THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

AUGUST 2024

Green shipping corridors

Screening first mover candidates for China's coastal shipping based on energy use and technological feasibility

XIAOLI MAO, YUANRONG ZHOU, ZHIHANG MENG, AND HAE JEONG CHO

ACKNOWLEDGMENTS

This work is conducted with generous support from Energy Foundation China. We thank the late Dr. Chuansheng Peng for his invaluable advice and sincere support for this work. We thank Dr. Chaohui Zheng, Dr. Kun Li, Mr. Shunping Wu, Mr. Yongbo Ji, Mr. Shengdai Chang, Professor Yan Zhang, Ms. Freda Feng, Ms. Liwei Ma, Mr. Feng Tian, and Ms. Lu Fu for their technical and policy comments and suggestions. Critical review of this work was provided by ICCT colleagues Chelsea Baldino and Tianlin Niu.

International Council on Clean Transportation
1500 K Street NW, Suite 650
Washington, DC 20005

communications@theicct.org | www.theicct.org | @TheICCT

EXECUTIVE SUMMARY

Greenhouse gas emissions from the maritime sector are on a growth trajectory incompatible with the climate goals of the Paris Agreement. In recent years, a novel collaboration framework called green shipping corridors (GSCs) has been gaining traction as a tool to speed decarbonization technology innovation in the maritime sector. As of December 2023, there were 44 GSC initiatives globally, yet none of these projects have been fully commissioned, an indicator of the challenges of coordinating these corridors. Compared with international routes, domestic routes could have the advantage of more stakeholder homogeneity. In some cases, a route could be operated by a single entity that owns the cargo as well as the vessels. By encouraging domestic routes to become GSCs, a country may attain the associated environmental and climate benefits while also accruing the experience necessary for instituting large-scale, multistakeholder, international GSC initiatives.

This study explores the opportunity for establishing GSCs for China's coastal shipping. We first quantitatively characterized China's coastal shipping activity based on open Automatic Identification System (AIS) data. The data allowed us to estimate energy use for various shipping routes and evaluate the technological feasibility of meeting that energy use with zero or near-zero life-cycle emission fuels. These fuels include renewable liquid hydrogen (LH_2) generated from renewable electricity, renewable methanol (MeOH) and renewable ammonia (NH_3) generated from renewable hydrogen, as well as direct renewable electricity. Based on these results, we identified three routes as first mover GSC candidates. For each GSC route, we estimated fuel demand for the first hypothetically deployed zero-emission vessel (ZEV) running on either renewable liquid hydrogen, renewable methanol, or renewable ammonia. We then presented a preliminary analysis of the cost to supply this fuel (Table ES1). In a previous ICCT study, we modeled and demonstrated that the cost of renewable ammonia and renewable methanol is similar to renewable hydrogen, so we only modeled and presented the cost of renewable hydrogen in this study (U.S. Maritime Administration [MARAD], 2024).

Table ES1

Green shipping corridor candidates and associated annual fuel cost for one zero-emission vessel in 2030

Route characteristics		Ship characteristics		Fuel demand (tonnes)				Annual at-the-pump cost of hydrogen (millions)[a]
Ports	Distance (nm)	Ship class	Capacity	Original fuel (VLSFO)	Methanol	Ammonia	Hydrogen	
Tianjin–Shanghai	700	Bulk carrier	57,000 DWT	475	1,000	1,070	153	¥8.4 ($1.2)
Shenzhen– Tianjin	1,400	Container	2,000 TEU	2,270	4,790	5,130	732	¥39.2 ($5.6)
Shanghai/ Ningbo–Zhoushan	75	Oil tanker	3,000 GT	49	103	111	16	¥0.7 ($0.1)
Total				**2,790**	**5,890**	**6,310**	**901**	**¥47.6 ($6.8)**

[a] Based on 2023 monetary values, using an exchange rate of ¥7 to US$1

This study finds that:

- **The technological feasibility of applying renewable marine fuels on China's coastal shipping routes is high.** Ships on all routes could use renewable methanol and renewable ammonia without the need to refuel en route. Renewable hydrogen works for most ships and routes except for a few routes traversed by tankers. Battery electric technology is the least feasible, although it is an option for certain ships on shorter regional routes.
- **The three first mover GSC candidates analyzed in this study could be served by ships running on renewable methanol, renewable ammonia, and renewable hydrogen.** The GSC candidates include two interregional routes, Yangtze River Delta to Bo Sea and Pearl River Delta to Bo Sea, and one intraregional route in the Yangtze River Delta region. These regions are home to some of the world's largest ports, including Tianjin, Shanghai, and Shenzhen, which are strategically positioned to commit to GSC initiatives. As an example, we found container ships could use renewable marine fuels to travel a shipping corridor spanning 1,400 nautical miles from Tianjin to Shenzhen.
- **To enable the first ZEVs on these routes, about 6,000 tonnes of renewable methanol or renewable ammonia, or 900 tonnes of renewable hydrogen need to be sourced.** This implies a total demand of 44~60 GWh of renewable electricity by 2030 to fuel the first mover GSC candidates. We assume this electricity is sourced from offshore wind energy to avoid the negative impacts electrolysis could have on the grid.
- **Policy interventions could help speed the deployment of more ZEVs in these corridors to deliver a meaningful reduction in greenhouse gases.** We estimate the at-the-pump cost of renewable hydrogen produced on site at the GSC ports could be $7.60/kg by 2030, more than 3 times the cost of conventional marine fuels on an energy-equivalent basis. With this cost assumption, stakeholders would need to pay around $7 million annually to deploy the first ZEVs in the proposed corridors by 2030. We also estimate that improvements in technology may only reduce the cost of renewable fuels by about 32% by 2050. While future renewable marine fuel costs may be lower or higher than our estimates, depending on developments in key areas such as the cost of electrolyzers, it is likely that a significant policy intervention will be needed to advance GSCs.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

China has an extensive coastline with well-equipped ports that enable a thriving coastal freight transport industry. Maritime shipping supplied over 50% of the country's entire freight transport demand in 2022 (Ministry of Transport of the People's Republic of China, 2023a). In recent years, the government has promoted waterborne shipping as a less carbon-intensive alternative to transporting freight by road (Ministry of Transport of People's Republic of China, 2023b).

Nevertheless, domestic shipping in China is still responsible for an estimated 6% of the country's total CO_2 emissions from the transportation sector (X. Mao, 2023; X. Mao & Meng, 2022). Options for decarbonizing the domestic maritime industry resemble those proposed for international shipping, namely improving energy efficiency in the short term and transitioning to low- and zero-carbon technologies in the mid-to-long term (X. Mao & Meng, 2022). In China, ships used for domestic and international transport may be built in the same shipyards, operated by the same companies, and serviced by the same ports and refueling infrastructure. That makes domestic shipping an ideal proving ground for piloting decarbonization technologies: Knowledge accumulated at the domestic level can diffuse to the international shipping sector and help industry players gain confidence and mature the market. This has become a popular model when adapting international best practices to China.[1]

One practice gaining momentum internationally is the establishment of green shipping corridors (GSCs). According to the Maersk Mc-Kinney Møller Center for Zero Carbon Shipping, a GSC could be a single point around a specific location, point-to-point between two ports, or a network route where alternative fuels with lower environmental impact than fossil-based fuels are deployed on ships (Maersk Mc-Kinney Møller Center for Zero Carbon Shipping [MMMCZCS], 2022a). Barriers to adopting zero-carbon fuels in the shipping sector include high fuel costs, lack of fuel supply, and the lack of port infrastructure and safety regulations for alternative fuels. Another challenge is the difficulty of coordinating among different stakeholders such as fuel producers, ship owners and operators, cargo owners, port authorities, and policymakers (Frontier Economics et al., 2019). GSCs have emerged as a strategic platform to overcome those barriers and accelerate the decarbonization of the shipping sector.

Focusing on a single route makes it easier for policymakers to identify and engage with key stakeholders and to create targeted regulatory measures. First mover regions or ports could benefit from financial incentives. Readiness for alternative fuels could also turn into a competitive advantage for shipowners, ports, and shippers (MMMCZCS, 2022b). Lessons learned from successful green shipping corridors could inform and encourage stakeholders and lead to the rapid adoption, or diffusion, of zero-emission shipping (Slotvik et al., 2022). As more international routes have been announced to transition to GSCs, China could start by exploring domestic GSCs to gauge stakeholder interest and market readiness.

The development of a GSC typically starts with pre-feasibility and feasibility analyses (Getting to Zero Coalition, 2021; MMMCZCS, 2022a). The pre-feasibility analysis involves region-specific research on potential alternative fuel supplies and costs, ship and voyage characteristics, trade flows, and the regulatory landscape. This work informs the process used to establish selection criteria and screen potential corridors. The selection criteria might vary but would in general be based on potential emission reductions, technical and economic feasibility, and stakeholder readiness. Once

1 Another example of this model is China's Domestic Emission Control Area. China implemented a localized version of an Emission Control Area (ECA) to evaluate whether and when domestic stakeholders are ready to comply with the International Maritime Organization's regulations for ECAs.

potential corridors are selected, a more detailed feasibility analysis examining the technological, regulatory, and commercial requirements can be conducted (Boyland et al., 2023).

