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JONES ACT SHIPPING CASE STUDIES: THE FEASIBILITY OF U.S. DOMESTIC GREEN CORRIDORS UTILIZING HYDROGEN AND WIND-ASSIST TECHNOLOGIES

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EXECUTIVE SUMMARY

Every large-scale economy is reliant on some form of cabotage law restricting shipping within its borders, and the United States is no exception. Under the Jones Act, cabotage between two domestic ports must be on vessels that are flagged, crewed, and built in the United States. These U.S.-flagged ships must conform to relevant domestic and international environmental standards.

The Biden administration has encouraged a transition to zero-emission shipping by 2050. New funding for research projects on zero-emission port infrastructure is provided by the U.S. Maritime Administration's Maritime Environmental and Technical Assistance program, the Bipartisan Infrastructure Law of 2021, and the Inflation Reduction Act of 2022. Therefore, there are policy incentives for promoting pilot projects that demonstrate a pathway to zero-emission shipping.

This study assesses the feasibility of four current Jones Act vessels completing their routes using renewably sourced liquid hydrogen via fuel cells. In a novel methodology, we also compare two wind-assisted technologies, rigid wing sails and rotor sails, to evaluate the fuel savings potential on these routes. These results can be seen encapsulated in Figure ES1. Lastly, we summarize the routes into domestic green corridors ready for investment, matching the needs of ports and vessels in these corridors with hydrogen stakeholders identified in the region by the U.S. Department of Energy's H2 Matchmaker tool.

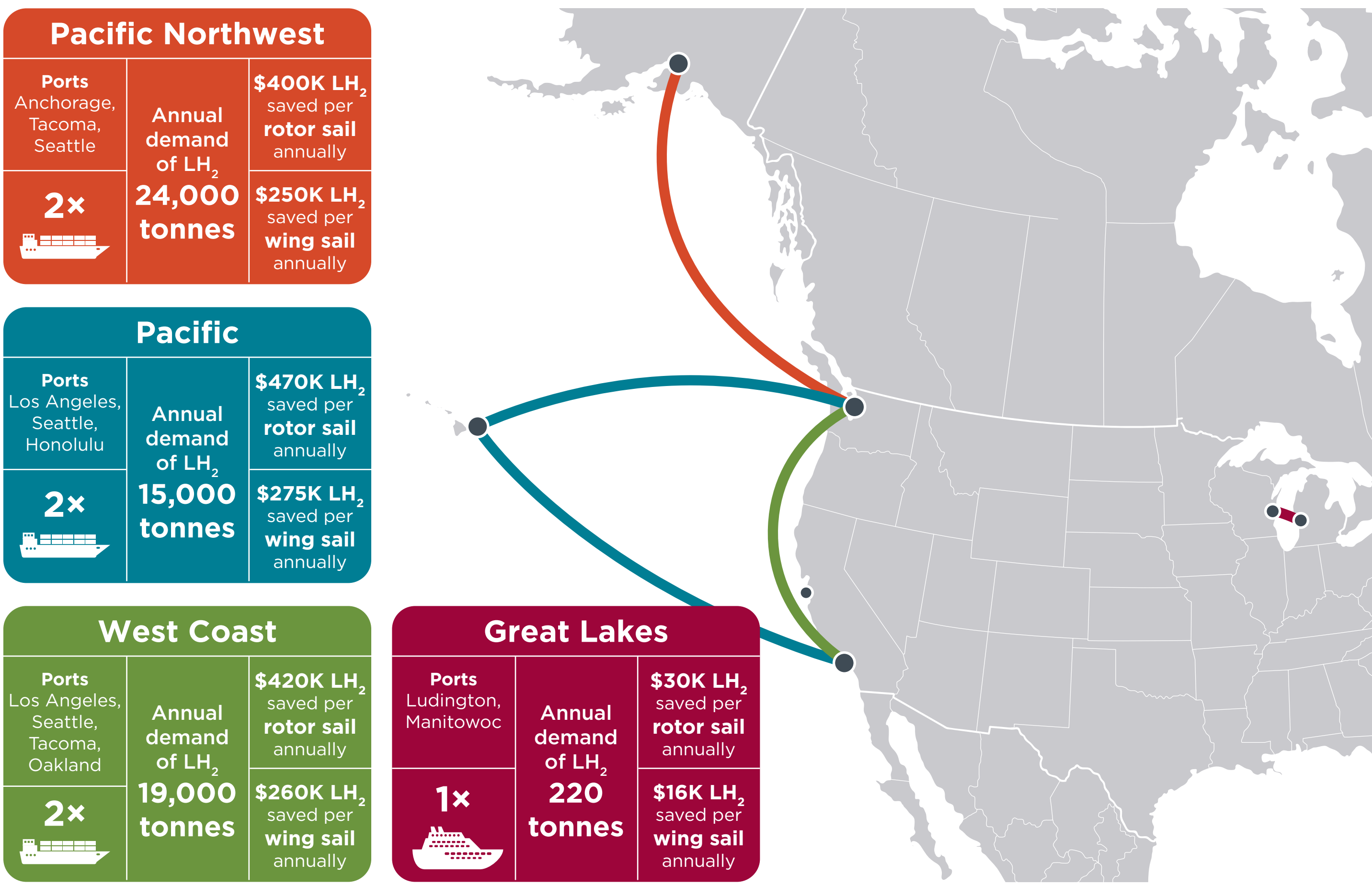

Figure ES1. A summary of four proposed corridors' liquid hydrogen demands and annual fuel savings provided by wind-assist technology.

We found the following results from our assessment:

- **Modeling of the four ships shows they could complete 99% of the legs making up their routes on liquid hydrogen alone, with no cargo space modification required.** While oceangoing vessels, on average, operate for 25 to 30 years before scrappage, the average age of the ships assessed is 43 years old. Jones Act ships tend to stay in service longer than other vessels because it is typically more expensive to build a ship to the law's specifications than it is to build a ship outside the United States. When these four ships are retired, their replacements could be powered solely by hydrogen.
- **Rotor sail performance was highly variable, with energy-generating capabilities heavily dependent on route location, heading, speed, or season.** Predominantly lateral east-west routes produced higher net energy-generation rates, along with routes operating in the fall or winter. The net energy-generating time from rotor sails in the fall and winter increased by more than 70% on the routes between Honolulu, Hawaii, and the California ports of Oakland and Los Angeles, and between Honolulu and Seattle, Washington.
- **Wing sails consistently produced net positive energy generation regardless of route, heading, or season.** However, the annual energy savings of wing sails were 40% lower than rotor sails. Given wing sails' passive capabilities to generate energy, they produce fuel savings more consistently than rotor sails but at lower rates.
- **A single rotor sail or wing sail can save tens of thousands of dollars in annual hydrogen fuel costs for a U.S. Great Lakes vessel and hundreds of thousands of dollars in hydrogen costs for U.S. ships on ocean routes.** Wind-assisted propulsion on the Pacific corridor saved the most in total fuel costs. However, wind assist on the Great Lakes provided the greatest percentage reduction in total fuel costs.
- **We identified four key Jones Act corridors in our modeling—the Pacific Northwest, the West Coast, the Pacific, and the Great Lakes.** Within these green domestic corridors, Los Angeles, Seattle, and Honolulu are identified as key ports. These corridors would need 60,000 tonnes of liquid hydrogen to support the nine routes and four vessels. These corridors are ripe with opportunities for zero-emission vessel feasibility projects. Several identified stakeholders, such as local hydrogen producers, may be able to move forward with the necessary infrastructure.

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INTRODUCTION

The Merchant Marine Act of 1920, more commonly known as the Jones Act, regulates cabotage in the United States. This protectionist-era law intends to ensure the availability of American-flagged ships in times of national emergency to act as auxiliaries for the U.S. Navy. The Jones Act mandates that shipping between two U.S. ports must be accomplished by U.S.-flagged vessels. In addition to being registered in the United States, ships belonging to the Jones Act fleet (JAF) must be owned and crewed by U.S. citizens, and constructed in a U.S. shipyard. Not every U.S.-flagged ship is part of the Jones Act fleet (JAF), but every JAF ship is registered in the United States and is thus bound to U.S. maritime law and under the sway of federal ambition.

Over 30% of vessels in the JAF are of advanced aged, having been built more than 25 years ago (Bonello et al., 2022). A ship's typical lifetime concludes at around 30 years of age, meaning many of the oceangoing JAF ships are close to end-of-life and likely have less efficient technologies onboard. However, while some of the JAF may be aging out of their duties, the routes between the U.S. ports they operate in will remain the same. This condition, along with the JAF's unique appointment under federal rule, makes them exceptional candidates for pilot projects to showcase zero-emission technology within domestic corridors.

In this report, we conduct four separate Jones Act case studies; each case study looks at a single ship and the routes it traveled between specific ports in a single year. We model the ships using fuel cells combined with renewably sourced liquid hydrogen in lieu of the ships' current fossil fuel propulsion and analyze how these four ships—if they were to become pilot projects—could begin to decarbonize the Jones Act fleet. Additionally, we evaluate two wind-assisted propulsion technologies, rotor and wing sails, to assess each their potential to reduce the alternative fuel demands for each route.

BACKGROUND

JONES ACT FLEET

The Jones Act fleet has a storied history and a complicated present. In 1920, Senator Wesley Jones of Washington introduced the Merchant Marine Act to Congress with the intent to safeguard the U.S. merchant marine fleet and its seamen. Thus, its shorthand moniker became the Jones Act.

A UMAS report identifies four requirements for a ship to be considered part of the JAF (Bonello et al., 2022):[1]

1. The ship is registered under the U.S. flag.
2. The ship is owned by U.S. citizens or by a corporation which has 75% of its stock owned by U.S. citizens,
3. All major components of the superstructure are fabricated in the United States.
4. The master, officers, and 75% of the on-board crew must be U.S. citizens.

