bold**) based on geographic proximity.

Table B1. Refueling ports and associated refueling hub

Aleutian Islands	Imabari Ko	Esquimalt Harbor	**South China Sea**
Adak Naval Air Station	Iwakuni Ko	Eureka	Cebu
Dutch Harbor	Kakogawa	Fort Ward	Haikou
Bo Sea	Kobe	Port Alice	Manila
Bayuquan	Komatsushima	Port Angeles	Mui Vung Tau
Dalian	Matsusaka	Port Orchard	Phu My
Huludao Gang	Matsuyama	Port Townsend	Zhanjiang
Inchon	Niihama	Portland	**South Korea - East**
Jinzhou Wan	Onomichi-Itozaki	Quartermaster Harbor	Chinae
Qingdao Gang	Osaka	Seattle	Masan
Qinhuangdao	Wakayama-Shimotsu Ko	South Bend	Pohang
Tianjin Xin Gang	Yokkaichi	Steveston	Pusan
Weihai	Yura	Tacoma	Ulsan
Yantai	**Kanto**	Vancouver	**South Korea - West**
Chubu	Chiba Ko	Victoria Harbor	Cheju Hang
Kinuura Ko	Funabashi	**Pearl River Delta**	Gwangyang Hang
Mikawa	Kashima Ko	Guangzhou	Mokpo
Nagoya Ko	Katsunan Ko	Hong Kong	Yosu
Omaezaki Ko	Kawasaki Ko	Huangpuxingang	**Taiwan Strait**
Shimizu Ko	Tateyama Ko	Huizhou	Chaozhou
Toba	Tokyo Ko	Lon Shui Terminal	Chi-Lung
Dixon Entrance	Yokohama Ko	Macau	Fuzhou
Porpoise Harbor	Yokosuka Ko	Shekou	Hua-Lien Kang
Prince Rupert	**Kyushu**	Yantian	Kao-Hsiung
Golden Horn Bay	Kagoshima Ko	**Russia - North**	Quanzhou
Bukhta Gaydamak	Karatsu	De Kastri	Su-Ao
Nakhodka	Nagasaki	Kholmsk	Tai-Chung Kang
Senbong	Naha Ko	Port Beringovsky	Tan-Shui
Slavyanka	Nakagusuku	Sovetskaya Gavan	Wenzhou
Vladivostok	Saiki Ko	**San Francisco Bay**	Xiamen
Vostochnyy	Shibushi Wan	Alameda	Zhangzhou
Hawaii	Wakamatsu Ko	Oakland	**Tohoku**
Honolulu	Yatsushiro Ko	Point Richmond	Aomori Ko
Kawaihae	**Miscellaneous**	Redwood City	Hachinohe Ko
Hokkaido	Lufeng Terminal	San Francisco	Kamaishi Ko
Abashiri Ko	Monterey	Sausalito	Miyako
Hakodate Ko	**Oceania**	**San Pedro Bay**	Ofunato
Ishikari Bay New Port	Majuro Atoll	El Segundo	Onahama Ko
Kushiro Ko	Pohnpei Harbor	El Segundo Off-Shore Oil Terminal	Sendai-Shiogama
Muroran Ko	Tarawa Atoll	Long Beach	**US/Mx Border**
Nemuro Ko	**Pacific Northwest**	Los Angeles	Ensenada
Otaru Ko	Astoria	Redondo Beach Harbor	San Diego
Tomakomai Ko	Bremerton	Sea of Japan	**Yangtze River Delta**
Wakkanai	Comox Harbor	Fukui Ko	Changshu
Inland Sea	Coos Bay	Miyazu	Lianyungang
Himeji	Edwards Point	Niigata Ko	Ningbo
Hiroshima	Empire	Sakai Ko	Shanghai
			Zhoushan

Appendix C. LH_2 annual demand results for all refueling hubs, across all four scenarios

Table C1 presents the annual refueling demand of LH_2 at all identified refueling hubs for all scenarios. S4 is the full deployment scenario which reflects the full business potential. S1 to S3 are transitional stages with fewer ships adopting liquid hydrogen and/or less port infrastructure investments.

Table C1. LH_2 annual demand for all refueling hubs, across all four scenarios

	LH_2 annual demand (tonnes)			
	S1	**S2**	**S3**	**S4**
Aleutian Islands	7,700	7,700	14,700	46,900
Bo Sea	5,000	31,100	5,000	32,000
Chubu	300	10,800	300	6,900
Dixon Entrance	1,800	9,900	300	7,900
Golden Horn Bay	10,100	42,900	8,000	39,700
Hawaii	300	300	100	100
Hokkaido	7,700	42,500	6,700	16,500
Inland Sea	6,000	18,700	3,600	10,200
Kanto	15,300	20,000	12,100	16,800
Kyushu	3,100	15,300	5,200	14,400
Misc	0	0	0	5,100
Oceania	100	100	100	100
Pacific Northwest	4,300	7,200	4,100	7,000
Pearl River Delta	16,000	53,900	16,000	54,000
Russia - North	2,200	10,800	700	1,900
San Francisco Bay	7,800	21,900	7,600	16,200
San Pedro Bay	72,200	252,400	71,800	241,400
Sea of Japan	700	1,100	2,000	7,500
South China Sea	6,500	17,700	6,500	18,700
South Korea - East	12,000	29,900	10,100	19,900
South Korea - West	2,800	4,500	6,900	18,700
Taiwan Strait	27,800	97,300	28,900	102,300
Tohoku	0	0	2,500	15,600
US/MX Border	400	400	400	400
Yangtze River Delta	21,000	38,800	16,700	33,300