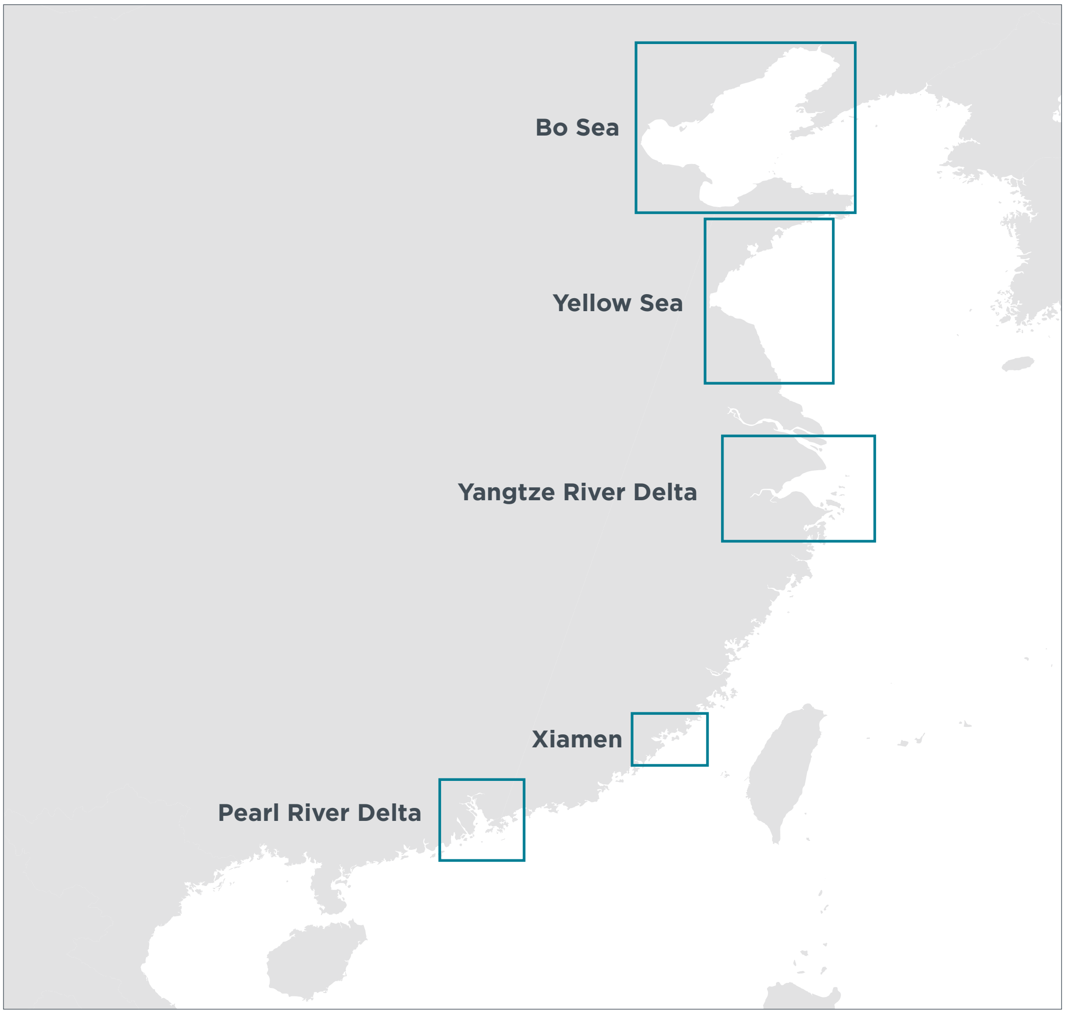
This analysis is a pre-feasibility study on establishing GSCs for China's coastal shipping. We first characterize China's coastal shipping activities using real-world ship movement data to identify the origins and destinations for each voyage. We then summarize the energy used by ships on each route and evaluate the technological feasibility of powering the ships on these routes using renewable liquid hydrogen produced from 100% renewable electricity, as well as renewable methanol (MeOH), renewable ammonia (NH_3) and renewable electricity in the form of batteries. The top three routes in terms of energy use and technological feasibility are selected as first mover GSC candidates. Finally, we chose one representative ship on each GSC to understand fuel demand and to estimate the cost of supplying the required amount of renewable marine fuel. A previous ICCT study showed that renewable ammonia and renewable methanol have a comparable at-the-pump cost as renewable liquid hydrogen on an energy-equivalent basis (MARAD, 2024). Therefore, we modeled and presented costs only for renewable hydrogen in this study, as detailed in the methodology section. We then present the results of our analysis, before closing with a discussion and key takeaways.

METHODOLOGY

DATA, STUDY REGION, AND SCOPE

We used vessel-tracking data from the Automatic Identification System (AIS) to characterize the traffic pattern of China's costal shipping.[2] We selected which ships to include in this study by analyzing AIS data for June 2021; 2021 was the most recent year of AIS data available and June is the busiest month for shipping activity in China (Mao & Rutherford, 2018). For this analysis, we retained the AIS data for ships with Maritime Mobile Service Identification (MMSI) numbers signifying that they belong to the Chinese fleet.[3] We then looked at the annual activity of ships in this dataset, retaining those ships that spent more than 90% of their time in China's coastal region. Figure 1 shows the study region including the major port clusters of the Bo Sea (BS), Yellow Sea (YS), Yangtze River Delta (YRD), Xiamen and Pearl River Delta (PRD). The retained AIS data is hereinafter referred to as the Chinese coastal ship activity data.

Figure 1
Study region



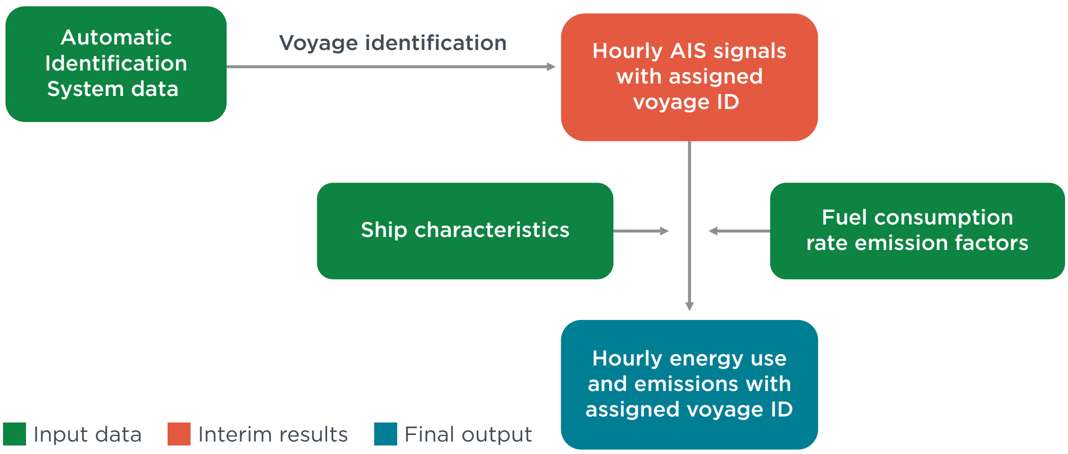
2 AIS data is commercially available through Spire Maritime, which acquired exactEarth Ltd. in 2021, and other vendors.

3 An MMSI number is a unique nine-digit number assigned to an AIS unit. The first three digits, called the Maritime Identification Digit, are country specific. China is assigned three MIDs, 412, 413, and 414. A table of Marine Identification Digits can be found here: https://www.itu.int/en/ITU-R/terrestrial/fmd/Pages/mid.aspx.

SHIP TRAFFIC PATTERNS AND ENERGY USE

ICCT's Systematic Assessment of Vessel Emissions (SAVE) model marries AIS ship activity data (e.g. hourly speed, location, draught) and data about ship technical characteristics (e.g. ship type, engine power, fuel type) from S&P Global to compile traffic patterns, energy use, and an emissions profile of the global fleet.[4] Methodologies are compatible with the *Fourth IMO Greenhouse Gas Study* (Faber et al., 2020). For AIS data that could not be matched to ships in the S&P Global database, we relied on the open-access tools from Global Fishing Watch (GFW), which uses machine learning to speculate basic ship characteristics such as ship type, gross tonnage, and length (Faber et al., 2020). After aggregating AIS data into hourly intervals, we interpolated the missing hours and assigned unique voyage IDs to specific ships using a voyage identification algorithm (Olmer et al., 2017, MARAD, 2024). Finally, using assumptions on engine fuel consumption rates and emission factors updated on a regular basis, we compiled hourly energy use and emissions for each ship and link this information to the voyage ID. The methodology flowchart is shown in Figure 2. We used the SAVE model outputs for 2021 in this study.