Out of 181 U.S.-flagged oceangoing vessels (defined as those that are also self-propelled and over 1,000 gross tonnes),[2] the UMAS report identified 98 vessels as part of the JAF (Bonello et al. 2022).[3] Any U.S.-flagged vessel is subject to a range of legal stipulations, including those related to safety, security, and environmental protection. Some of the key legal requirements for U.S.-flagged vessels include:

- *Compliance with the International Convention for the Safety of Life at Sea (SOLAS).* SOLAS is an international treaty that sets minimum safety standards for ships, including structural integrity, stability, and safety equipment.
- *Compliance with U.S. Coast Guard regulations.* The U.S. Coast Guard enforces a wide range of safety, security, and environmental regulations on U.S.-flagged vessels. These regulations cover everything from fire safety and navigation to pollution prevention and crew training.
- *Compliance with U.S. labor laws.* U.S.-flagged vessels are subject to U.S. labor laws, including those related to wages, working conditions, and crew safety.
- *Compliance with environmental regulations.* U.S.-flagged vessels must comply with a range of environmental regulations, including those related to air emissions, ballast water management, and oil spill prevention.
- *Compliance with U.S. trade regulations.* U.S.-flagged vessels are subject to various trade and commerce regulations, including customs, tariffs, and economic sanctions.

UNITED STATES GREEN MARITIME INFRASTRUCTURE INVESTMENT

The United States has established several policies aimed at promoting zero-emission shipping. The U.S. Maritime Administration's Maritime Environmental and Technical Assistance Program provides technical and financial assistance to help U.S. ports and shipping companies reduce emissions and improve environmental performance.

1 UMAS is a partnership between maritime consultancy group UMAS International Ltd. and the University College London (UCL) Energy Institute.

2 There are also thousands of Jones Act-compliant inland water barges and tugs that are not considered in this study.

3 In the UMAS report, there is a caveat regarding the accuracy of JAF numbers, given the scarcity of data on the four requirements for the U.S. fleet.

The 2021 Infrastructure Investment and Jobs Act, also known as the Bipartisan Infrastructure Law, allocated $17 billion to investments in port infrastructure, including funds for zero-emission equipment and facilities. The Inflation Reduction Act (IRA), signed into law in August 2022, provides tax credits for clean energy technology. Lastly, the Clean Air Act, first passed in 1963 and amended several times since then, instructs the U.S. Environmental Protection Agency (EPA) to set primary National Ambient Air Quality Standards to protect public health.

HYDROGEN PRODUCTION AND INFRASTRUCTURE IN THE U.S.

In October 2023, the U.S. Department of Energy (DOE) announced the selection of seven regional hydrogen hubs (H2Hubs) to receive $7 billion in funding from the Infrastructure Investment and Jobs Act. The selected hubs must match the federal money with a cost share of more than $40 billion. (U.S. Department of Energy [U.S. DOE], 2023). Additionally, under the Inflation Reduction Act, qualified facilities that produce, store, or distribute hydrogen can receive a tax credit of up to 30% of the facility's cost.[4] To stimulate both supply and demand for hydrogen DOE has published a tool to match hydrogen producers with hydrogen stakeholders, including ports (U.S. DOE, 2022).

The H2Hubs Matchmaking tool is used in this report to reference regional stakeholders and producers who could aid in the infrastructure development of hydrogen bunkering facilities at the JAF ports. The tool identifies the location of "clean hydrogen" producers, as shown in Figure 1. The DOE defines clean hydrogen in the H2Hubs context the same as in the Infrastructure Investment and Jobs Act: "hydrogen produced with a carbon intensity equal to or less than 2 kilograms of carbon dioxide-equivalent produced at the site of production per kilogram of hydrogen produced." However, when considering hydrogen as a fuel, it is key to consider its entire life cycle: if fossil fuels are used to produce the hydrogen, the bulk of emissions may be shifted upstream. Previous ICCT research identified risks with carbon capture and storage from H_2 produced from fossil fuels (Zhou et al., 2021). Under the IRA, renewable electricity and clean hydrogen plants can receive a production tax credit of 2.6 cents per kWh and up to $3 per kilogram of hydrogen in 2023. For context, the average cost of producing hydrogen in the United States was $4.30 per kilogram in 2020 (Zhou et al., 2022).

4 The level of the credit provided is based on carbon intensity, up to a maximum of 4 kilograms of CO_2 to kilogram of H_2 equivalent.

Figure 1. United States hydrogen producers as identified by the H2 Matchmaker Tool

GLOBAL WARMING POTENTIAL OF HYDROGEN

Liquid hydrogen used in fuel cells has been identified as a solution to decarbonize the maritime sector due to its scalability and high energy density compared to its alternative fuel counterparts (Minnehan & Pratt, 2017). Nevertheless, no silver bullet alternative fuel has yet been identified in maritime shipping, and all have drawbacks attached to their climate benefits. In a series of papers, the ICCT has discussed the application of liquid hydrogen in fuel cells (Mao et al., 2020), portside hydrogen infrastructure (Georgeff et al., 2020), hydrogen with rotor sails (Comer et al., 2022), and the price of renewable-sourced hydrogen in the U.S. (Zhou et al., 2022). As the world begins to invest time, research, and money into hydrogen, it is valuable to go over its baseline characteristics as fuel, as concerns have appeared as more research comes to light.

Hydrogen is the smallest atom and molecule, with two atoms of hydrogen bonding together to form H_2. Since it is such a small molecule, it needs specialized infrastructure to reduce its leaking between materials without resistance (Georgeff et al., 2020). Hydrogen has a very cold boiling point of -252°C; it must be kept under pressurize and insulated to remain in its highest energy density state as a liquid. Therefore, specialized infrastructure—such as that used in the space industry, but not yet on a large scale in other industries—would need to be used to reduce boil-off and loss of energy. Compressed hydrogen gas is stable at room temperature and, therefore, more forgiving infrastructure-wise. However, it is less energy dense, meaning more space will be needed to store it on board or at the port. Though compressed hydrogen gas is more stable, storing it still requires proper materials to minimize leakage.

A study commissioned by Britain's Department for Business, Energy, and Industrial Strategy looked at the atmospheric impacts of a global hydrogen economy (Warwick et al., 2022). Although hydrogen is not a greenhouse gas (GHG), leaks of hydrogen would trigger adverse reactions with other gases in the atmosphere, including methane, water vapor, and ozone. Nevertheless, the report concluded that the benefits from reducing CO_2-equivalent emissions outweigh the disadvantages that can come from H_2 leakage. The 20-year global warming potential (GWP) obtained from modeling was 33, with an uncertainty range of 20 to 44. The GWP for a 100-year time horizon was identified as 11 ± 5. Even when assuming the worst leakage scenario for hydrogen, it's still an improvement when compared to the burning of fossil fuels, with the benefits of hydrogen likely outweighing the drawbacks of fossil fuel usage. While hydrogen-powered ships are in their early pilot stages, leakage would be a costly flaw, behooving ship owners to invest in engines with the lowest slip or leakage rate.

WIND-ASSIST TECHNOLOGIES

In 2018 the International Maritime Organization agreed to GHG emissions reduction targets for the maritime sector (International Maritime Organization, 2018). Since then, there has been a renewed interest in utilizing alternative fuels (Chou, 2021) and renewable sources of energy, one example being wind-assist propulsion systems (WAPS) in the shipping industry (Barreiro et al., 2022; Chou, 2021; Shukla & Ghosh, 2009).

WAPS continue to show promise for commercial marine applications, including rotor sails (also known as a Flettner rotor), towing kites, soft sails, rigid wing sails, and suction wing sails (Chou, 2021; De Marco et al., 2016; D. Ferrer Desclaux, personal communication, August 23, 2022; Lu & Ringsberg, 2020). These technologies generally work by exposing sails, airfoils, or rotating cylinders to environmental wind, thus generating thrust in the direction of the ship's motion (Clayton, 1987; De Marco et al., 2016; Mittal & Kumar, 2003). However, ship owners and operators have had to contend with multiple financial, economic, and environmental barriers ahead of any industry-wide WAPS adoption. These barriers include concerns about the structural cohesion of ship and sail, cargo handling, and hidden costs (Rehmatulla et al., 2017; Rojon & Dieperink, 2014).

In this report, we focus on the rotor sail and rigid wing sail, utilizing the rotor sail methodology laid out in Comer et al. (2022) and including wing sails due to their potential net energy savings. These two WAPS are further explained in Table 1 and the following paragraphs.

Table 1. WAPS technology overview

Technology	 *E-Ship 1*, built for German company Enercon, uses four vertical rotor sails. **Rotor sail**	 A rendering shows a wing sail-powered ship under development by Swedish company Oceanbird. **Wing sail**
Description	• Vertical cylinders (some with capping end plates) that rotate rapidly, creating forward lift or thrust in crosswind conditions • Uses the Magnus effect, or the lift caused by a spinning object • Key size parameter(s): cylinder height and diameter • Active: external power input required for operation • Stowable	• Rigid aerodynamic structures that deploy vertically to generate forward lift in crosswind flow with minimal drag • Uses angle of attack for trim, meaning the angle at which the sail meets the air is adjusted to maintain stable lift • Key size parameter(s): exposed surface area and various flap/no-flap configurations • Passive: no external power input required for operation • Stowable
Range of estimated energy savings	0.4%–50% of total power demand demonstrated	5%–30% of total power demand demonstrated

Rotor sails and wing sails have been the subject of much research as they have been shown to generate usable propulsive power at a wide range of wind angles relative to a vessel's course (Bergeson & Greenwald, 1985; Lu & Ringsberg, 2020; Talluri et al., 2016). Real-world trials of the rotor sail have demonstrated average fuel savings of approximately 8%–20% per year (Wind Ship Association, 2022). In their broader survey of WAPS for ships ranging from 2,300 tons deadweight to more than 300,000 tons deadweight, Chou (2021) found a fuel-savings potential of 0.4%–50% for the rotor sail and 5%–30% for wing sails per voyage. The large range of variability in documented fuel savings arises from differences in vessel size; differences in the WAPS devices, including the number of devices deployed, their speed ratio, the size and shape of the areas exposed to wind, their relative symmetry, aspect ratio and physical position on deck; as well as operational cruise characteristics (Clayton, 1987).

WAPS performances are also sensitive to the specific aspects of design and implementation. Often, WAPS are included on a ship to offset propulsion load from a main engine system; the power generated from the WAPS allows the main engine to be adjusted down without any loss in forward speed (Barreiro et al., 2022). To our knowledge, real-world trials using multiple different WAPS in concert have yet to be conducted, likely due in part to the fact that WAPS control programs and trim strategies are very specific to the type of technology. In other words, it is difficult in practice to sync and optimize the operations of more than one type of wind-assist technology while a ship is underway (D. Ferrer Desclaux, personal communication, August 23, 2022). For simplicity (and perhaps efficiency), single types of WAPS are used on a given vessel and chosen according to the anticipated weather conditions along the intended route or routes.