Appendix D. LH_2 infrastructure need at top 10 refueling hubs, across all scenarios

Table D1. Stable and flexible demand, top 10 refueling hubs, across all four scenarios

	S1				S2				S3				S4			
	Stable Demand tonnes/week	Peak Demand	Number of Tanks	Number of Refueling Vessel Visits	Stable Demand tonnes/week	Peak Demand	Number of Tanks	Number of Refueling Vessel Visits	Stable Demand tonnes/week	Peak Demand	Number of Tanks	Number of Refueling Vessel Visits	Stable Demand tonnes/week	Peak Demand	Number of Tanks	Number of Refueling Vessel Visits
Aleutian Islands	400	800	3	2	400	800	3	2	600	1,000	4	3	1,500	1,900	10	2
Golden Horn Bay	500	1,000	3	4	1,500	2,200	10	5	400	700	3	2	1,400	2,200	10	5
Hokkaido	400	800	3	3	1,400	2,400	9	6	400	700	3	2	600	1,000	7	-
Kanto	700	1,300	5	4	900	1,400	6	3	500	900	4	2	600	900	4	2
Pearl River Delta	900	1,200	6	2	1,500	2,700	10	7	900	1,200	6	2	1,500	2,700	5	13
San Francisco Bay	300	900	3	3	900	1,300	6	3	300	900	3	3	600	1,000	3	4
San Pedro Bay	2,500	3,300	16	5	6,700	8,600	42	12	2,500	3,400	16	5	6,200	8,600	4	50
South Korea - East	400	700	3	2	800	1,500	6	4	400	900	3	3	600	1,200	2	6
Taiwan Strait	800	1,000	6	1	3,300	3,800	21	3	900	1,100	6	1	3,400	3,800	1	23
Yangtze River Delta	700	1,300	5	4	1,200	1,900	8	5	600	1,300	4	5	1,100	1,500	1	9

Table D1 presents the stable and flexible LH_2 refueling demand for the top 10 refueling hubs and the associated infrastructure need for all scenarios. S4 represents full deployment.

Appendix E. Sample calculation on expanding tank size

We estimated that under the most restricted deployment scenario, three on-site storage tanks at the Aleutian Islands hub are enough to supply stable demand. We further estimated that three storage tanks would need dedicated land of about 1,000 m^2. If the same area is repurposed to install a single flat-bottom cylindrical tank, which has a diameter of about 30 m, we could build one with a height of 30 m to accommodate the more than tripled stable demand at full deployment scenario. This scaled-up tank, with a capacity of about 20,000 m^3, is less than 50% of the commercialized terminal tank KHI has envisioned at 50,000 m^3.

Appendix F. Glossary used in this analysis

Ship voyage	Corridor	A shipping route frequently used by ships, between two ports
	Leg	A nonstop trip between two ports, one segment of a voyage
	Voyage	One trip on a corridor
	Unattained voyage	A voyage that cannot be completed if the ship servicing it is powered by hydrogen fuel cells
	Port-to-port distance	Sea distance between two ports, or the distance a ship needs to travel between two ports
Refueling infrastructure	Refueling port	Port that offers refueling service for ships
	Refueling hub	A group of refueling ports that are geographically proximate to each other
	Refueling infrastructure	Fuel tanks that can be connected to ships to transfer fuel
	Truck-to-ship (TTS)	Refueling from tanks loaded on the chassis of a truck to a receiving vessel
	Ship-to-ship (STS)	Refueling from cargo tanks of a refueling vessel to a receiving vessel
	Port-to-ship (PTS)	Refueling from on-site storage tanks or pipelines to a receiving vessel
	Boil-off rate	Evaporation rate of tanks storing liquefied gas
	Tank fill limit	The percentage of a tank's volume that can be used to hold liquid fuels
	Shell-to-shell safety distance	The distance between two adjacent flammable liquid storage tanks for safety concerns
Refueling demand	Stable demand	The average amount of weekly LH_2 demand in a given month
	Peak demand	The highest amount of weekly LH_2 demand in a given month
	Flexible demand	The difference between peak and stable demand
Marine fuel	Liquid ammonia	Ammonia (NH_3) is a carbonless fuel that is a competitor of liquid hydrogen. The energy density is nearly double of that of LH_2, but ammonia is also colorless and toxic.
	Liquid hydrogen	Hydrogen in liquid form (LH_2) is the lightest element on the periodic table. It burns at extreme intensity and has been used for decades by the space industry as rocket fuel. Hydrogen can only be liquefied at extremely low temperatures, and thus it must be stored in double insulated cryogenic tanks to prevent boil off.
	LNG	Liquefied natural gas (LNG) is natural gas (primarily methane) that has been cooled to cryogenic temperatures and can be burned as fuel in marine vessels.