Figure 2
Methodology flowchart



TECHNOLOGICAL FEASIBILITY OF RENEWABLE MARINE FUEL

The methodology used in this study to evaluate the technological feasibility of powering a ship by liquid hydrogen fuel cell systems, battery electric systems, ammonia fuel cell systems, and methanol combustion engines is described in detail in previous ICCT studies (Comer, 2019; X. Mao, Georgeff, et al., 2021; X. Mao, Rutherford, Osipova, & Comer, 2020; X. Mao, Rutherford, Osipova, & Georgeff, 2022). We compared the energy required to complete each voyage with the energy provided by the amount of renewable marine fuel a ship could carry on board. If the former is greater than the latter, a voyage could not be completed without refueling. The ratio between the two—or how many times a ship would need to refuel to complete the voyage or voyages—is shown in Equation 1. This ratio was used to evaluate the technological feasibility of using a renewable marine fuel option with a corresponding propulsion system (Table 1); The higher the ratio, the lower the feasibility. Information on the density and energy density of fuel was obtained from Mao et al. (2022) and the available volume for fuel storage was obtained from Comer (2019).

4 Maritime data provider IHS Markit was acquired by S&P Global in 2022.

$$R_{i,j} = \frac{E_{i,j}}{D_j \times ED_j \times V_f} \quad (1)$$

Where:

$R_{i,j}$ is the number of times ship i needs to be refueled to complete the voyage(s) for each case when using fuel j

$E_{i,j}$ is the energy input needed for ship i to operate on fuel j in kWh

D_j is the density of fuel j in kg/m^3

ED_j is the energy density of fuel j in kWh/kg

V_f is the available volume for fuel storage on board in cubic meters

Table 1

Renewable marine fuels and corresponding propulsion systems considered in this study

Fuel type	Propulsion system	Abbreviation
Renewable liquid hydrogen	Fuel cell	Hydrogen-FC
Renewable ammonia	Internal combustion engine	Ammonia-ICE[a]
Renewable methanol	Internal combustion engine	Methanol-ICE
Renewable electricity	Battery electric	Battery electric

[a] We considered an ammonia-ICE system for its potential to reduce life-cycle GHG emissions to zero or near zero. However, there are other concerns associated with this system, such as the hazards of unburned ammonia, as well as NO_x emissions (de Vries, 2019).

For ships that are matched by GFW data, we lacked the inputs—namely engine volume and power—to apply the above methodology. As a result, we approximated these inputs based on statistical relationships between engine power, engine volume, and gross tonnage, as shown in Equation 2. When these statistical relationships could not be established due to lack of data, we used the average engine power and engine volume instead. Note that cargo ship and tanker are generic ship types for ships matched with GFW data.

$$PME_{i,c} = 0.4650 \times GT_{i,c} + 205.7615 \quad (2)$$

$$PME_{i,c} = 0.4650 \times GT_{i,c} + 205.7615$$

$$PME_{i,c} = 0.4650 \times GT_{i,c} + 205.7615$$

Where:

$P_{ME\_i,c}$ is the main engine power for cargo ship i, in kW

$GT_{i,}c$ is the gross tonnage of cargo ship i

$P_{ME\_i,t}$ is the main engine power for tanker i, in kW

$GT_{i,t}$ is the gross tonnage of tanker i

$V_{f\_i,c}$ is the volume taken up by the existing fuel tanks on board cargo ship i, in m^3

FUEL COST FOR THE FIRST ZERO-EMISSION VESSELS DEPLOYED ON GSC CANDIDATES

After selecting the GSC candidate ships, we chose one representative ship—based on average ship capacity and activity—to be the first ZEV deployed in each of the GSCs. For GSCs selected for multiple ship classes, we chose the ship class that consumed the most energy. We did not include ships that had been matched to voyages using GFW data as this data lacks the detailed ship characteristics needed to support an informative analysis of fuel demand and cost. We then estimated the ships' annual fuel demand in 2021 using the SAVE model. All selected ships used very low sulfur fuel oil (VLSFO) as their original fuel. We converted that demand to renewable marine fuel options assuming equivalent energy output as shown in Equation 3 (Comer, 2019). The energy densities of fuels were taken from Mao et al. (2022). The efficiency of propulsion equipment associated with different fuel types, including traditional combustion engines and fuel cells, was taken from Comer (2019) and Mao et al. (2022).

$$FC_{i,j} = FC_{i,LSHFO} \times \frac{ED_{LSHFO}}{ED_j} \times \frac{\eta_{ICE}}{\eta_{p,j}} \tag{3}$$

Where:

$FC_{i,j}$	is the fuel consumption of ship *i* when operating on fuel *j*, in kg
$FC_{i,LSHFO}$	is the fuel consumption of ship *i* when operating on VLSFO, in kg
ED_{LSHFO}	is the energy density of VLSFO in kWh/kg
ED_j	is the energy density of fuel *j* in kWh/kg
η_{ICE}	is the thermal efficiency of an internal combustion marine engine, which we assume is 50%
$\eta_{p,j}$	is the efficiency of the propulsion equipment associated with using fuel *j*

We modeled the cost of supplying renewable liquid hydrogen for this study as equal to the cost for its derivatives, including renewable ammonia and renewable methanol, which we considered comparable to each other on an energy-equivalent basis (MARAD, 2024). We assumed renewable hydrogen production would be located at the port, with minimal hydrogen delivery needed between facilities. Given the geographical advantage of ports as well as the limit of onshore land, we considered offshore wind to be the electricity source for renewable hydrogen production in this study. To ensure the renewability of hydrogen, we assumed that hydrogen production is directly connected to offshore wind electricity, rather than receiving electricity from the grid.[5] Because wind electricity is only generated when it is windy, such a direct-connection scenario would mean that the production of renewable hydrogen would be limited by how often the wind facility runs. The cost of supplying renewable hydrogen includes two main components: hydrogen production and hydrogen refueling.

We adopted the same discounted cash flow (DCF) model as in previous ICCT studies and updated certain data assumptions to estimate the production cost of renewable hydrogen for this study (S. Mao et al., 2021). Particularly, we collected the capital cost and operational cost of offshore wind projects, adjusted by inflation (China Electricity Council, 2020; Huang et al., 2020; International Energy Agency & Nuclear Energy Agency, 2020; Sherman et al., 2020; Jin, 2022; Guo et al., 2023; International Renewable Energy Agency [IRENA], 2023). These costs include generating the power in offshore locations and transmitting the power to the shore. We assume the capacity factor of offshore wind—the ratio of average energy produced to the theoretical maximum power output—to be 35% in China in 2023 (Sherman et al., 2020; Guo et al., 2023; IRENA, 2023). Researchers expect renewable capital and operational costs to decrease, while the capacity factor increases in the future due to technology improvements. Thus, to project future offshore wind electricity cost, we follow the cost reduction and capacity factor improvement trends used in the National Renewable Energy Laboratory annual technology baseline report (National Renewable Energy Laboratory [NREL], 2020). The assumed capital cost, operational cost, and capacity factor, along with our estimated levelized cost of offshore wind by year, are shown in Table 2. The capacity factor and levelized cost are inputs to the hydrogen DCF model.

5 Renewable hydrogen could also be produced with grid electricity if the hydrogen producer signs a power-purchase agreement with a renewable power supplier. Such a practice is not yet common in China and thus we do not model this scenario in this study.

Table 2
Costs of producing offshore wind in China

	Capital cost	Operational cost	Capacity factor	Levelized cost of offshore wind power
2023	¥17,780/kW ($2,540/kW)	¥205/kW/year ($29/kW/year)	35%	¥480/MWh ($69/MWh)
2030	¥13,720/kW ($1,960/kW)	¥180/kW/year ($26/kW/year)	37.5%	¥365/MWh ($52/MWh)
2040	¥12,400/kW ($1,770/kW)	¥160/kW/year ($23/kW/year)	38.7%	¥320/MWh ($46/MWh)
2050	¥11,215/kW ($1,602/kW)	¥145/kW/year ($21/kW/year)	39.8%	¥280/MWh ($40/MWh)

Note: Based on 2023 monetary values, using an exchange rate of ¥7 to US$1.

We collected the capital cost of alkaline water electrolysis from recent, China-specific studies (Zhang et al., 2023; China Hydrogen Alliance, n.d.).[6] Our data assumptions for the hydrogen DCF model are shown in Table 3. Because the market and technology for electrolyzers is still developing, we expect costs to decrease and efficiency to improve in a linear trend. To account for unforeseeable upfront costs, we multiplied the capital cost of an alkaline electrolyzer system by a contingency factor of 1.2, consistent with previous studies (S. Mao et al., 2021; Zhou et al., 2022). As the hydrogen plant in this analysis is getting electricity directly from offshore wind, we consider a 10% discount in the capacity factor to account for potential transmission disruptions and the need to ramp the electrolysis process up and down (Apostolaki-Iosifidou et al., 2019).

6 Alkaline is the dominant and most developed type of electrolyzer in China, which is why we estimated renewable hydrogen production cost based on this system. However, alkaline is less flexible than some other types of electrolyzers for ramping up and down. It is possible that other types of electrolyzers might be adopted in the future, such as proton exchange membrane (PEM) because of its rapid system response and dynamic operation (van Haersma Buma et al., 2023). Using these other types of electrolyzers would lead to higher hydrogen costs than estimated in this study.