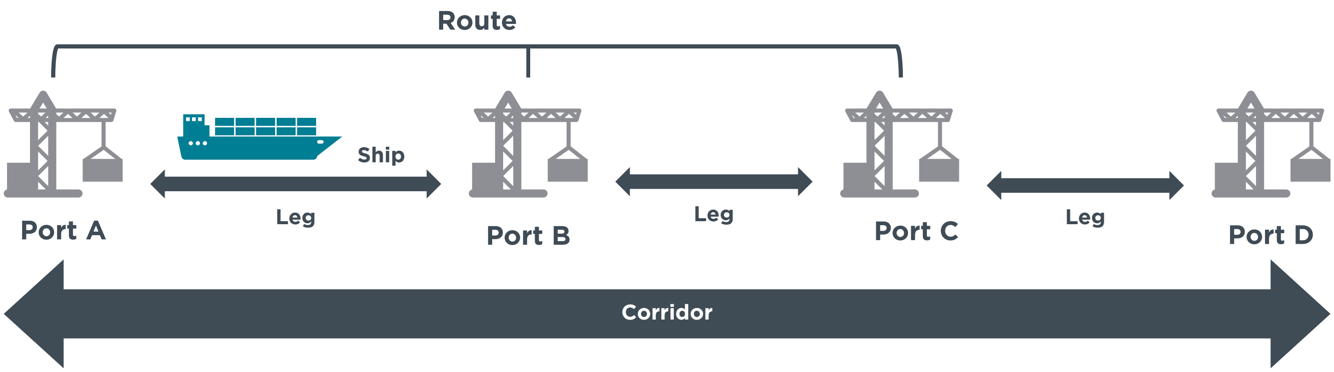
Billions of weather observations are collected from many different instruments every day worldwide. The main weather parameters—temperature, humidity, pressure, and horizontal wind—effectively describe the atmosphere at a specific place and time.

With more observations, a complete picture of the true weather is possible. But it is practically easier to get observations near major population centers and on land; beyond a few miles from shore, there is far less infrastructure to support routine weather observations. To overcome such a limitation, feasibility modeling (described in a subsequent section) can be used for weather analysis and forecasts, even over remote oceans. Past weather records and forecasts thus enable the ship operators and owners to assess the viability of using WAPS.

The depth of WAPS feasibility modeling has been explored in other publications (e.g., Talluri et al., 2016). For this report, incorporating WAPS with ships using zero-emission fuel will aid in determining the power savings and subsequent fuel savings provided by WAPS in the shipping corridors performed by the selected JAF ships. A full techno-economic WAPS feasibility assessment is beyond the scope of this study. Rather, the objective is to determine whether it would be possible to "attain" various voyages using just green energy for the JAF and along targeted shipping corridors. To address this inquiry, we will use a year of vessel tracking data from 2019, detailed weather inputs, and simple WAPS models for the rotor sail and wing sails.

METHODOLOGY

In this section, the selection of the JAF routes, hydrogen and WAPS calculations, and energy demands related to the respective ports are described. We use ICCT's Systematic Assessment of Vehicle Emissions (SAVE) Model for energy demands of the ships in 2019 (Olmer et al., 2017). Novel inclusions for this work are the addition of rotor sails and rigid wing sails and the pairing of the routes with hydrogen hubs and stakeholders. A summary of the terminology used in the methods is shown in Figure 2.



Term	Definitions of terms	Results of investigation	Wind-assist application analysis
Ship	One of the four modeled Jones Act ships	Ship characteristics, total distance traveled, CO_2 emissions produced	Feasibility of wind assist on a ship of this class and size
Leg	Any continuous vessel movement between two full-stop points. Full-stop means the vessel shuts down its propulsion engine; point is usually a terminal at a port	Ports visited, average energy of route, hydrogen capacity, average hydrogen demand by leg, attainability of LH2 and fuel cells	Median and average hourly energy savings, total year of energy savings, percent of time operating with net positive energy generation, performance impacts based on latitude, speed, season, and heading
Route	May consist of one or more legs on a journey between origin and destination		
Corridor	Summary of routes aggregated by port and proximity	Fuel demands, infrastructure demands, total price of hydrogen fuel, hydrogen stakeholder matching	Hydrogen fuel savings using wind-assist technology

Figure 2. Summary of methodology terms

SELECTION OF JAF SHIPS AND ROUTES

Using IHS Markit data on ship characteristics,[5] we identified 98 vessels that qualify as Jones Act ships based on the stipulations outlined in Bonello et al. (2022). A preliminary Geographic Information System (GIS) analysis was used to plot the Automatic Identification System (AIS) positions of the 98 vessels. Four of these ships were chosen for this study based on various criteria. Three of the four ships were selected because their respective ages were over the global median age for scrappage. All four ships were deployed several times to the same ports over the year and had unique owners, ensuring the pilot project concept could be introduced to as many key players in the JAF environment as possible. The choice of four ships ensured a

5 Automatic identification system data were provided by exactEarth and ship characteristics data by IHS Markit. IHS Markit merged with S&P Global in February 2022.

small sample size so that concise and local considerations could be applied, while also looking at the routes of these ships as examples of corridors that could be candidates for decarbonization.

ESTIMATIONS OF HYDROGEN FUEL DEMAND

The energy demands of the four ships for the entire year of 2019 were estimated using ICCT's SAVE Model (Olmer et al., 2017). AIS points recorded every hour provided a speed over ground and heading. When paired with ship characteristics, which supply engine specifications, we could estimate the energy demand of each of our selected ships. AIS points then were coalesced into legs based on when the ships berthed or anchored, which was determined by the speed over ground and proximity to shore.

To characterize legs as feasible, we compared the available space on board for zero-emission fuel storage with the zero-emission fuel needed to travel between the origin and destination berthing points. For liquid hydrogen using fuel cells, our methodology was based on the equations put forth in Mao et al. (2020), which uses the energy demand of the leg, previously estimated by SAVE. This energy demand was then compared with the energy calculated to be theoretically provided by the alternative fuel. This theoretical amount of alternative fuel was based on engine room specifics, the energy density of liquid hydrogen, and the fuel cells' efficiency. Each route is a collection of legs with the same destination and origin. Not every destination and origin are interchangeable in a route due to different energy demands based on the route's heading. For example, a voyage from Los Angeles to Hawaii may be more energy-intensive than one from Hawaii to Los Angeles due to several factors, including wind patterns, storms, and ocean currents. A corridor is a summation of the routes between two ports and has further implications for infrastructure.

After the hydrogen demands were recorded, the ports within the corridors were assigned to hydrogen stakeholders based on their proximity, as of December 2022, to hydrogen stakeholder sites identified in the H2 Matchmaker tool developed by the U.S. Department of Energy (2022). This was done to connect active stakeholders to the demands of these theoretical pilot projects for a fuller consideration of switching to zero-emission fuels.

WAPS ENERGY CALCULATIONS

In this study, we modeled two WAPS types on the selected JAF vessels: the rotor sail and the wing sail. We estimated the energy generation for a single WAPS device and, therefore, did not consider WAPS interactions between multiple elements and the resulting wake flow effects (Bordogna et al., 2019). We assume that fuel/energy savings would scale approximately linearly with additional rotor sail or wing sail elements, as assumed by Comer et al. (2022). Our approach treats aerodynamic effects and hydrodynamic resistance as independent of each other. We approximate the impact of the latter hydrodynamic effects using a constant factor if the vessel position is less than or greater than 5 nautical miles from shore, i.e., a net power increase of 10% for inshore transit or 15% for offshore transit.

Comer et al. (2019) and Comer et al. (2022) provides full descriptions of the approach used for estimating power generated by the rotor sail per hour of AIS data gathered. The important aspects are repeated here for completeness. The lift, drag, and power coefficients for the rotor sail follow from the parametric model of Tillig and Ringsberg (2020), based on the rotor sail spin ratio of three, width/height aspect ratio of six, and the respective power input coefficient. Thus, the rotor sail is considered an active

WAPS, with variable input power depending on environmental winds and the rotation rate required to maintain a constant spin ratio. We assumed that the rotor sail was fitted with endplates, each with a diameter of two times the rotor sail diameter, yielding a modification to the rotor sail lift coefficient (Badalamenti & Prince, 2008). The impact of the endplate on drag and power input required was assumed to be negligible. Because the wind varies between the surface and the upper reaches of the chosen WAPS elements (30–40 meters above the water surface), we calculated the average wind vectors (true and apparent) in 6-meter vertical increments using the modeled vertical wind profile (Tillig & Ringsberg, 2020).

For the wing sail, the chosen airfoil is the NACA-2412 with a variable angle of attack (AOA) from -18° to 19.25° relative to the average apparent wind, which we calculated. We chose the airfoil lift and drag coefficient polar diagram that best corresponds to airflow characteristics over open water (D. Ferrer Desclaux, personal communication, August 23, 2022).[6] We set the wing sail dimensions to be 30 m in height by 10 m in width, amounting to an exposed area of 300 m^2. The choice of the wing sail size and area was based on a comparison to prior implementations in the literature (Bergeson & Greenwald, 1985; Chou, 2021), and we kept this area the same for all JAF vessels studied herein. The trim strategy for the wing sail maximized the lift-to-drag ratio for each apparent wind condition encountered by an AIS, thus ensuring the greatest possible forward thrust in each hour.[7] This implies that the optimal AOA would be found regardless of whether the apparent wind was from the port or starboard directions. We additionally used fixed camber, or the curvature of the wing sail, which can be optimized in real-world applications. Lastly, we assumed the wing sails operate passively, that is no external power input is required to function.

For both the rotor sail and the wing sail, we assumed they were active so long as the net power generated was positive while accounting for any power inputs required (in the case of the rotor sail). We assumed that the resulting lift and drag forces act at the vessel's center of mass; the net force acting on the vessel is the difference between lift and drag components in the longitudinal direction. We did not include the effects of side forces and drift. More complex models incorporate rudder angle adjustments and drag to counteract the drift tendency. We assumed that such impacts can be accounted for through the hydrodynamic resistance factor mentioned above. Lastly, we applied a constant efficiency-reduction factor of 0.75 to account for transfer losses between WAPS power generation and forward propulsion (Lele & Rao, 2016). The power was summarized by hour, converting the unit to energy, kWh.

Comprehensive weather detail is required over large geographic areas to fully evaluate the potential feasibility of incorporating WAPS as part of zero-emissions shipping corridors. The atmospheric data for this study came from the European Centre for Medium-Range Weather Forecasts ERA5 reanalysis (Hersbach et al., 2020). Reanalysis is a technique that draws together multitudes of weather observations in a physically realistic computer weather model to produce a single picture of the pressure, temperature, and wind at any one time. The reanalysis technique overcomes some of the practical limitations in weather observations and can provide weather maps for all land and ocean areas.[8] Thus, one of the strengths of this work is that it explicitly attributes the

6 Airfoil cl/cd polars from the NACA2412 can be found at: http://airfoiltools.com/airfoil/details?airfoil=naca2412-il

7 To "trim" is to adjust the aerodynamic forces on the control surfaces so that the apparatus maintains a set efficiency.

8 The ERA5 data are available at a horizontal resolution of 0.25° latitude x 0.25° longitude, at up to 37 altitudes, every hour, via the Copernicus Climate Change Service. https://www.ecmwf.int

most comprehensive set of weather observations to vessel movements for the duration of the study period, rather than relying on coarse, background climatological data.

The method for calculating quantities of interest from the raw weather input is detailed in Comer et al. (2019, 2022). The true wind (actual speed and direction as experienced by a stationary observer) was attributed to the chosen vessels at every position, each hour, for the entire year of 2019 by interpolating directly from the three-dimensional weather model. The apparent wind (wind speed and direction as experienced by an observer that is not stationary) is an hourly average, and we assumed that both the true wind from the weather model and the ship motions are steady for each interval.

WAPS on the selected ships are applicable for their ship types. Bulk carriers, previously modeled in Comer et al. (2022), are ideal for WAPS application due to their flat decks. However, it is important to note that WAPS is not limited to flat-decked vessels. Ro-ro (roll-on/roll-off) ferries are plausible and have several new builds planned (Mandra, 2023). Ro-ro cargo vessels do not have to stack containers above deck like traditional containerships. This allows them to have lower interaction between cargo and WAPS. Finally, WAPS may be more challenging to place on fully cellular container vessels, due to the containers being stacked on deck, but this does not rule out WAPS applications completely. WAPS can be elevated above the height limit of the containers or a single WAPS element can be placed on the bow of the ship (Blenkey, 2021).

CORRIDOR SUMMARY

Corridors were identified based on ports and regional route density. A corridor is a collection of routes and ports; some ports may appear in multiple corridors. A corridor can support more than one zero-emission vessel as well. When summarizing wind-assist benefits on a corridor level, the net energy produced by each WAPS is converted into tonnes of LH_2 fuel that can be avoided because of the wind propulsion produced. This equation is based on Georgeff et al. (2022) and modified below:

$$LH_{2Avoided} = 1.2 \times \sum \frac{E_{net,}\ WAPS}{ED_{LH2} \times \eta_{LH2}} \quad (1)$$

Where:

$LH_{2Avoided}$ is LH_2 that would be replaced by WAPS propulsion energy, in tonnes;

$E_{net,}\ WAPS$ is the net propulsion energy by each WAPS system, in kWh;

ED_{LH2} is the energy density of LH_2 is 33,300 kWh/tonne (Comer, 2019);

η_{LH2} is the efficiency of proton exchange membrane hydrogen fuel cells, assumed to be 54% (Comer, 2019); and

1.2 is an assumed 20% fuel margin for safety reasons.

After finding the amount circumvented using WAPS we can then apply the price of fuel saved.

$$ES_{per\ corr.} = LH_{2Avoided} \times C_{LH2,US} \quad (2)$$

Where:

$ES_{per\ corr.}$ is the estimated savings of circumvented hydrogen per corridor in USD; and

$C_{LH2,US}$ is $4,300 USD/tonne, the estimated average hydrogen production cost in the United States in 2020 (Zhou et al., 2022).

RESULTS

Four ships were investigated in this report. Each ship represents a series of unique routes specific to communities reliant on JAF. First, we will summarize the ships' needs (as seen in Table 2) and then investigate their associated routes.

HYDROGEN FEASIBILITY

Table 2. Summary of the ships investigated.

Ship name	Cargo type	Deadweight tonnage	Company	Age (years)	Ports	Number of legs	Fuel	CO_2 emissions produced in 2019 (tonnes)	Total distance traveled (nm)
Midnight Sun	Ro-ro cargo ship	22,000	TOTE Maritime Alaska LLC	20	Anchorage, AK Tacoma, WA	109	Distillate	166,000	136,000
Horizon Reliance	Container ship (fully cellular)	46,000	Pasha Hawaii	43	Honolulu, HI Los Angeles, CA	76	Distillate	69,000	110,000
Mahimahi	Container ship (fully cellular)	31,000	Matson Navigation Co Inc	40	Oakland, CA Honolulu, HI Seattle, WA	109	Distillate	83,000	118,000
Badger	Ro-pax passenger/ vehicle ferry	3,000	Interlake	70	Ludington, MI Manitowoc, WI	534	Diesel[9]	2,000	15,000

The *Midnight Sun*, the youngest ship of the four, traveled the most distance, sailing over 130,000 nautical miles in the year. It had a regular schedule, making more than 100 voyages in one year between Tacoma and Anchorage, with each voyage approximately 1,400 nautical miles. According to our ICCT SAVE Model, its routes produced the highest emissions of CO_2 of the four ships, over 160,000 tonnes a year, because of its average 42 MWh energy demand per voyage. It is a ro-ro cargo vessel, meaning it is specialized in storing vehicles and the trailers of tractor-trailers, and can hold up to 600 twenty-foot equivalent units (TUEs).

The largest of the four ships investigated is the *Horizon Reliance*, a fully cellular container ship of 45,000 DWT and 2,400 TEUs. It completed 76 routes between Los Angeles and Honolulu in 2019, providing "the broadest scope of ocean transportation services between Hawaii and the Mainland," as stated by Pasha Hawaii (2022). At 43 years old, it is past the typical 30-year life span of an oceangoing vessel. It was estimated to produce 69,000 tonnes of CO_2 a year on its routes.

The *Mahimahi* had the most diverse routes, traveling 109 voyages between California, Hawaii, and Washington. It is also an advanced-age containership at 40 years old, and its voyages were estimated to produce 83,000 tonnes a year of CO_2.

Lastly, the Great Lakes' ro-pax (roll-on/roll-off and passenger) ferry, the SS *Badger*, is the oldest ship, at 70 years of age. The ship operates from May to October, crossing Lake Michigan along what is a roughly 45-mile gap in U.S. Highway 10 between Manitowoc, Wisconsin, and Ludington, Michigan. In 2019, there were 534 voyages recorded by AIS data, a reasonably high number given its relatively short route of 40 nautical miles. Its short routes, along with being only active in warmer months, account for its lower annual CO_2 emissions. It is still a noteworthy case to investigate given the

9 The *Badger* is a historic coal-powered vessel but will be switching to diesel in the near future; this analysis reflects the current dimensions for a diesel engine.

Badger's history of being a coal-fired ship and recent engine improvements to reduce its pollution (Coal-powered SS Badger to convert to new fuel source, 2022).

Based on the fuel capacity provided by IHS and calculated engine volumes, we estimated that the oceangoing ships *Horizon Reliance*, *Midnight Sun*, and *Mahimahi* have 8,000, 4,000, and 5,900 m^3, respectively, of available space on board for conversion to liquid hydrogen storage and fuel cells. We estimated approximately 500 m^3 of available space for the Great Lakes *Badger*. These vessels currently run on fossil fuel. Therefore, if converted to zero-emission vessels using renewably produced liquid hydrogen via fuel cells, they can eliminate shipping-based pollution, including 320,000 tonnes a year of CO_2 on their routes.

Our SAVE Model identified 17 unique routes by the four modeled ships. That number was reduced to nine routes after filtering out routes with operation times of under 100 hours and routes for which voyages were not both started and finished in 2019. These routes and their locations are summarized in Table 3.

Table 3. Routes summarized by hydrogen demand and attainability using liquid hydrogen

Vessel (route)	Route ID	Hours en route in a year	Distance (nm)	Ports	Average hourly energy demand per leg (MWh)	Hydrogen capacity (m^3)	Average leg hydrogen demand (m^3)	Attainability by LH_2 + fuel cells
***Midnight Sun* (ANC → TAC)**	MS.1	3,200	1,380	Anchorage, Tacoma	46	5,935	4,418	98%
***Midnight Sun* (TAC → ANC)**	MS.2	3,500	1,440	Tacoma, Anchorage	39		4,891	96%
***Horizon Reliance* (HNL → LAX)**	H.1	3,800	2,250	Honolulu, Los Angeles	10	8,709	2,530	100%
***Horizon Reliance* (LAX → HNL)**	H.2	2,600	1,990	Los Angeles, Honolulu	19		3,346	100%
***Mahimahi* (OAK → HNL)**	MM.1	2,300	1,940	Oakland, Honolulu	27	6,924	1,706	100%
***Mahimahi* (HNL → SEA)**	MM.2	2,600	2,170	Honolulu, Seattle	28		5,070	100%
***Mahimahi* (SEA → OAK)**	MM.5	950	780	Seattle, Oakland	24		4,829	100%
***Badger* (LUD → MAN)**	B.1	600	38	Ludington, Manitowoc	2	473	12	100%
***Badger* (MAN → LUD)**	B.2	570	41	Manitowoc, Ludington	2		14	100%

Based on each leg's energy demands, the routes are highly feasible to be powered by liquid hydrogen via fuel cells. Only the Tacoma-Anchorage routes had slightly lower feasibility (96%) due to the seasonal increase of travel distance in winter months. Despite over 1,000 nautical miles between ports, the ocean routes did not require additional assistance to be powered by liquid hydrogen, such as additional refueling ports or cargo substitution, compared to the transpacific shipping routes investigated in Mao et al. (2020). The Great Lakes routes have lower hydrogen demands, given the shorter routes, and always were attainable by liquid hydrogen alone.

WIND PROPULSION RESULTS

For an entire year over the nine routes, 2,700 MWh of energy was estimated to be generated by a single rotor sail, and 1,700 MWh was estimated to be produced by a wing sail. The wing sail was modeled to be passive, meaning no energy was required to operate; it therefore had consistent net energy production, with the main contributing factor being the angle of the wind. The wing sail had greater operational flexibility due to its higher lift-to-drag ratios at smaller apparent wind angles (i.e., greater resultant headwinds). A wing sail would average 82 kWh of energy produced on a leg in the ocean and 47 kWh on a leg in the Great Lakes routes and provide net positive energy production 98% of the time.

For the rotor sail, peak energy generation was found for apparent wind angles of 40 degrees to 60 degrees and did not generate net positive forward thrust for apparent wind angles smaller than approximately 12 degrees to 15 degrees. This resulted in the rotor sail being active 49%–70% of time it spent en route on the ocean, while on the Great Lakes routes, the rotor sail was active 76%–80% of the time. The rotor sail produced a leg average of 136 kWh net energy on the ocean routes and 92 kWh on the Great Lakes route. Although the wing sail was shown to generate net positive energy a greater fraction of the time en route because the lift-to-drag ratio is higher, the overall magnitude of lift/thrust forces was smaller relative to the rotor sail. This is summarized in Table 4 below.

Table 4. Summary of wind-assist savings potential broken down by route, season, and location.

	Route ID (Port → Port)	Season	Rotor sail average hourly energy generated per leg (kWh)	Rotor sail % of time generating net positive energy	Wing sail average hourly energy generated per leg (kWh)	Wing sail % of time generating net positive energy
Ocean	**H.1 (Honolulu → Los Angeles)**	Fall/Winter	121	66%	58	98%
		Spring/Summer	78	51%	43	98%
	H.2 (Los Angeles → Honolulu)	Fall/Winter	125	72%	59	99%
		Spring/Summer	92	68%	46	98%
	MM.1 (Oakland → Honolulu)	Fall/Winter	111	72%	67	99%
		Spring/Summer	83	67%	58	99%
	MM.2 (Honolulu → Seattle)	Fall/Winter	178	69%	89	99%
		Spring/Summer	96	70%	60	99%
	MM.5 (Seattle → Oakland)	Fall/Winter	201	56%	98	97%
		Spring/Summer	135	61%	82	99%
	MS.1 (Anchorage → Tacoma)	Fall/Winter	203	62%	118	98%
		Spring/Summer	195	54%	129	97%
	MS.2 (Tacoma → Anchorage)	Fall/Winter	83	58%	46	98%
		Spring/Summer	52	41%	30	96%
Lake	**B.1 (Ludington → Manitowoc)**	Fall*	205	78%	112	98%
		Spring/Summer	122	78%	82	99%
	B.2 (Manitowoc → Ludington)	Fall*	148	96%	93	100%
		Spring/Summer	68	77%	59	99%

*_Badger_'s schedule goes from mid-May through mid-October. For this study, spring and summer was April through September. Fall and Winter was October through March.

Influences on wind energy savings: Latitude

The meteorology analysis showed stronger true wind over oceans than the Great Lakes; the difference amounted to 2–3 m/s^{-1} (about 4–6 knots). The divergences from average for vessel speed and true/apparent winds were greater over the ocean than the Great Lakes. Together, these suggest that WAPS fuel-saving potential is higher, yet more volatile in general, over the ocean versus the Great Lakes. We found that the apparent winds were generally higher for voyages where the true wind was a headwind instead of a trailing wind (especially along the routes between Hawaii and the West Coast). The results also highlight the gradual pattern for increased net energy savings from WAPS at higher latitudes, especially for the rotor sail, as seen in Figure 3.

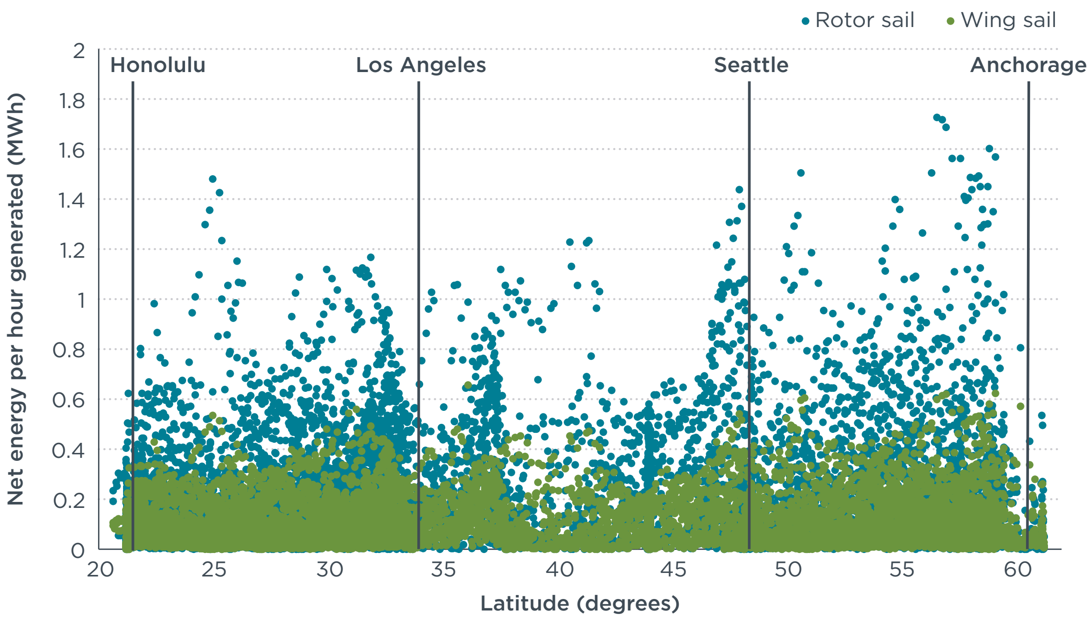


Figure 3. Wind-assisted propulsion net energy produced in one operating hour at different latitudes

Influences on wind energy savings: Heading

Along with latitude, the cardinal direction, or heading, of the route influenced the effectiveness of the WAPS. For the wind sail on the ocean, traveling in a western direction produced the highest percentage of net positive energy (98.4%). For rotor sails, southwest headings produced the highest percentage of net positive energy (72.7%), and the north headings caused the highest hourly average of net energy with 41 kWh. The Great Lakes routes were consistently eastern and western headings; the east heading, or going from Manitowoc to Ludington, generated more hourly net energy via both the wing sail (+8%) and the rotor sail (+10%) than going west from Ludington to Manitowoc. Overall, the northern route between Honolulu and Seattle completed by the *Mahimahi* had the highest average WAPS energy generation. These results are summarized in the following Figure 4.

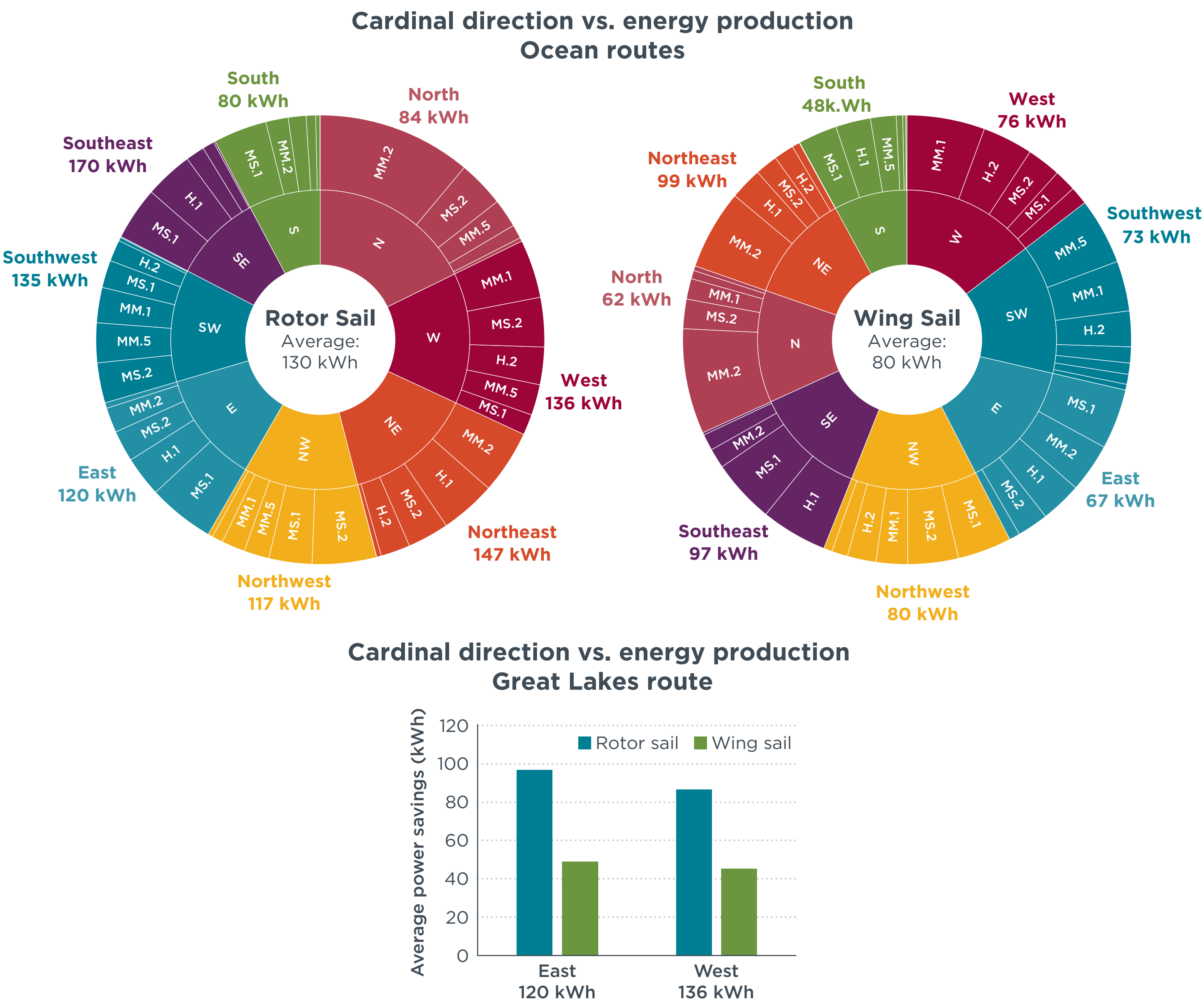


Figure 4. Heading of route versus average hourly energy produced

Influences on wind energy savings: Speed

A vessel's speed over the ground positively affected both types of WAPS. A rotor sail can produce 7.9 kWh of net energy in an hour for every knot a vessel speeds up, and wing sails can produce 4.6 kWh of net energy in an hour for every knot a vessel speeds up. There were two notable peaks in net energy production in both WAPS methods, as seen in Figure 5. At approximately 15 knots, the hourly net energy production for rotor sails was 88 kWh and 60 kWh for wing sails. At 22 knots, the hourly net energy production was 147 kWh for rotor sails and 87 kWh for wing sails.

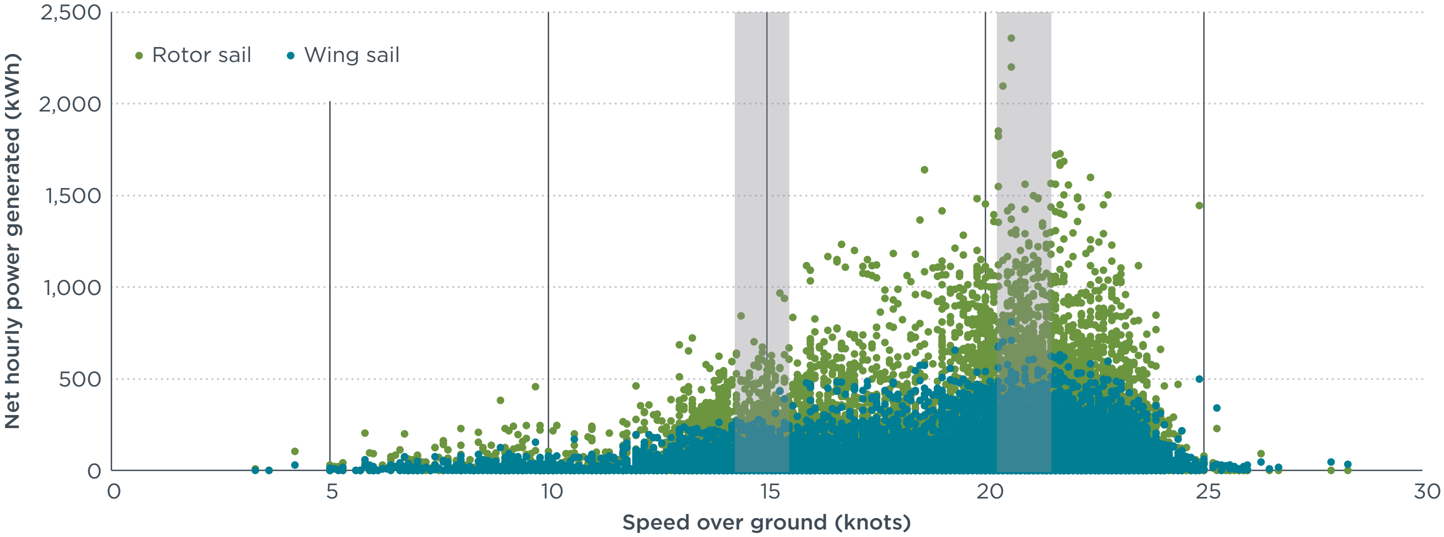


Figure 5. Scatter plot of speed over ground versus net hourly energy production of rotor sails and wing sails

Influences on wind energy savings: Seasonality

The median energy savings for oceangoing vessels using either the rotor or wing sail were comparable, with median values ranging from about 0.1%–0.6%. Yet, we found appreciable differences for maximum values ranging from 1.2%–7.0% using the wing sail and 2.6%–25.4% using the single rotor sail. There are two reasons that explain these findings. First, distributions of energy savings potential are skewed. When more hourly intervals were measured by wind-assist type, the technologies had smaller energy savings potential, while infrequent interval measurements skewed toward greater energy savings potential. Second, in optimal wind conditions where both systems could operate, the rotor sail generated more energy on average, but the wing sail was active for a greater fraction of time en route. Regardless, the rotor sail demonstrated greater overall energy savings potential (by a factor of about 2 to 4 times) when active. As a final point on oceangoing vessel results, seasonal differences in energy savings potential were significant for both the rotor and wing sail—as much as 50%–70% greater in the fall, winter, and spring versus summer for most routes.

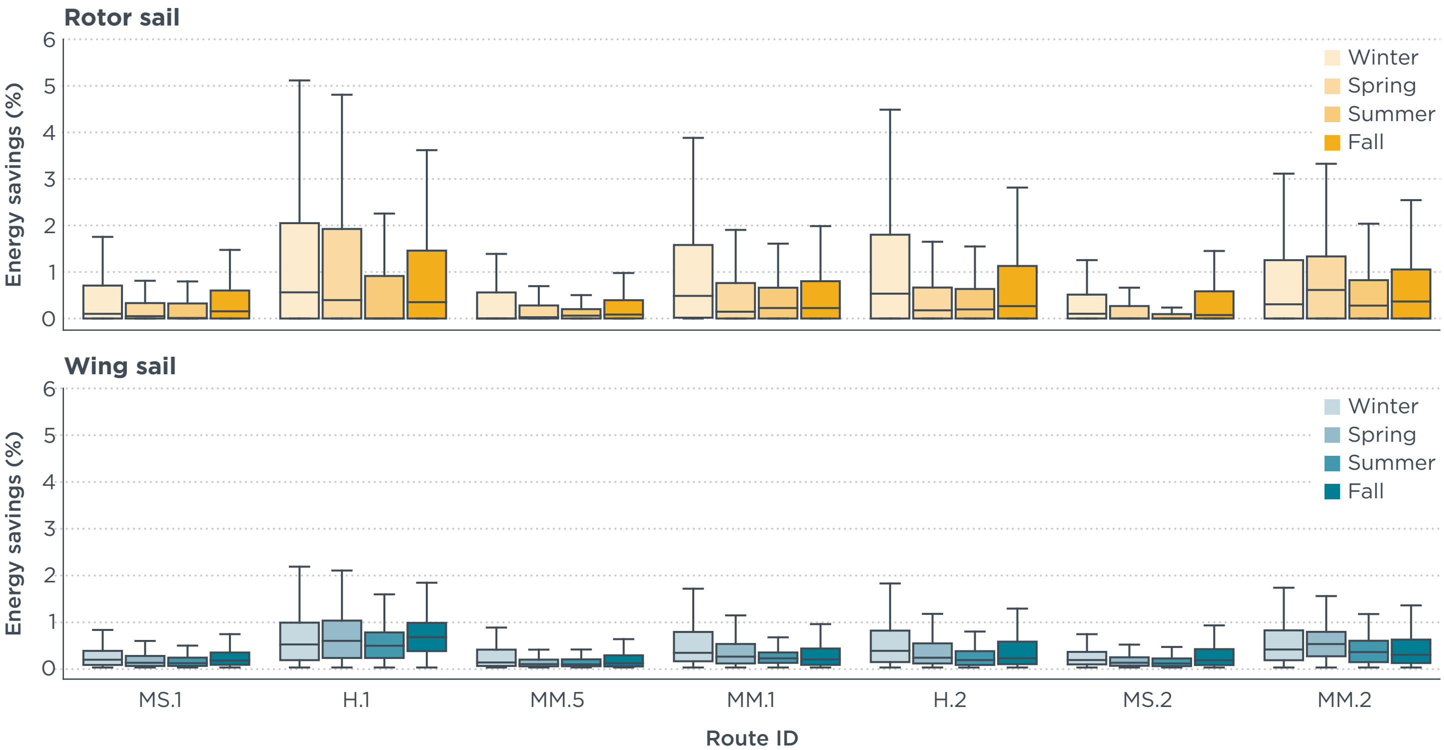


Figure 6. Seasonal distributions of potential hourly energy savings using WAPS for oceangoing vessels during 2019

For the *Badger* operating on the Great Lakes corridor, appreciable energy savings using WAPS appear to be possible, especially due to the vessel's smaller energy demands. Energy savings for the Badger as a percentage of total fuel costs was about 5 times greater than for oceangoing vessels; the median relative energy saved ranged from 1.8%–4.6% for the rotor sail and 1.3%–2.4% for the wing sail on the *Badger*, whereas the maximum values were 13.8%–25.2% for the rotor sail and 5.3%–11.0% for the wing sail. Though our data sample for the *Badger* is limited to the spring, summer, and fall of 2019 (the ferry does not operate in winter), there is still notable seasonal variation. Median energy savings is twice as large in fall as in the spring and summer.