Table 3
Data assumptions for modeling hydrogen production costs

Type of electrolyzer	Alkaline
Plant lifetime	30 years
Plant capacity factor	Values in Table 2 multiplied by 90%
Capital cost	¥4,200/kW in 2023 ¥2,450/kW in 2050
Contingency factor to adjust capital cost	1.2x
Electrolyzer efficiency	66% in 2023 78% in 2050
Electrolyzer lifetime	64,000 hours in 2023 100,000 hours in 2050
Fixed operational cost	4% of capital cost
Renewable electricity cost	Estimated values in Table 2
Water cost	¥6.5 per tonne of water
Water consumption	12.5 kg water per kg hydrogen
Discount rate	8%

Sources: Christensen (2020); S. Mao et al. (2021); Wang and Huang (2024); Zhou et al. (2022); Zhang et al. (2023); China Hydrogen Alliance (n.d.)

Renewable hydrogen produced through water electrolysis is in its gaseous form. Therefore, the at-the-pump cost includes the liquefaction cost, liquid hydrogen storage cost, and the bunkering cost for liquid hydrogen. While liquid hydrogen can be pumped to ships in three ways (Georgeff et al., 2020), this study assumes a loading arm system connects storage tanks at the port to the vessels.

We obtained formulas from Argonne National Laboratory's Hydrogen Delivery Scenario Analysis Model (2024) to calculate the capital cost of the liquefier and liquid storage tank, based on their respective capacities, and adjusted for inflation to the 2023 dollar value (Equation 4 and Equation 5). We used these formulas to corroborate the calculated costs with the values provided in other studies and found the numbers matched (IRENA, 2022). Based on the information from previous studies, we assume the capacity limit of a liquefier and a storage tank to be 200 tonnes per day and 3,000 m^3, respectively (Georgeff et al., 2020; Argonne National Laboratory, 2024). This means multiple liquefiers and storage tanks would be needed when hydrogen demand is high. In addition to capital costs, we also considered the cost of electricity needed for liquefaction; we assume the energy input to be 12 kWh per kilogram of hydrogen based on previous studies (U.S. Department of Energy, 2019; IRENA, 2022; Argonne National Laboratory, 2024). We use the same renewable electricity cost in Table 2 for liquefaction. The remaining costs for bunkering liquid hydrogen to ships would include the piping and loading arms, terminal facilities, and a jetty designed for hydrogen specifically, which we estimate from previous studies to be about $425 per kilogram of hydrogen capacity (IRENA, 2022; KBR, 2022). We use the same DCF assumptions in Table 3 to get the levelized unit cost. Given the uncertainties and limited information on liquefiers, storage, and bunkering costs, we do not make projections for their future costs. We do not consider land requirement and land costs in this study. We also do not include fuel taxes in our at-the-pump hydrogen price.

$$CapEx_{liquefaction} = 5600 \times Liquifier\ Capacity^{0.8} \times 1.3 \tag{4}$$

Where:

$CapEx_{liquefaction}$	is the liquefaction capital cost in 2023 U.S. dollars
Liquifier Capacity	is liquefier capacity in kilograms

$$Cost_{storage\ tank} = 48404 \times Tank\ Capacity^{0.5941} \times 2 \tag{5}$$

Where:

$Cost_{storage\ tank}$	is the storage tank cost in 2023 U.S. dollars
Tank Capacity	is tank capacity in cubic meters

RESULTS

ENERGY USE, TECHNOLOGICAL FEASIBILITY, AND FIRST MOVER GSC CANDIDATES

To characterize China's coastal shipping patterns, we define interregional routes as routes connecting two different port clusters. Intraregional routes are defined as routes connecting two ports within the same port cluster. According to the analysis, it is estimated there were 12,250 Chinese vessels performing coastal transport service in China in June 2021. The average transport distance is around 490 nm for interregional routes and 170 nm for intraregional routes. As shown in Table 4, all ships traveled both interregional and intraregional routes. Bulk carriers stood out among the ship types: They were the primary users of interregional routes and also traveled the longest interregional routes. Bulk carriers were more active in northern China (Figure 3). The largest group of ships, identified by the GFW data as "tankers," predominantly travel intraregionally and appeared to be most active in the Yangtze River Delta region (Figure 4).

Table 4

Vessels and route patterns along China's coastline in June 2021

Ship class		Number of ships	Mean gross tonnage	Average voyage length/nm		Number of voyages	
				Interregional	Intraregional	Interregional	Intraregional
Bulk carrier		867	29,200	750	140	4,300	2,280
Container ship		227	18,500	450	230	792	1,780
General cargo ship		312	5,480	450	290	813	1,930
Oil tanker		591	4,570	500	200	2,350	2,330
Chemical tanker		267	3,640	440	220	1,360	2,920
Other[a]	**Tanker**	5,950	556	380	54	890	29,900
	Cargo carrier	4,030	1,460	430	90	2,340	21,500

[a] Ships matched by the Global Fishing Watch database. We could identify only generic ship classes for these vessels; we included those identified as cargo carriers and tankers.

Figure 3
Traffic pattern for interregional bulk carriers along China's coastline in June 2021

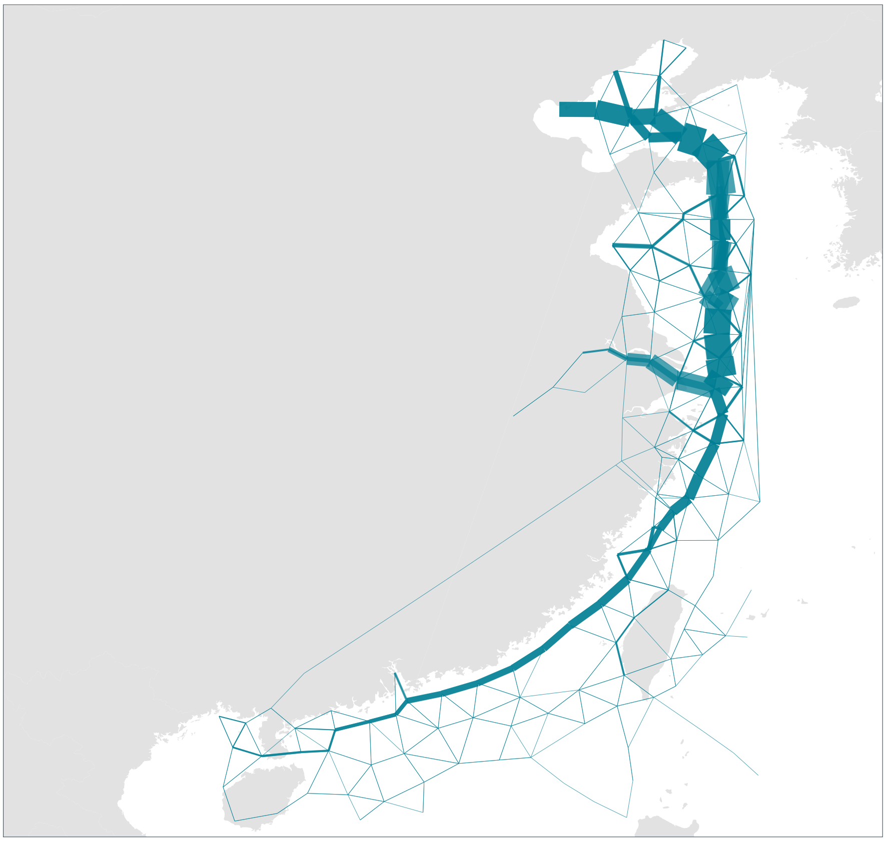
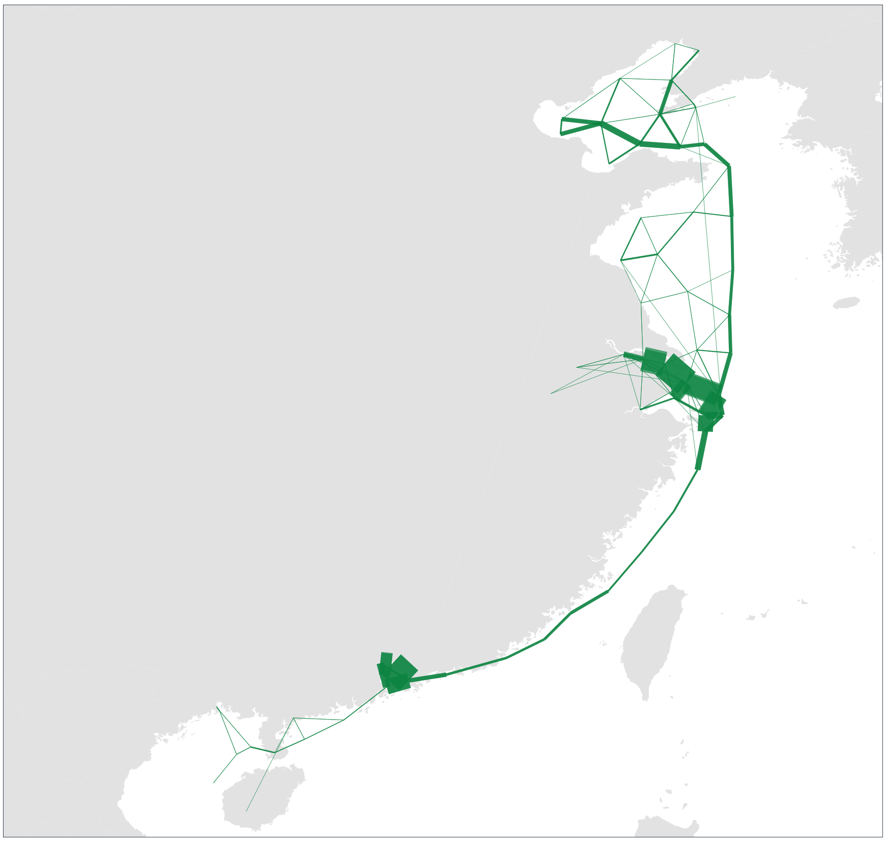


Figure 4
Traffic pattern for "other" tankers along China's coastline in June 2021



After determining energy use at the route level, we ranked the top five routes requiring the most energy for each ship class. We also provided the average number of refuelings needed for the ship classes to complete voyages on these routes if the ships were powered by renewable marine fuel (Table 5). Our findings are listed below:

- Bulk carriers used the highest amount of energy on the Yangtze River Delta–Bo Sea route, consistent with the ship traffic pattern identified above.
- Tankers, as identified by the GFW data, consumed the most energy out of all groups. Nearly half of that energy consumption took place in the Yangtze River Delta region.
- Four of the major ship classes—bulk carriers, container ships, oil tankers, and general cargo ships—consumed more energy on interregional routes than intraregional routes.
- Chemical tankers consumed more energy on intraregional routes.
- The top route by energy use for all classes except container ships involved the Yangtze River Delta region.
- Among the different renewable marine fuel options, the use of methanol or ammonia in an internal combustion engine proved to be feasible for all ship traffic evaluated.
- The use of hydrogen in fuel cells is feasible except for oil tankers, chemical tankers, and other tankers.
- Battery electric technology is the least feasible option as only certain ships on shorter regional routes can use this energy source without recharging.

Table 5

Top five routes for energy use by ship class and refuelings needed for each route

Route	Energy use (GWh)	Number of refuelings needed			
		Methanol-ICE	Ammonia-ICE	Hydrogen-FC	Battery electric
Bulk carrier					
YRD-BS	339	0	0	0	2
PRD-BS	96	0	0	0	3
YRD regional	51	0	0	0	0
BS regional	43	0	0	0	0
YS-BS	16	0	0	0	1
Container ship					
PRD-BS	98	0	0	0	2
YRD regional	19	0	0	0	0
YRD-PRD	17	0	0	0	1
PRD regional	8	0	0	0	2
YS regional	5	0	0	0	0
Oil tanker					
YRD-BS	67	0	0	0	4
YRD regional	67	0	0	0	1
PRD-BS	39	0	0	1	7
PRD regional	37	0	0	0	1
PRD-YRD	13	0	0	0	3
Chemical tanker[a]					
YRD regional	36	0	0	0	2
YRD-BS	25	0	0	1	6
PRD-YRD	7	0	0	1	7
PRD regional	5	0	0	0	1
General cargo ship					
YRD-BS	25	0	0	0	2
PRD-YRD	21	0	0	0	2
BS-Xiamen	11	0	0	0	2
YRD regional	8	0	0	0	0
PRD regional	3	0	0	0	0
Other: Tankers					
YRD regional	583	0	0	0	3
PRD regional	397	0	0	0	3
BS regional	123	0	0	0	3
YRD-BS	49	0	0	1	8
Xiamen regional	31	0	0	1	5
Other: Cargo ships					
YRD regional	100	0	0	0	1
YRD-BS	54	0	0	0	1
PRD regional	32	0	0	0	1
BS regional	27	0	0	0	0
Xiamen regional	7	0	0	0	2

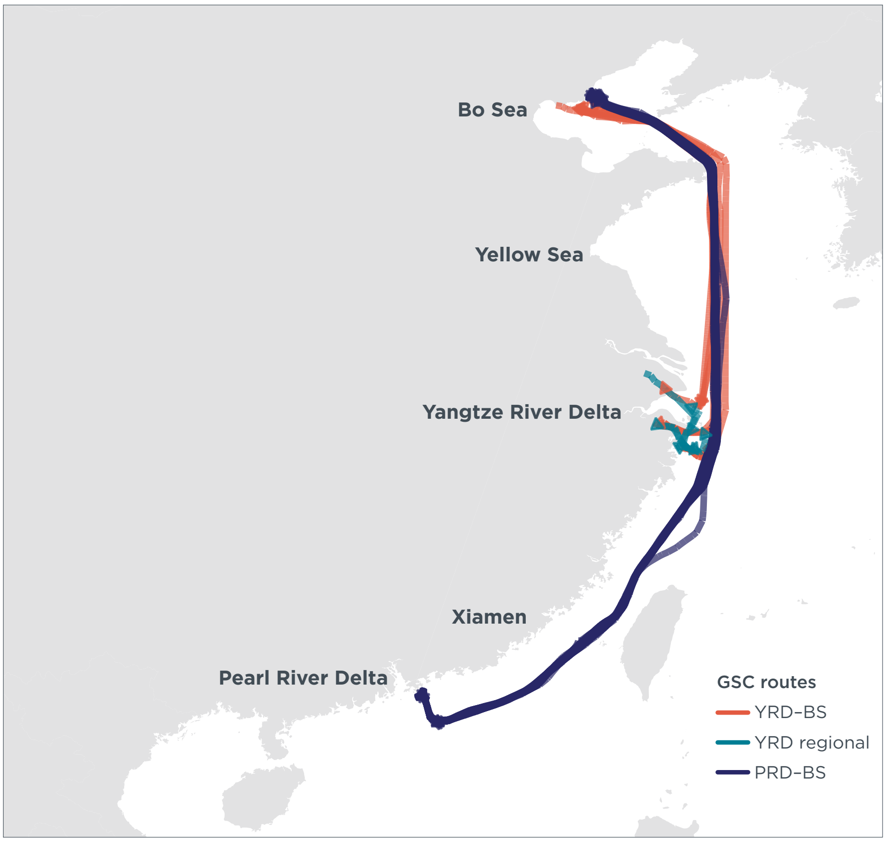
Note: YRD = Yangtze River Delta, BS = Bo Sea, PRD = Pearl River Delta, YS = Yellow Sea
[a] We identified only four major routes for chemical tankers.

Because the top routes for energy use overlapped among the ship classes, we narrowed our selection to three GSC candidates. We then chose one ship per candidate route as a case study to understand how much renewable marine fuel would be needed on an annual basis. Although bulk carriers, general cargo ships, and oil tankers share the same top route (YRD–BS), we chose a bulk carrier for the case study as it is the dominant cargo ship type along China's coast. We selected oil tankers over chemical tankers for the YRD regional route as there are more oil tankers using the route. Finally, we selected container ships for the PRD–BS route. Information about the selected GSC candidates, ship classes, and ship activity are depicted in Table 6 and Figure 5.

Table 6
Hypothetical activity for one zero-emission vessel on each GSC route, based on 2021 activity data

Route characteristics			Ship characteristics			Ship activity	
GSC routes	Typical origin–destination pair	Route length (nm)	Ship class	Gross tonnage	Engine power (kW)	Annual voyages	Energy use per voyage (MWh)
YRD–BS	Tianjin–Shanghai	700	Bulk carrier	31,000	9,960	9	275
PRD–BS	Shenzhen– Tianjin	1,400	Container	23,000	5,190	44	252
YRD regional	Shanghai/Ningbo-Zhoushan	75	Oil tanker	2,952	735	7	29

Figure 5
Traffic patterns for the three hypothetical zero-emission vessels on the GSC routes, based on 2021 activity data



The demand for different renewable marine fuel options by the hypothetically-deployed ZEVs is presented in Table 7. In total, the candidate GSCs could need 901 tonnes of liquid hydrogen, or 6,310 tonnes of ammonia, or 5,890 tonnes of methanol to support the deployment of the first ZEVs, or one ship on each of the three routes. Since we assume all these fuels will be derived from renewable hydrogen, which is generated with renewable electricity, we estimated an implied demand for renewable electricity of about 44~60 GWh by 2030. For context, China has set a 2025 goal for annual production of 100,000–200,000 tonnes of renewable hydrogen and annual generation of 3,300 TWh renewable electricity. Although the estimated demand for ammonia and methanol is more than 6 times in weight that of liquid hydrogen to support the first zero-emission vessels on candidate Chinese coastal GSCs, the corresponding volume suggests a potential problem for hydrogen (Table 7). Liquid hydrogen, although it has a high gravimetric density, requires much more space on a ship due to lower fuel supply system volumetric density compared to ammonia and methanol, making them less preferrable as marine fuel for cargo ships on which every cubic meter is valuable.

Table 7
Annual fuel and electricity demand for the first zero-emission vessels deployed in 2030

Candidate GSC (typical origin-destination)	Fuel demand (tonnes) per ship				Fuel demand (m^3) per ship				Renewable electricity demand[a] (GWh)
	Original fuel	Methanol	Ammonia	Liquid hydrogen	Original fuel	Methanol	Ammonia	Liquid hydrogen	
Tianjin–Shanghai	475	1,000	1,070	153	522	1,260	1,570	3,830	7.4~10
Shenzhen–Tianjin	2,270	4,790	5,130	732	2,490	6,030	7,510	18,300	35~49
Shanghai/ Ningbo-Zhoushan	49	103	111	16	54	130	163	400	0.8~1
Total	**2,790**	**5,890**	**6,310**	**901**	**3,070**	**7,420**	**9,240**	**22,500**	**44~60**

[a] The range reflects the conversion rate of different hydrogen-derived fuels. For methanol, we assumed a conversion efficiency of 79%; for ammonia, we assumed a conversion efficiency of 84%, according to MARAD (2024).