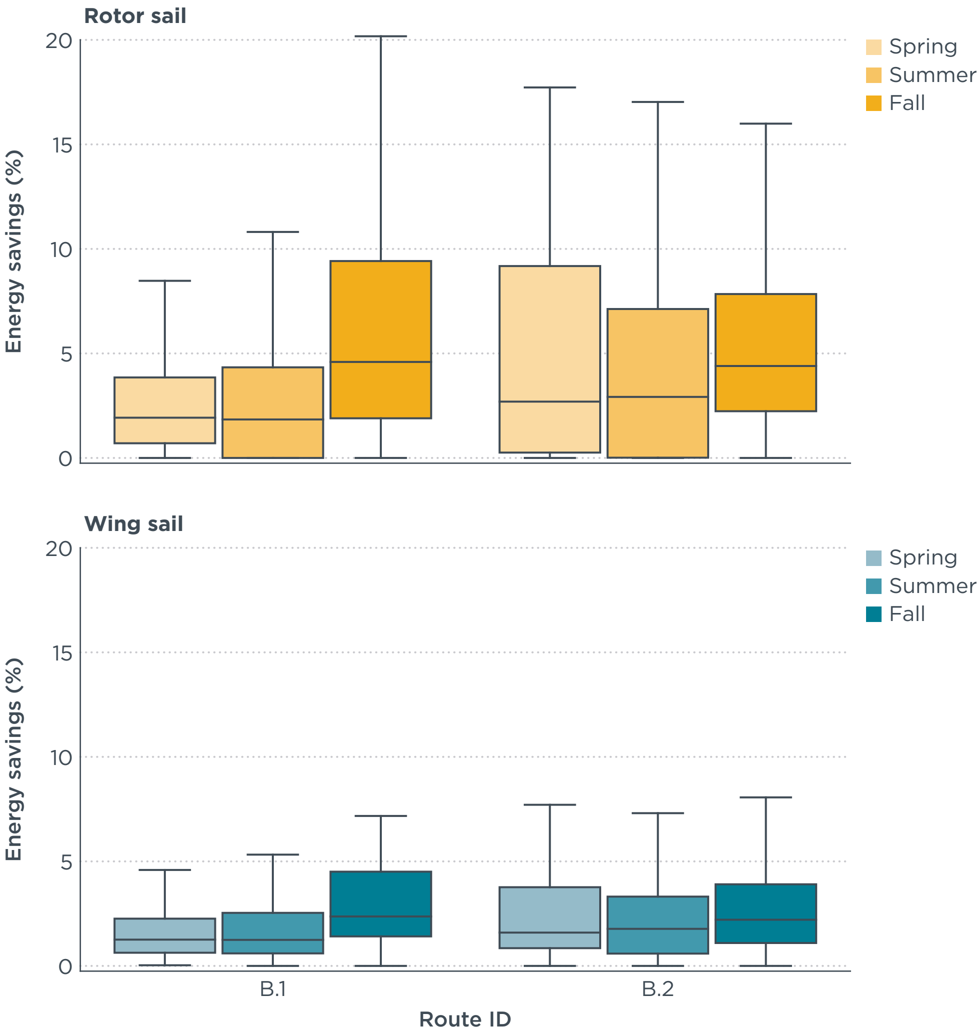


Figure 7. Seasonal distributions of potential hourly energy savings using WAPS on the *Badger* in the Great Lakes during 2019

GREEN DOMESTIC CORRIDORS

We identified four corridors: the Pacific Northwest corridor, which connected Anchorage with both Tacoma and Seattle; the West Coast corridor, which connected Seattle, Tacoma, Oakland, and Los Angeles; the Pacific Corridor, which connected Honolulu to Los Angeles and Seattle; and the Great Lakes corridor between Manitowoc and Ludington. The three ocean-based corridors supported two vessels each, and the Great Lakes corridor supported a single vessel. This is summarized in Figure 8.

Table 5 shows annual hydrogen demand, potential savings from wind-assist technologies, and applicable stakeholders for the four routes. The corridor needing the most liquid hydrogen fuel in a year was the Pacific Northwest corridor, requiring 24,000 tonnes for two ships. However, 94 fewer tonnes of LH_2 fuel would be needed by using rotor sails on the route and wing sales could save 60 tonnes of fuel. This would equate to $400,000 in savings from a single rotor sail or $250,000 in savings from a single wing sail. The regional hydrogen stakeholders identified using the H2 Matchmaker tool were Mighty Pipeline Inc., Modern Electron, Booster Fuels Inc., US Oil-Par Pacific, and Tacoma Power.

The West Coast corridor involved the most ports and over 10,000 legs over four routes between Tacoma, Seattle, Los Angeles, and Oakland. The West Coast corridor saw an annual demand of 19,000 tonnes of LH_2. Using rotor sails could save 98 tonnes of LH_2 fuel and using wing sails could save 60 tonnes of fuel. This would equate to $420,000 in savings caused by a single rotor sail or $260,000 in savings from a single wing sail. The regional hydrogen stakeholders identified using the H2 Matchmaker tool were Modern Electron, Booster Fuels Inc., US Oil-Par Pacific, Tacoma Power, Avangrid Renewables, Torrent Energy, Ways2H Inc., Raven SR, and Waimana Hydrogen.

The Pacific corridor was unique because it connected Hawaii to the continental U.S. via Los Angeles and Seattle. Two ships could operate in this corridor and complete 11,000 legs on three routes in a year. The three ports saw a collective annual demand of 15,000 tonnes of liquid hydrogen. This corridor benefited the most from wind assist; 110 tonnes of LH_2 fuel consumption could have been avoided by using rotor sails on the route and 65 tonnes of fuel could have been saved using wing sails. This would equate to $470,000 in savings caused by a single rotor sail or $275,000 in savings from a single wing sail. The regional hydrogen stakeholders identified using the H2 Matchmaker tool were Modern Electron, Booster Fuels Inc., Avangrid Renewables, Torrent Energy, Ways2h Inc., Hawaii Hydrogen Alliance, and Hawaii Natural Energy Institute.

The final corridor discussed is the Great Lakes corridor, a ferry extension of U.S. Highway 10 between Wisconsin and Michigan, recently labeled a marine highway by the U.S. Maritime Administration. A single ship operated 1,200 legs across Lake Michigan during its 2019 spring through fall season. It had the lowest annual LH_2 demand of 220 tonnes a year. Approximately 8 tonnes of the LH_2 fuel could be saved by using rotor sails on the route, or 4 tonnes of fuel could be saved using wing sails. This would equate to $30,000 in savings using a single rotor sail or $16,000 in savings from a single wing sail. The regional hydrogen stakeholders identified using the H2 Matchmaker tool were Constellation and Kohler Infrastructure.

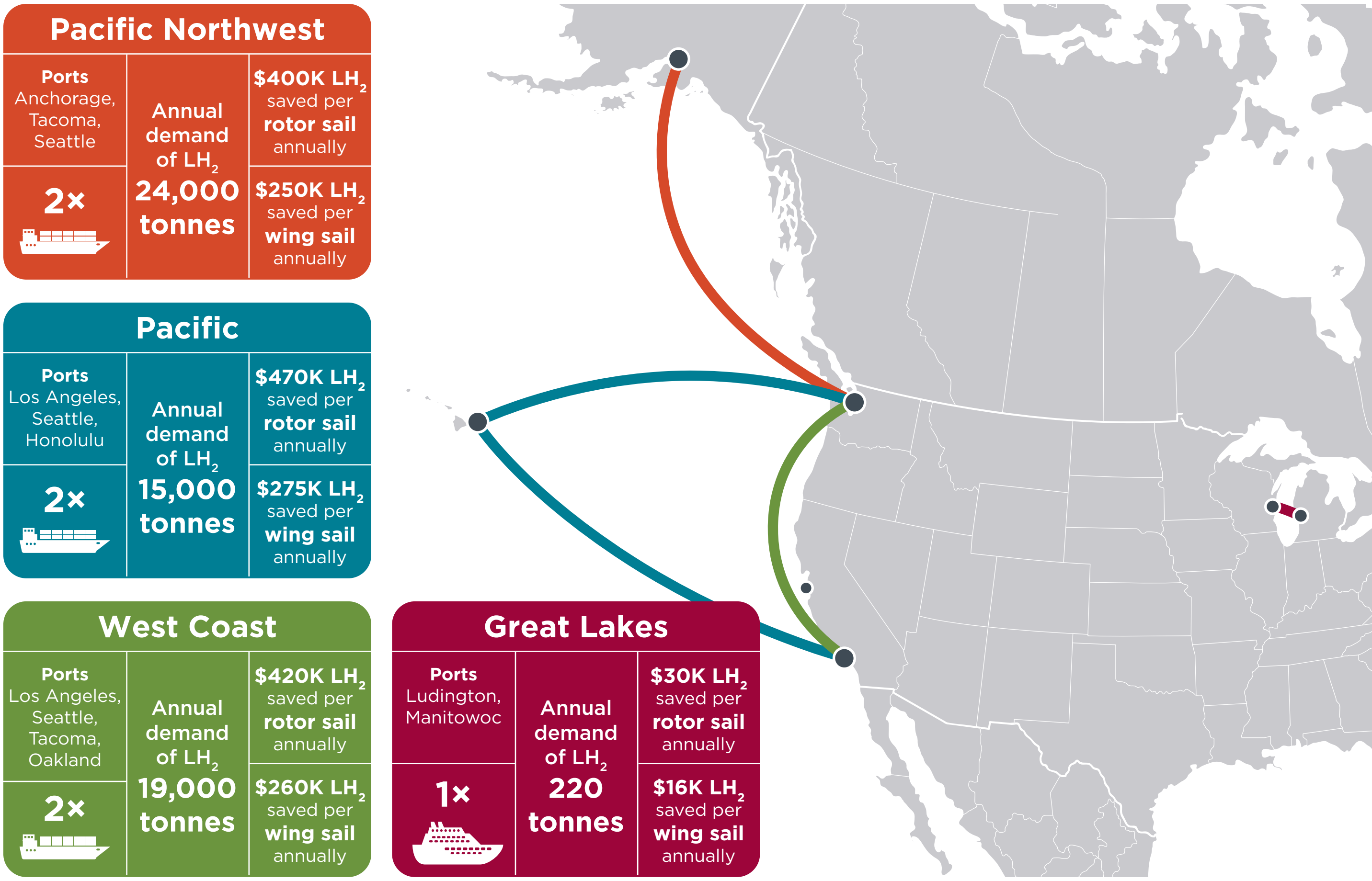


Figure 8. Summary graphic of locations, fuel demands, and wind-assisted fuel savings per corridor

Table 5. Corridor results including applicable shareholders associated with hydrogen production and distribution

Corridor	Annual demand of LH_2 (tonnes)	LH_2 fuel avoided by rotor sail (tonnes)	LH_2 fuel avoided by wing sail (tonnes)	Stakeholders
Pacific Northwest	24,100	94	60	Mighty Pipeline Inc., Modern Electron, Booster Fuels Inc., US Oil-Par Pacific, Tacoma Power
West Coast	19,000	98	60	Modern Electron, Booster Fuels Inc., US Oil-Par Pacific, Tacoma Power, Avangrid, Torrent Energy, Ways2h Inc., Raven SR, Waimana Hydrogen
Pacific	15,200	110	64	Modern Electron, Booster Fuels Inc., Avangrid, Torrent Energy, Ways2h Inc., Hawaii Hydrogen Alliance, Hawaii Natural Energy Institute
Great Lakes	220	8	4	Constellation, Kohler Infrastructure

DISCUSSION

This study's results demonstrate that WAPS can effectively reduce fuel consumption and greenhouse gas emissions in the shipping industry, particularly in domestic green corridors. The findings suggest that wind-assist technologies can be particularly beneficial in the United States, which has a diverse range of wind profiles that can be harnessed to improve vessel efficiency. Domestic routes also do not need additional accommodations—such as an extra stop or cargo replacement—to achieve zero-emission capabilities, unlike their transpacific counterparts.