CASE STUDY: COST OF SUPPLYING HYDROGEN FUEL FOR FIRST ZEVS DEPLOYED ON GSC CANDIDATES

The cost of supplying the fuel for the first ZEVs deployed on candidate Chinese coastal GSCs is presented in Table 8 below. The at-the-pump cost is the final cost of renewable hydrogen fueled to the ships, which includes production, liquefaction, storage, and bunkering costs. All numbers are in 2023 monetary values, with U.S. dollars in parentheses.

We estimated the levelized production cost of renewable liquid hydrogen using offshore wind to be ¥34 ($4.80) per kg hydrogen in 2030, and the at-the-pump cost to be ¥53 ($7.60) per kg hydrogen. The cost of liquefaction, storage, and bunkering is roughly ¥15–¥20 ($2.20–$2.80) per kg of hydrogen. This hydrogen production cost estimate is based on a number of unpredictable factors, such as future electroyzer costs, the cost of capital financing, and the cost of renewable electricity (Navarrete & Zhou, 2024). Thus, these costs could be lower or higher than we modeled. Nonetheless, we expect the production cost of renewable hydrogen to decrease in the future; the decreasing cost is a combined effect of decreasing renewable electricity cost, increasing capacity factor, decreasing electrolyzer capital cost, and improvements in electrolyzer efficiency.

Table 8

Levelized production cost and the at-the-pump cost of renewable liquid hydrogen produced through water electrolysis

	Levelized production cost per kilogram	At-the-pump cost per kilogram
2030	¥34 ($4.80)	¥53 ($7.60)
2040	¥27 ($3.80)	¥43 ($6.20)
2050	¥21 ($3.00)	¥36 ($5.20)

Note: Costs are presented in 2023 monetary values.

The total amount needed to pay for supporting the first hypothetically deployed ZEVs annually on GSC candidates by 2030 is estimated at $6.8 million (Table 9). Although we only modeled the cost of renewable hydrogen, the at-the-pump cost for renewable ammonia and renewable methanol that are derived from renewable hydrogen would be similar on an energy basis (< 1.5% lower). This is because while renewable ammonia and methanol have higher fuel production costs than hydrogen due to additional conversion processes, the refueling cost would be significantly lower and can utilize existing infrastructure (MARAD, 2024).

Table 9

At-the-pump cost of supplying annual fuel demand for the first ZEV in 2030

Candidate GSC (typical origin–destination)	Fuel demand (tonnes)				At-the-pump cost of hydrogen (millions)
	Original fuel	Methanol	Ammonia	Hydrogen	
Tianjin–Shanghai	475	1,000	1,070	153	¥8.4 ($1.20)
Shenzhen–Tianjin	2,270	4,790	5,130	732	¥39.2 ($5.60)
Shanghai/ Ningbo–Zhoushan	49	103	111	16	¥0.7 ($0.10)
Total	**2,790**	**5,890**	**6,310**	**901**	**¥47.6 ($6.80)**

Note: Costs are presented in 2023 monetary values.

DISCUSSION

To help stakeholders envision the practicality of rolling out Chinese coastal GSCs, we presented the potential fuel demand for the first ZEVs to be deployed on three candidate routes. If all ships along those routes start using methanol, ammonia, or liquid hydrogen, the potential demand could present a major challenge to sourcing these fuels with zero or near-zero life-cycle GHG emissions (Table 10). For context, the existing largest renewable hydrogen production plant in China can generate around 20,000 tonnes of renewable hydrogen annually (Collins & Xu, 2023). This is 13% of the total 149,000 tonnes of liquid hydrogen that would be required if ships on these routes are powered by hydrogen exclusively. Even more tonnes of renewable hydrogen would be needed if some ships opt to use methanol or ammonia, which would be produced with hydrogen, resulting in energy conversion loss (MARAD, 2024). The Chinese clean energy producer Goldwind, which has signed a deal to supply shipping giant Maersk, initiated a clean methanol project in the Inner Mongolia autonomous region in northern China with an expected annual production of 500,000 tonnes of green methanol using both the electrolysis and biogenic pathways (Yang & Tunagur, 2024). This is only half of the methanol needed to support a full methanol-fueled fleet on proposed Chinese coastal GSC candidates.

Table 10

Projected demand for renewable marine fuel on candidate GSCs under the full deployment scenario

Candidate GSC	Ship class	Number of ships	Fuel demand (tonnes)		
			Methanol	Ammonia	Liquid hydrogen
YRD–BS	Bulk carrier	526	418,000	443,000	64,000
PRD–BS	Container ship	60	85,000	90,000	13,000
YRD regional	Tankers	1,700	471,000	498,000	72,000
Total		**2,230**	**974,000**	**1,031,000**	**149,000**

We did not include battery electric technology when estimating projected fuel demand because of its low feasibility compared with liquid hydrogen, ammonia, and methanol (Table 5). However, the use of battery electric ships is preferable because batteries are more efficient at converting electricity to energy. All other fuel options considered in this analysis are produced using renewable electricity, which can result in energy loss during the conversion process. In this study, we found that battery electric technology is feasible for certain ships on regional routes. Combining findings from a previous ICCT study (X. Mao, Georgeff, Rutherford, & Osipova, 2021), we can argue that battery electric technology is highly feasible for small ships deployed on short routes. Feasibility for medium-sized ships is constrained by route distance, and large ships would require advanced battery technology.

For the reasons stated above and in the detailed in the methodology section, our hydrogen cost estimate should be viewed with caution. First, we assumed that the hydrogen needed to support the first ZEV deployments will be produced in electrolysis plants located within ports. We also assumed that the renewable electricity required to electrolyze water will be generated within the same ports, presumably from offshore wind farms. This might be a practical solution for decarbonizing a single ship. If more zero-emission ships are deployed on these routes, the ports might not be able to supply all fuel needs as estimated in Table 10. Specifically, to supply 149,000 tonnes of liquid hydrogen each year, the corresponding electrolysis capacity would be as high as 2.7 GW, while the cumulative installed capacity in all of China was only 1 GW in 2023 (Le & Selvaraju, 2024). Furthermore, given that the typical capacity of an alkaline electrolyzer in China is about 5 MW (Zhong, 2023), it would require more than 540 electrolyzers to fulfill the total liquid hydrogen demand at the three port clusters in Table 10. Alternatively, the expanded demand for renewable marine fuel can be sourced from outside of the ports, potentially in a centralized location where green hydrogen can be produced on a large scale with relatively cheaper renewable electricity. However, the required amount of installed capacity and land required for generating renewable electricity inland can be a barrier. The fuels would also need to be transported to the ports and bunkered into the ships. The feasibility and cost of transporting a large amount of hydrogen needs to be further studied.

As an initial screening study, this paper discussed little about how and when to prioritize different renewable marine fuel options and the practical fuel production pathways for the candidate GCSs. Due to different levels of technology maturity, feedstock availability, costs, and risks, fuel selection would need to be addressed in a technology roadmap analysis, which could be done in a follow-up study. Even if a specific fuel type stands out, various production pathways could result in vastly different life-cycle GHG intensity values as well as cost. Unfortunately, the pathways with better climate performance are usually the more expensive ones. A recent ICCT publication identifies bio-methanol made from gasifying miscanthus or corn stover as the best in terms of overall performance as future marine fuel in the Great Lakes region in the United States (MARAD, 2024). However, the availability of waste biomass feedstocks for biofuel production in China is very limited (Foreign Agricultural Service, 2023).

Finally, there's no policy in place or in the planning stages to ensure the sustainability of renewable marine fuel produced in China. We only considered the scenario of producing renewable hydrogen through a direct connection to renewable electricity. Theoretically, electrolysis hydrogen could also receive electricity from the grid. However, ensuring that grid-produced hydrogen is purely zero emission would require stringent regulations on the certification of renewable electricity combined with a robust renewable purchasing framework, such as power purchase agreements (Malins, 2019). Both the European Union and the United States have released or proposed rules on regulating electricity for renewable hydrogen production (Ding et al., 2024; Commission Delegated Regulation (EU) 2023/1184, 2023). Similar rules are currently lacking in China. While using grid electricity could allow electrolyzers to run at a higher capacity factor when compared with wind-produced electricity, the hydrogen producer would also pay more for grid electricity. Depending on the life-cycle GHG intensity of the renewable source and how expensive the grid fee is in a given region, the cost of a direct connection can be cheaper or more expensive than a grid connection (Zhou et al., 2022). The European Union's Emission Trading System and its FuelEU Maritime initiative are policy designs that could help close the price gap between renewable and fossil fuels (Wärtsilä , 2024). China could consider expanding its existing emission trading system program to include marine fuel producers as well as shipbuilders. China could also consider regulations to reduce the life-cycle GHG intensity of marine fuels as soon as possible.

CONCLUSION

With the growing interest in GSC initiatives globally, we looked at how this concept could be applied in China on domestic shipping routes. This study identified first mover GSC candidates for China's coastal shipping based on route-level energy consumption and the technological feasibility of using renewable marine fuel to supply that demand. The three GSC candidates included two interregional routes, Yangtze River Delta–Bo Sea (Shanghai-Tianjin) and Pearl River Delta–Bo Sea (Shenzhen-Tianjin), and one intraregional route in the Yangtze River Delta region (Shanghai/Ningbo-Zhoushan). These regions are home to some of the world's largest ports and are strategically positioned to commit to GSC initiatives. The port of Tianjin in the Bo Sea region has built the first zero-emission terminal in China. The terminal is fully automated, with all operations powered by clean electricity generated from an on-site onshore wind farm and solar farm. The port of Shanghai, located in the Yangtze River Delta region, has just completed its first ship-to-ship renewable methanol bunkering in April 2024. In the Pearl River Delta region, the Hong Kong government unveiled an action plan in December 2023 to build its port into a bunkering hub for "green methanol" and other "clean fuel." Ships on GSCs are potential buyers of these clean fuels and electricity.

We then estimated the potential demand for renewable marine fuel when the first ZEV is deployed on each of the three GSCs. In total, stakeholders would need to source about 900 tonnes of renewable liquid hydrogen, or an equivalent 6,000 tonnes of renewable methanol or renewable ammonia, which implies a demand for 44~60 GWh of renewable electricity. China has set a goal to produce 100,000–200,000 tonnes of renewable hydrogen and 3,300 TWh of renewable electricity annually by 2025. Only a very small share of these volumes would be needed to support the first ZEVs on the proposed GSCs.

Finally, we provided a case study to understand the cost of supplying the renewable marine fuel required to hypothetically deploy the first ZEVs on these GSCs. The at-the-pump cost of renewable liquid hydrogen produced on-site at the GSC ports could be $7.60/kg by 2030. This estimate is more than 3 times higher than the current cost of VLSFO on an energy-equivalent basis.[7] Deploying the first three ZEVs on the proposed GSCs by 2030 would require paying about $7 million for fuel annually. As technology costs decrease and production efficiency increases over time, our cost estimate for renewable hydrogen could drop to about $5.20/kg by 2050, a reduction of approximately 32%. Depending on other factors—such as the cost of electrolyzers, the cost of financing electrolysis, and the cost of renewable electricity—fuel costs could be lower or higher in 2030 and beyond. Without proper policy intervention, the GSCs most likely would be difficult to implement to a larger scale.

To summarize, it is technologically feasible to power ships on renewable fuel, including methanol, ammonia and hydrogen, on the first mover GSC candidates we selected for China's coastal shipping. Battery electric technology is feasible for certain ships on regional routes. As key stakeholders in GSC initiatives, ports are strategically positioned to supply the needed renewable marine fuel. Fuel demand for renewable methanol, renewable ammonia and renewable hydrogen for the first ZEVs on these routes implies a need for approximately 44~60 GWh of renewable electricity in China by 2030, which is only a fraction of planned installed capacity of renewable electricity in China by that time. A major challenge is the cost, as making and supplying renewable marine fuel is expected to remain expensive within the next 5 years. Although not evaluated as part of this study, building or retrofitting ships to run on these fuels also would be more expensive than constructing ships with conventional designs (Meng &

7 According to Ship & Bunker, recent VLSFO price in Hong Kong was $611/mt, which can be converted to approximately $0.015/MJ. Source: https://shipandbunker.com/prices#VLSFO.

Rutherford, 2024). Stakeholders willing to share the costs and associated risks could launch the first ZEVs on these green shipping corridors. However, policy interventions could be considered to speed the deployment of more ships on GSCs and to deliver a meaningful reduction in greenhouse gases.

REFERENCES

Apostolaki-Iosifidou, E., Mccormack, R., Kempton, W., Mccoy, P., & Ozkan, D. (2019). Transmission design and analysis for large-scale offshore wind energy development. *IEEE Power and Energy Technology Systems Journal*, *6*(1), 22–31. https://doi.org/10.1109/JPETS.2019.2898688

Argonne National Laboratory. (n.d.). *Hydrogen delivery scenario analysis model (HDSAM)* (V4.5) [Computer software]. Retrieved February 14, 2024, https://hdsam.es.anl.gov/index.php?content=hdsam

Boyland, J., Talalasova, E., & Rosenberg, A. (2023). *Annual progress report on green shipping corridors 2023*. Global Maritime Forum. https://cms.globalmaritimeforum.org/wp-content/uploads/2023/11/Global-Maritime-Forum_Annual-Progress-Report-on-Green-Shipping-Corridors_2023.pdf

China Electricity Council. (2020). 海上风电发展 [Development of offshore wind]. https://www.cec.org.cn/upload/1/pdf/1609832927904.pdf

China Hydrogen Alliance. (n.d.). *Big data platform for hydrogen industry* [Database]. Retrieved May 18, 2022, from https://www.chinah2data.com/#/client/database/StandardBaseList

Christensen, A. (2020). *Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe*. International Council on Clean Transportation. https://theicct.org/publication/assessment-of-hydrogen-production-costs-from-electrolysis-united-states-and-europe/

Collins, L., & Xu, Y. (2023, May 26). World's largest green hydrogen project—China's 260MW Kuqa facility—to be commissioned at the end of May. *Hydrogen Insight.* https://www.hydrogeninsight.com/production/world-s-largest-green-hydrogen-project-chinas-260mw-kuqa-facility-to-be-commissioned-at-the-end-of-may/2-1-1457242

Comer, B. (2019). *Transitioning away from heavy fuel oil in Arctic shipping*. International Council on Clean Transportation. https://theicct.org/publication/transitioning-away-from-heavy-fuel-oil-in-arctic-shipping/

Commission Delegated Regulation (EU) 2023/1184 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin, OJ L 157, 11–19 (2023). http://data.europa.eu/eli/reg_del/2023/1184/oj

de Vries, N. (2019). *Safe and effective application of ammonia as a marine fuel*. [Master's thesis, Delft University of Technology]. TU Delft Repository. http://resolver.tudelft.nl/uuid:be8cbe0a-28ec-4bd9-8ad0-648de04649b8

Ding, Y., Baldino, C., & Zhou, Y. (2024). *Understanding the proposed guidance for the Inflation Reduction Act's Section 45V Clean Hydrogen Production Tax Credit*. International Council on Clean Transportation. https://theicct.org/publication/proposed-guidance-for-the-inflation-reduction-act-45v-clean-hydrogen-tax-credit-mar29/

Faber, J., Hanayama, S., Zhang, S., Pereda, P., Comer, B., Hauerhof, E., Schim van der Loeff, W., Smith, T., Zhang, Y., Kosaka, H., Adachi, M., Bonello, J.-M., Galbraith, C., Gong, Z., Hirata, K., Hummels, D., Kleijn, A., Lee, D., Liu, Y., … Yuan, H. (2020). *Fourth IMO greenhouse gas study.* International Maritime Organization. https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

Frontier Economics, UMAS, E4tech, & CE Delft. (2019). *Reducing the maritime sector's contribution to climate change and air pollution: Identification of market failures and other barriers to the commercial deployment of emission reduction options* [Report for the UK Department for Transport]. https://assets.publishing.service.gov.uk/media/5d24aaf7e5274a2f9d175695/identification-market-failures-other-barriers-of-commercial-deployment-of-emission-reduction-options.pdf

Foreign Agricultural Service. (2023). *Biofuels Annual—People's Republic of China.* U.S. Department of Agriculture. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels%20Annual_Beijing_China%20-%20People%27s%20Republic%20of_CH2023-0109

Georgeff, E., Mao, X., Rutherford, D., & Osipova, L. (2020). *Liquid hydrogen refueling infrastructure to support a zero-emission U.S.–China container shipping corridor.* International Council on Clean Transportation. https://theicct.org/publication/liquid-hydrogen-refueling-infrastructure-to-support-a-zero-emission-u-s-china-container-shipping-corridor/

Getting to Zero Coalition. (2021). *The next wave: Green corridors*. Getting to Zero Coalition. https://globalmaritimeforum.org/report/the-next-wave-green-corridors/

Guo, X., Chen, X., Chen, X., Sherman, P., Wen, J., & McElroy, M. (2023). Grid integration feasibility and investment planning of offshore wind power under carbon-neutral transition in China. *Nature Communications*, *14*(1), 2447. https://doi.org/10.1038/s41467-023-37536-3

Huang, B., Zhang, Y., & Wang, C. (2020). 中国"十四五"新能源发展研判及需要关注的问题 [Research and issues on new energy development in China's "14th Five-Year Plan"]. *Electric Power*, *53*(1). http://www.csee.org.cn/pic/u/cms/www/202004/10185609ydzx.pdf

Institute for Climate Change and Sustainable Development at Tsinghua University et al. (2021). *China's long-term low-carbon development strategies and pathways Comprehensive Report*. Springer; China Environment Publishing Group. https://doi.org/10.1007/978-981-16-2524-4

International Energy Agency & Nuclear Energy Agency. (2020). *Projected costs of generating electricity 2020*. International Energy Agency. https://www.iea.org/reports/projected-costs-of-generating-electricity-2020

International Renewable Energy Agency. (2022). *Global hydrogen trade to meet the 1.5 °C climate goal: Part II—Technology review of hydrogen carriers.* https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Apr/IRENA_Global_Trade_Hydrogen_2022.pdf