However, it is worth noting that there may be differences in the fraction of time that WAPS operate across different shipping routes. While the results of this study suggest that WAPS can be effective on the chosen set of routes, further research is needed to determine how these technologies perform in different operating conditions and across different routes.

There are many examples of implementing multiple WAPS elements simultaneously, usually of the same WAPS type. Many WAPS-implementation concepts feature multiple elements aligned longitudinally and in the transverse direction. Our analysis demonstrates that energy savings increase linearly with additional WAPS elements. However, studies have shown that WAPS elements situated close to one another can interfere with and reduce overall wind-assist efficiency (e.g., Bordogna et al., 2020).

The fact that some separation between WAPS elements is recommended restricts how these technologies can be installed on different vessels. Container ships have minimal areas free of cargo. For this vessel type, installations of one or two WAPS elements could be limited to bow or stern locations. Bulk and modified cargo carriers have relatively unobstructed above-deck areas, allowing greater flexibility to locate multiple WAPS elements away from cranes or other offloading rigs. Ro-ro or ro-pax vessels often have available upper-deck space and few operational limitations for the placement of WAPS, as much of the cargo is stored below deck. However, other constraints for locating multiple WAPS elements can apply, such as air drafts or any disruption of wind due to superstructures. Some concepts for bulk carriers and crude tankers involve three or more WAPS elements installed along the length of the deck, such as along the vessel's center line (e.g., Anemoi Marine Technologies rotor sails on the M/V *Afros*). Similar longitudinal alignment configurations are possible for other types of tankers, but the elements are offset in the transverse direction to account for storage tanks that can protrude above the deck centerline (e.g., LNG carriers). Locating a WAPS far from the vessel's center of mass—fore, aft, transverse, as well as high above the water line—will impact WAPS efficiency. In general, when more energy is generated by WAPS there is increased potential for yaw/heeling moments, such that some degree of vessel maneuvering is required to counteract these forces. In turn, these countermeasures incur additional energy demand and/or resistance on the vessel, thereby decreasing the energy-saving potential with WAPS.

Another important factor to consider is future innovation in WAPS technologies and the cost of retrofitting existing vessels. As the cost of renewable energy technologies continues to decline and more companies adopt sustainable business practices, WAPS will likely become increasingly cost-effective and attractive to ship owners and operators. However, there are still significant costs associated with retrofitting vessels with these technologies, and further research is needed to determine how these costs may change over time.

Future research should focus on exploring the potential of WAPS to reduce greenhouse gas emissions in the context of global shipping, as well as the potential impacts of these technologies on other aspects of the industry, such as shipbuilding and rerouting due to storms. Additionally, it will be important to continue monitoring the adoption and effectiveness of WAPS technologies in the maritime sector to identify opportunities for further innovation and improvement.

CONCLUSION

With federal funding being released for port infrastructure and zero-emission projects, this study demonstrates an opportunity for investment in the United States' domestic Jones Act fleet. Our results found evidence of the feasibility of fueling domestic routes using renewably sourced liquid hydrogen through fuel cells. The fuel needs of zero-emission vessels decrease when using technologies such as wind-assisted propulsion. An investigation of the differences between wind-assisted propulsion systems, especially between rotor and wing sails, found notable fuel savings that can alleviate the higher costs of zero-emission fuel.

Overall, one rotor sail produced higher annual fuel savings than one wing sail, but the wing sail generated the most net positive energy. When looking at the nine routes of the four ships, wind-powered fuel savings depended on the season, heading, latitude, and vessel speed. The highest annual fuel savings for an ocean route was from Anchorage to Tacoma in the fall/winter, with annual hourly energy savings of 200 kWh using a rotor sail. The highest annual hourly net energy production for a wing sail was 130 kWh on the spring/summer route between Anchorage and Tacoma.

Using the modeled ships and routes, four green domestic corridors emerged. The Pacific Northwest corridor could support zero-emission vessels, and WAPS could avoid the use of 60 tonnes to 94 tonnes of hydrogen. This would save $250,000 to $400,000 in fuel costs per year using a single wing sail or rotor sail. The West Coast corridor supports two zero-emission vessels with WAPS reducing hydrogen needs by 60 tonnes to 98 tonnes. This would result in $260,000 to $420,000 of fuel cost savings a year using a single wing or rotor sail. The Pacific corridor supports two zero-emission vessels and WAPS could reduce hydrogen needs by 64 tonnes to 110 tonnes. The highest potential savings in fuel costs, of $275,000 to $470,000, were found in this corridor. Finally, the Great Lakes corridor connecting Michigan and Wisconsin can support a single ro-pax ferry similar to the Badger, using only 220 tonnes of liquid hydrogen a year. A single sail reduces hydrogen use by 4 tonnes to 8 tonnes, an annual cost savings of $16,000 to $30,000.

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APPENDIX

The following figure and table provide information on the variables that impact the effectiveness of wind-assist technologies, including apparent wind angle and wind speed.

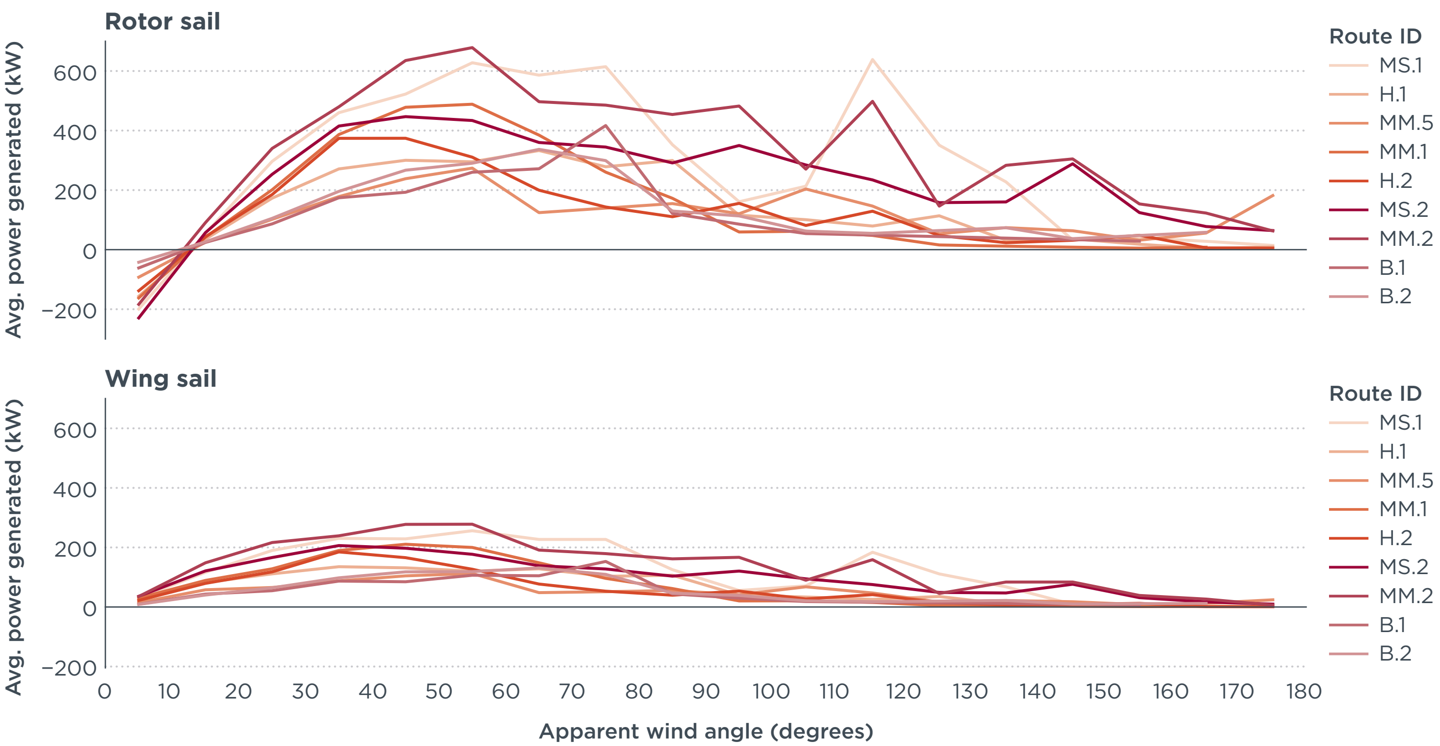

Figure A1. Average power generated versus apparent wind angle for all voyages during 2019. The route IDs are provided in Table 3.

Table A1. Routes and wind conditions encountered in the study period. Average wind conditions and vessel speeds are provided; the values in parentheses indicate the standard deviations for each quantity.

Vessel (route)	Route ID	Hours en route*	True wind (m s⁻¹)	Speed over ground (kt)	Apparent wind (m s⁻¹)
***Midnight Sun* (ANC → TAC)**	MS.1	3,221	6.3 (3.5)	21.4 (2.2)	11.5 (5.1)
***Midnight Sun* (TAC → ANC)**	MS.2	3,513	6.3 (2.8)	20.0 (2.4)	12.2 (5.2)
***Horizon Reliance* (HNL → LAX)**	H.1	3,810	6.8 (2.3)	15.4 (1.8)	11.8 (4.2)
***Horizon Reliance* (LAX → HNL)**	H.2	2,628	6.3 (2.8)	20.0 (1.6)	10.7 (4.6)
***Mahimahi* (OAK → HNL)**	MM.1	2,319	6.5 (2.9)	20.3 (2.2)	10.7 (4.6)
***Mahimahi* (HNL → SEA)**	MM.2	2,612	6.8 (3.2)	21.1 (2.7)	12.8 (4.7)
***Mahimahi* (SEA → OAK)**	MM.5	953	6.1 (3.4)	19.4 (3.5)	7.5 (4.3)
***Badger* (LUD → MAN)**	B.1	353	5.1 (2.3)	13.7 (0.4)	8.5 (3.2)
***Badger* (MAN → LUD)**	B.2	374	5.5 (2.6)	13.7 (0.5)	8.6 (3.0)

*En route refers to cruise phase only