International Renewable Energy Agency. (2023). *Renewable power generation costs in 2022*. https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022

Jin, C. (2022). 海上风电项目全寿命周期的成本构成及其敏感性分析 [Cost composition and sensitivity analysis of whole life cycle of offshore wind power projects]. *Solar Energy* (03),10-16. https://www.desn.com.cn/news/show-1489692.html

KBR. (2022). *Landed cost of hydrogen carriers*. Clean Air Task Force. https://cdn.catf.us/wp-content/uploads/2023/05/23054736/catf-kbr-landed-cost-hydrogen-carriers.pdf

Koty, A. C. (2021, May 6). *China's carbon neutrality pledge: Opportunities for foreign investment*. Dezan Shira & Associates. https://www.china-briefing.com/news/chinas-carbon-neutrality-pledge-new-opportunities-for-foreign-investment-in-renewable-energy/

Le, M. K., & Selvaraju, K. (2024, June 4). *China set to smash national hydrogen targets, solidifying lead in global electrolyzer market* [Press release]. Rystad Energy. https://www.rystadenergy.com/news/china-hydrogen-targets

Li, M., Virguez, E., Shan, R., Tian, J., Gao, S., & Patiño-Echeverri, D. (2022). High-resolution data shows China's wind and solar energy resources are enough to support a 2050 decarbonized electricity system. *Applied Energy*, *306*(Part A), 117996. https://doi.org/10.1016/j.apenergy.2021.117996

Maersk Mc-Kinney Møller Center for Zero Carbon Shipping. (2022a). *Green corridors: Feasibility phase blueprint*. https://cms.zerocarbonshipping.com/media/uploads/documents/220929_Green-Corridors_Feasibility-Blueprint.pdf

Maersk Mc-Kinney Moller Center for Zero Carbon Shipping, Port of Rotterdam, Port of Hamburg, Port of Gdynia, Port of Tallinn, & Port of Roenne. (2022b). *Northern European and Baltic green corridor prefeasibility study*. Maersk Mc-Kinney Moller Center for Zero Carbon Shipping. https://cms.zerocarbonshipping.com/media/uploads/publications/Northern-European-Baltic-Green-Corridor-Prefeasibility-Study.pdf

Malins, C. (2019). *What does it mean to be a renewable electron?* International Council on Clean Transportation. https://theicct.org/publication/what-does-it-mean-to-be-a-renewable-electron/

Mao, S., Basma, H., Ragon, P.-L., Zhou, Y., & Rodríguez, F. (2021). *Total cost of ownership for heavy trucks in China: Battery electric, fuel cell, and diesel trucks*. International Council on Clean Transportation. https://theicct.org/publication/total-cost-of-ownership-for-heavy-trucks-in-china-battery-electric-fuel-cell-and-diesel-trucks/

Mao, X. (2023). *Potential pathways for decarbonizing China's inland waterway shipping*. International Council on Clean Transportation. https://theicct.org/publication/marine-china-inland-shipping-fs-feb23/

Mao, X., Georgeff, E., Rutherford, D., & Osipova, L. (2021). *Repowering Chinese coastal ferries with battery-electric technology*. International Council on Clean Transportation. https://theicct.org/publication/repowering-chinese-coastal-ferries-with-battery-electric-technology/

Mao, X., & Meng, Z. (2022). *Decarbonizing China's coastal shipping: The role of fuel efficiency and low-carbon fuels*. International Council on Clean Transportation. https://theicct.org/publication/china-marine-decarbonizing-chinas-coastal-shipping-role-of-fuel-efficiency-and-low-carbon-fuels-factsheet-en-jun22/

Mao, X., & Rutherford, D. (2018). *Delineating a Chinese emission control area: The potential impact of ship rerouting on emissions*. nternational Council on Clean Transportation. https://theicct.org/publication/delineating-a-chinese-emission-control-area-the-potential-impact-of-ship-rerouting-on-emissions/

Mao, X., Rutherford, D., Osipova, L., & Comer, B. (2020). *Refueling assessment of a zero-emission container corridor between China and the United States: Could hydrogen replace fossil fuels?* International Council on Clean Transportation. https://theicct.org/publication/refueling-assessment-of-a-zero-emission-container-corridor-between-china-and-the-united-states-could-hydrogen-replace-fossil-fuels/

Mao, X., Rutherford, D., Osipova, L., & Georgeff, E. (2022). *Exporting emissions: Marine fuel sales at the Port of Singapore*. International Council on Clean Transportation. https://theicct.org/publication/marine-singapore-fuel-emissions-jul22/

Meng, Z., & Rutherford, D. (2024). *Financing zero-emission vessel shipbuilding in China*. International Council on Clean Transportation. https://theicct.org/publication/financing-zero-emission-vessel-shipbuilding-china-feb24/

Ministry of Transport of the People's Republic of China. (2023a, January 6). 2022年交通运输行业发展统计公报 [Communique of China's transport industry development statistics in 2022]. https://xxgk.mot.gov.cn/2020/jigou/zhghs/202306/t20230615_3847023.html

Ministry of Transport of People's Republic of China. (2023b, July 31). 交通运输部在节能降碳、推进交通运输生态环境保护工作方面的主要措施 [Recent actions to reduce energy consumption and carbon intensity, as well as environmental protection of the transport sector] [Press conference summary]. https://www.mot.gov.cn/2023wangshangzhibo/2023seventh/zhibozhaiyao/202307/t20230731_3877775.html

Navarrete, A., & Zhou, Y. (2024, May 20). The price of green hydrogen: How and why we estimate future production costs. *International Council on Clean Transportation Staff Blog*. https://theicct.org/the-price-of-green-hydrogen-estimate-future-production-costs-may24/

National Renewable Energy Laboratory. (2020). *2020 Transportation Annual Technology Baseline.* https://atb.nrel.gov/transportation/2020/about

Olmer, N., Comer, B., Roy, B., Mao, X., & Rutherford, D. (2017). *Greenhouse gas emissions from global shipping, 2013–2015: Detailed methodology*. International Council on Clean Transportation. https://theicct.org/publications/GHG-emissions-global-shipping-2013-2015

Sherman, P., Chen, X., & McElroy, M. (2020). Offshore wind: An opportunity for cost-competitive decarbonization of China's energy economy. *Science Advances*, *6*(8), eaax9571. https://doi.org/10.1126/sciadv.aax9571

Slotvik, D. A., Endresen, Ø., Eide, M., Skåre, O. G., & Hustad, H. (2022). *Insight on green shipping corridors: From policy ambitions to realization* (Nordic Roadmap Publication No. 3-A/1/2022). Nordic Council of Ministers. https://futurefuelsnordic.com/insight-on-green-shipping-corridors/

U.S. Department of Energy. (2019). *Current status of hydrogen liquefaction costs*. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/19001_hydrogen_liquefaction_costs.pdf?Status=Master

U.S. Maritime Administration. (2024). *Feasibility study of future energy options for Great Lakes shipping.* Prepared for MARAD by the International Council on Clean Transportation. https://theicct.org/publication/feasibility-study-of-future-energy-options-for-great-lakes-shipping-march24/

van Haersma Buma, B. N. D., Peretto, M., Matar, Z. M., & van de Kaa, G. (2023). Towards renewable hydrogen-based electrolysis: Alkaline vs proton exchange membrane. *Heliyon*, *9*(7), e17999. https://doi.org/10.1016/j.heliyon.2023.e17999

Wang, J., & Huang, J. (2024, March 25). 淡化海水，如何用得起用得好? [How to afford and better utilize desalinated sea water?]. *Xinhua Daily Telegraph*. http://www.news.cn/mrdx/2024-03/25/c_1310768861.htm

Wärtsilä. (2024). *Sustainable fuels for shipping by 2050: The 3 key elements of success.* https://www.wartsila.com/insights/whitepaper/sustainable-fuels-for-shipping-by-2050-industry-report

Yang, C., & Tunagur, E. (2024, April 19). China looks to lead low-carbon methanol production. *Lloyd's List Intelligence.* https://www.lloydslist.com/LL1148919/China-looks-to-lead-low-carbon-methanol-production

Zhang, W., Li, X., Yang, J., Liu, J., & Xu, C. (2023). Economic analysis of hydrogen production from China's province-level power grid considering carbon emissions. *Clean Energy*, *7*(1), 30–40. https://doi.org/10.1093/ce/zkac091

Zhong, R. (2023, October 16). 电解槽向"大型化"迈进 [Electrolyzers are moving toward "large scale"]. *China Energy News.* http://paper.people.com.cn/zgnyb/html/2023-10/16/content_26022924.htm

Zhou, Y., & Searle, S. (2022). *Cost of renewable hydrogen produced onsite at hydrogen refueling stations in Europe*. International Council on Clean Transportation. https://theicct.org/publication/fuels-eu-onsite-hydro-cost-feb22/

Zhou, Y., Searle, S., & Pavlenko, N. (2022). *Current and future cost of e-kerosene in the United States and Europe*. International Council on Clean Transportation. https://theicct.org/publication/fuels-us-eu-cost-ekerosene-mar22/

www.theicct.org

communications@theicct.org

@theicct.org

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION