BRIEFING

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Roadmap to a zero-emission port: A case study in Port of Yangpu

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INTRODUCTION

Ports are hubs of international trade, where ships, cargo handling equipment, trucks, and locomotives work around the clock to move cargo to their final destinations. With all these activities consuming energy, ports are also emission hot spots, causing public health concerns for nearby communities. Therefore, ports are ideal targets for emission reduction efforts and low- and zero-emission zone pilot programs. For example, the San Pedro Bay ports complex set greenhouse gas (GHG) reduction targets, compared to 1990 levels, of 40% by 2030 and 80% by 2050 (Ports of Los Angeles and Long Beach, 2017). The Port of Oslo has made similar pledges, with a specific goal of cutting GHG emissions 85% below 2017 levels by 2030 and completely decarbonizing over the long term (Port of Oslo, n.d.).

China is home to seven out of the 10 world-leading container ports by twenty-foot equivalent unit (TEU) which are also noted for their operational performance (United Nations Conference on Trade and Development, 2021; The World Bank, 2022). Although none of these ports in China have announced climate ambition and environmental performance goals similar to those of the San Pedro Bay ports or the Port of Oslo, many have taken initial steps toward decarbonization (China Waterborne Transport Research Institute, 2020). While decarbonization measures may need to be integrated incrementally into the development plans of a larger established port, they could happen quickly in fast-developing ports, like ports in Hainan. After being designated a Hainan Free Trade Port in 2020,[1] the Port of Yangpu foresees a dramatic increase in ship traffic in the coming years (Poon, 2022). Ahead of this expected increase, there is an opportunity for the Port of Yangpu to develop a strategy to decarbonize its operations.

In this briefing, we design technological roadmaps for the Port of Yangpu to decarbonize by 2050. We define "decarbonization" as zero well-to-wake (WTW) carbon dioxide equivalent (CO_2e) emissions, consistent with criteria set by the Race-to-Zero campaign under the United Nations Climate Change Conference (Race to

1 The Free Trade Port is a package of policy incentives that make it easier for foreign investors to do business. Among the over 180 incentives rolled out, there are three "zero tariff" lists, and 15% income tax incentives for corporations and individuals. Details can be found on their official website at hnftp.gov.cn.

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Zero Expert Peer Review Group, 2022). GHG emissions are quantified as CO_2e using 100-year global warming potential (CO_2e100) and 20-year global warming potential as a comparison (CO_2e20).

METHODS

To develop the technological roadmaps for the Port of Yang to decarbonize by 2050, we first quantify its existing emissions to serve as the baseline, project future emissions under a business-as-usual scenario, and then project emissions under scenarios that prioritize implementation of different decarbonization technologies at varying paces. To perform all the above, we refer to several previous ICCT studies:

» We quantified a port emissions inventory for Port of Yangpu for the year 2019 using the global online Port Emissions Inventory Tool (Mao & Meng, 2023).[2] We converted the inventory results into CO_2e emissions based on the 100-year and 20-year global warming potentials for carbon dioxide (1 for both GWP100 and GWP20), methane (29.8 for GWP100 and 82.5 for GWP20), and nitrous oxide (273 for both GWP100 and GWP20) from the Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC, 2022). We use these values as the emissions baseline.

» We reviewed technological readiness, GHG emissions reduction potential, and cost perspectives of port equipment decarbonization measures as reported in a forthcoming ICCT paper by Meng, Sturrup, and Zhang. This informed the parameters and assumptions that were used to construct different roadmap scenarios.

» We referred to existing ICCT studies on the WTW CO_2e emissions reduction potential of decarbonization technologies and fuel options, which are detailed in Table 1.

Table 1. Assumptions for well-to-wake CO_2e emission reduction potentials of different decarbonization technologies

Emissions source group	Decarbonization technology	WTW CO_2e emissions reduction potential	
		CO_2e100	CO_2e20
Vessels	Shore power	Equal to grid mix percentage of renewably sourced electricity (see Table 2 for assumptions)	
	Zero-emission fuel[a]	81.5%-100%[b]	
	Liquefied natural gas[c]	7.4%[d]	-11.3%[d]
Cargo handling equipment	Electrification	Equal to grid mix percentage of renewably sourced electricity (see Table 2 for assumptions)	
	Liquefied natural gas	9%[e]	-12.8%[e]
On-road vehicles	Electrification	Equal to grid mix percentage of renewably sourced electricity (see Table 2 for assumptions)	
	Liquefied natural gas	9%[e]	-12.8%[e]
	Hydrogen fuel cell	81.5%-100%	

[a] A mixture of different alternative marine fuels (Kjeld Aabo, 2022). For simplicity, we assume that the "zero-emission" definition for all fuels regardless of fuel type is the equivalent CO_2e100 intensity of green hydrogen produced with renewable electricity.

[b] We assume baseline well-to-wake CO_2e100 emissions factors for current marine fuels as 91.7 g/MJ (Comer, O'Malley, Osipova, & Pavlenko, 2022), and that for hydrogen produced from renewable electricity and used in fuel cells as 17 g/MJ (Zhou, Zhang, & Li, 2022), so a reduction of 81.5% by 2030. By 2050 this reduction would reach 100% as the entire fuel production process uses renewable electricity.

[c] Liquefied natural gas refers to fossil-based types only.

[d] Based on Comer & Osipova (2021) and Comer et al. (2022) and assuming the best-performing liquified natural gas engines on the market today with the lowest methane slip for 2-stroke engines.

[e] Based on Mottschall, Kasten, and Rodríguez (2020), assuming the low methane-emitting engines (high-pressure direct injection natural gas engines). We also assume cargo handling equipment uses engines with similar WTW CO_2e emission factors.

2 The global online Port Emissions Inventory Tool (goPEIT) is available at gopeit.org. Access is granted upon request.

The emissions projection is a simple multiplication of baseline emissions with two types of impact factors: growth factors and control factors, which drive the change of emissions in different directions. In the following sections, we introduce the assumptions for these factors in different scenarios, discuss the results, and conclude with recommendations for Port of Yangpu.

SCENARIOS

We designed four scenarios, representing four different technological roadmaps for the Port of Yangpu. In this section, we first introduce cargo throughput growth assumptions that apply to all scenarios, and then discuss decarbonization technology penetration assumptions pertaining to each different scenario. A summary of all assumptions is listed in Table 2.

In 2019, ships, cargo handling equipment, and on-road vehicles in Port of Yangpu emitted a total of 62 thousand tonnes of CO_2e100 within the port boundary while moving 50 million tonnes of cargo (Mao & Meng, 2023). Because of the COVID pandemic, 2020 may have been an atypical year for shipping. As a result, we use the 2019 inventory for our 2020 baseline emissions projection. Although the port is determined to increase its cargo throughput after being designated a Hainan Free Trade Port, it is unlikely to maintain a high growth rate forever. To estimate growth, we use a logistic curve of historical cargo throughout development in Port of Shanghai, the largest port in China (China Ports Association, 2021), as we expect Port of Yangpu to grow similarly.[3] The projection of cargo throughput growth rate, illustrated in Figure 1, is the only growth factor considered and is a set assumption across all scenarios, as we do not expect any decarbonization actions to alter the port's economic development plan.

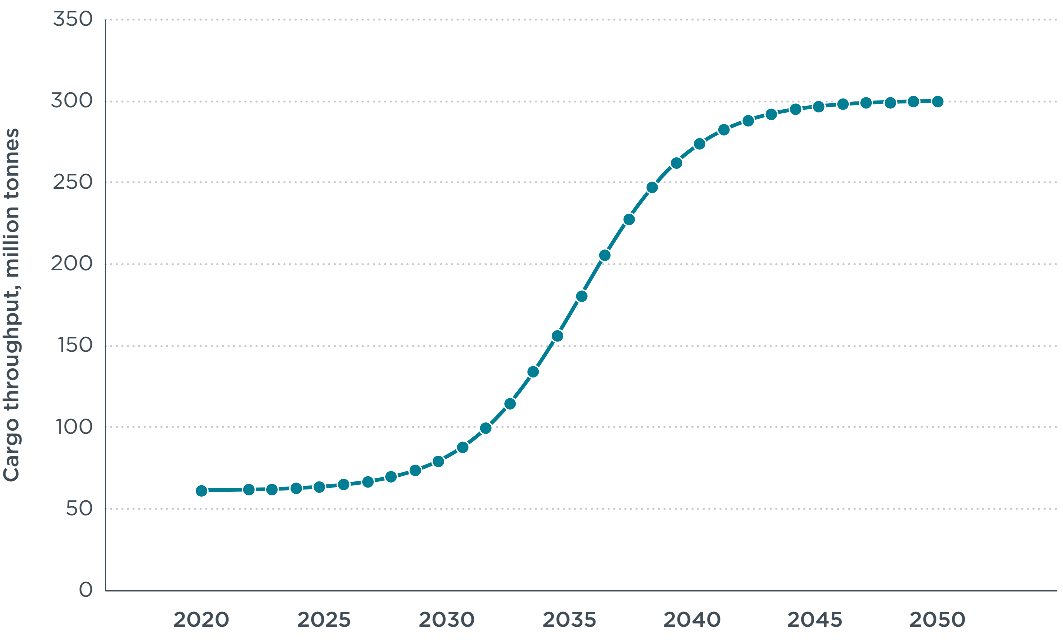

Figure 1. Cargo throughput projection of Port of Yangpu, 2020-2050

3 Historical cargo throughput data is collected from the China Ports Yearbook for multiple years (1990-2020). An S-curve is fitted to the data with the formula y=4.23/(1+EXP(-0.415*(x-2005)))+1.08, where x denotes year, and y denotes the ratio between cargo throughput of year x and starting year 1990. A similar formula is then applied to cargo throughput of Port of Yangpu with the starting year as 2020 and ending year as 2050. The specific formula is y=4.23/(1+EXP(-0.415*(x-2035)))+1.08.

Announced Ambitions scenario

By the end of 2019, Hainan had equipped 16 roll-on/roll-off passenger (ro-pax) ferry terminals with shore power, which used a little over 2 million kWh of electricity that same year (Water Transport Bureau of China's Ministry of Transport, 2020). According to the emissions inventory for the Port of Yangpu (Mao & Meng, 2023), this was just 7% of total at-berth vessel energy use in 2019. Because Hainan is included as a Domestic Emission Control Area, which will mandate shore power connections for certain China-flagged ships in the coming years, we anticipate the adoption of shore power to grow steadily. The 2019 emissions inventory for the Port of Yangpu showed that nearly all port equipment used fossil fuel (Mao & Meng, 2023). The Hainan Carbon Peaking Action Plan promotes the use of electricity in energy end-use sectors in ports, as well as new energy sources, including liquified natural gas (LNG) and hydrogen (Hainan Provincial People's Government, 2022). As a result, we assume a mildly increasing trend of penetration for LNG and hydrogen adoption in all three emission source groups under the Announced Ambitions (AA) scenario. China has set New Energy Vehicle targets for heavy-duty vehicles (12% by 2025, 17% by 2030, and 20% by 2035), which we use as AA assumptions and linearly inflate that rate by 5% every 5 years. The future of marine fuels is uncertain, and we anticipate a mix of zero-emission fuel options for different vessel segments.[4] For this study, we referred to a fuel mix forecast for a two-stroke fleet from IHS Markit and used it as our AA scenario assumption (Ports of Los Angeles and Long Beach, 2017),[5] as we anticipate most vessels visiting the Port of Yangpu by 2050 would be ocean-going vessels. Assumptions for the AA scenario are as follows:

- By 2050, vessels' at-berth energy consumption is fully replaced with either electricity (70%) or zero-emission fuels (30%).
- By 2050, 60% of cargo handling equipment's energy consumption is replaced with either electricity (30%) or LNG (30%).
- By 2050, 60% of on-road vehicles' current energy consumption of diesel fuel is replaced with either electricity (35%), hydrogen (20%), or LNG (5%).
- The rate of electrification of on-road vehicles is faster than that of cargo handling equipment.
- LNG plays a growing but moderate role for vessels and cargo handling equipment, and a limited role for on-road vehicles.

The final control factor relates to WTW CO_2e emissions of electricity to be used in Port of Yangpu to fit our definition of a zero-emission port. We projected the percentage of renewably sourced electricity to be used in Hainan between 2020 and 2050. As of now, the percentage of renewably sourced electricity in Hainan's grid mix is at the national average level of 32% (China Electricity Council, 2022). Using this as the starting point, we assume the grid mix percentage of renewably sourced electricity to gradually increase to 90% by 2050 (Institute for Climate Change and Sustainable Development at Tsinghua University, 2021).[6]

4 The "zero-emission fuel" definition, found under Table 1, note a, is the equivalent CO_2e100 intensity of green hydrogen produced with renewable electricity.

5 In the MAN-ES fuel mix forecast, by 2050 around 60% of fuel supply would come from LNG, LPG, ethane, methanol, and ammonia, with both carbon-neutral and fossil-based options. We assume that approximately 50% of those could qualify as delivering zero life-cycle GHG emissions.

6 The study assumes that 90.4% of electricity generated in China by 2050 is sourced renewably in order to meet a 2°C aligned carbon budget.

Partial Decarbonization scenario

Under the Partial Decarbonization (PD) scenario, penetration of decarbonization technologies is generally higher and faster than in the AA scenario. We anticipate that the penetration of decarbonization technologies would be faster in a port-controlled equipment, such as cargo handling equipment, harbor craft, and on-road vehicles used within the port boundary. As an example, the Port of Shenzhen has already replaced 70% of its cargo handling equipment's energy consumption with electricity and has planned for drayage truck electrification in its 2020–2025 Five-Year Plan (Shenzhen Municipal Transportation Bureau, 2022). As a result, it is our assumption that 90% of the energy consumption of cargo handling equipment and all on-road vehicles in Port of Yangpu will use some form of decarbonization technology by 2050. Furthermore, we assume the grid mix of renewably sourced electricity will be 100% by 2050. In this scenario, LNG uptake in vessels remains constant at 5%. For cargo handling equipment and on-road vehicles, we assumed the same LNG penetration rates as in the AA scenario. Assumptions for the PD scenario are as follows:

» By 2040, vessels' at-berth energy consumption is fully replaced with either electricity (40%) or zero-emission fuels (60%).

» By 2050, 90% of cargo-handling equipment's energy consumption is replaced with either electricity (60%) or LNG (30%).

» By 2050, on-road vehicles' energy consumption is fully replaced with either electricity (70%), hydrogen (25%), or LNG (5%).

» Electricity penetration in on-road vehicles is faster than that in cargo-handling equipment.

» LNG plays a limited role for vessels and on-road vehicles.

Full Decarbonization scenario

In the Full Decarbonization (FD) scenario, we assume a higher and more rapid penetration of decarbonization technologies than in the PD scenario and no reliance on LNG. We assume that the 100% penetration of decarbonization technologies for cargo handling equipment and on-road vehicles will take place sooner than in the PD scenario, and that electricity is prioritized over hydrogen fuel cells. This is because renewable hydrogen uses renewable electricity as a production input and the conversion process would lead to inevitable energy loss. The grid mix percentage of renewably sourced electricity is assumed to reach 100% by 2045, five years earlier than the PD scenario. Apart from that, we assume a 100% penetration rate for zero-emission technology for all emission sources by 2050 in order to construct a pathway for a true zero-emission port by 2050. Assumptions for the FD scenario are as follows:

» By 2035, vessels' at-berth energy consumption is fully replaced with zero-emission fuels.

» By 2040, on-road vehicles' energy consumption is fully replaced with either electricity (10%) or hydrogen (90%).

» By 2050, port emissions reach net zero.

» LNG plays no role in this transition.

LNG-bridging scenario

Many provinces in China have highlighted the use of LNG to reach decarbonization targets in several sectors, including the marine sector. However, using LNG often results in higher WTW CO_2e emissions than the fuels it replaces because of methane emissions (Pavlenko et al., 2020). Because ships usually have long life spans, investing in LNG-fueled ships and infrastructure could result in stranded assets as governments focus on reducing total GHG emissions, including methane, and not just carbon dioxide (Climate, 2023; Fricaudet et al., 2022). In order to evaluate the efficacy of using LNG, particularly fossil LNG, as a bridging fuel to help transition the shipping industry in China to the decarbonization path, we developed an LNG-bridging scenario that builds on the current momentum of LNG adoption in the shipping sector. Under this scenario, LNG would penetrate at a much higher rate in the next decade and then be gradually replaced by other decarbonization technologies by 2050. Assumptions for the LNG scenario are as follows:

» By 2040, vessels' at-berth energy consumption is replaced with either electricity (60%), LNG (25%), or zero-emission fuels (15%).

» LNG penetration in vessels would peak at 30% by 2035 and be gradually scaled back to 15% by 2050.

» LNG penetration in cargo handling equipment would peak at 70% by 2035 and be scaled back to 50% by 2050.

» LNG penetration in on-road vehicles would peak at 55% by 2035 and be gradually replaced by electricity, ending with a 10% penetration by 2050.

Table 2. Summary of assumptions used in different scenarios

Model year		2025	2030	2035	2040	2045	2050
Cargo throughput growth rate compared to 2020 level		14%	55%	219%	383%	424%	430%
Announced Ambitions							
Vessels	**Shore power penetration**[a]	20%	30%	40%	50%	60%	70%
	Zero-emission fuel penetration	5%	10%	15%	20%	25%	30%
	LNG penetration	5%	7.5%	10%	12.5%	15%	17.5%
Cargo handling equipment	**Electrification penetration**	5%	10%	15%	20%	25%	30%
	LNG penetration	5%	10%	15%	20%	25%	30%
On-road vehicles	**Electrification penetration**	12%	17%	20%	25%	30%	35%
	LNG penetration	5%	20%	30%	20%	10%	5%
	Hydrogen fuel cell penetration	0%	2%	5%	10%	15%	20%
Grid mix percentage of renewably sourced electricity		40%	50%	60%	70%	80%	90%
Partial Decarbonization							
Vessels	**Shore power penetration**	30%	40%	50%	60%	50%	40%
	Zero-emission fuel penetration	10%	20%	30%	40%	50%	60%
	LNG penetration	5%	5%	5%	5%	5%	5%
Cargo handling equipment	**Electrification penetration**	10%	20%	30%	40%	50%	60%
	LNG penetration	5%	10%	15%	20%	25%	30%
On-road vehicles	**Electrification penetration**	20%	30%	40%	50%	60%	70%
	LNG penetration	5%	20%	30%	20%	10%	5%
	Hydrogen fuel cell penetration	2%	5%	10%	15%	20%	25%
Grid mix percentage of renewably sourced electricity		45%	60%	70%	80%	90%	100%
Full Decarbonization							
Vessels	**Shore power penetration**	40%	50%	55%	40%	25%	0%
	Zero-emission fuel penetration	15%	30%	45%	60%	75%	100%
	LNG penetration	0%	0%	0%	0%	0%	0%
Cargo-handling equipment	**Electrification penetration**	25%	40%	55%	70%	85%	100%
	LNG penetration	0%	0%	0%	0%	0%	0%
On-road vehicles	**Electrification penetration**	30%	45%	60%	75%	90%	90%
	LNG penetration	0%	0%	0%	0%	0%	0%
	Hydrogen fuel cell penetration	4%	8%	10%	10%	10%	10%
Grid mix percentage of renewably sourced electricity		60%	75%	90%	95%	100%	100%
GHG emissions reduction potential of hydrogen		81.5%	85%	88.5%	92%	95.5%	100%
LNG-bridging							
Vessels	**Shore power penetration**	30%	40%	50%	60%	50%	40%
	Zero-emission fuel penetration	0%	0%	5%	15%	30%	45%
	LNG penetration	15%	25%	30%	25%	20%	15%
Cargo handling equipment	**Electrification penetration**	5%	10%	15%	20%	25%	30%
	LNG penetration	20%	60%	70%	70%	65%	50%
On-road vehicles	**Electrification penetration**	12%	17%	20%	30%	55%	70%
	LNG penetration	25%	38%	55%	45%	20%	10%
	Hydrogen fuel cell penetration	0%	0%	5%	10%	15%	20%
Grid mix percentage of renewably sourced electricity		45%	60%	70%	80%	90%	100%

[a] Penetration refers to the ratio of the current year fleet's energy use supplied by shore power.

RESULTS AND DISCUSSION

With the establishment of Hainan as a special economic zone, cargo throughput in Free Trade Ports in Hainan, including the Port of Yangpu, is expected to grow. We anticipate the Port of Yangpu's cargo throughput to grow by 430% between 2020 and 2050 (Table 2). As shown in Table 3, with the current Announced Ambitions scenario, the port's climate impact would peak by 2040, and end with nearly triple the 2020 baseline level in terms of WTW CO_2e100 emissions by 2050. The AA scenario does not decarbonize the port by 2050.

The PD and FD scenarios provide two technological roadmaps to decarbonize emissions sources partly or fully at the port by 2050. These roadmaps, although different in end-goal ambitions, peak the port's WTW CO_2e100 emissions at a lower level compared to the AA scenario. The PD scenario helps to peak WTW CO_2e100 emissions at approximately 2.3 times the 2019 level by 2040. Emissions then fall by 2050 to a level similar to 2019. This is still considered partial decarbonization, as the scenario name suggests, since it provides an over 60% reduction from the AA level by 2050. By 2050, 66,000 tonnes of WTW CO_2e100 emissions remain, which will have to be removed by other measures to make the port zero-emission by 2050. If the port was to follow the more aggressive FD scenario, WTW CO_2e100 emissions would peak at about 32% higher than the 2019 level by 2035, and eventually achieve zero WTW CO_2e100 emissions by 2050, assuming green hydrogen has zero WTW CO_2e100 emissions by this time (Table 2, Figure 2).

Apart from the above roadmaps, we also estimated a scenario in which LNG is adopted as a bridging solution to reaching zero emissions and so is prioritized in the early years of the transition. Our results show that the port's climate impact would not be reduced over the next two decades compared with the AA scenario if measured by CO_2e100. Using CO_2e20, the LNG bridging scenario performs worse than the AA scenario until 2040. This is because methane slip in marine engines and upstream GHG emissions from producing fossil LNG make its climate impact higher than conventional fuels (Pavlenko et al., 2020). This scenario also leaves the port with a major surplus of WTW CO_2e emissions which will have to be removed by other measures should the port decide to become a zero-emission port by 2050 (Table 3, Figure 2).

Table 3. CO_2e trajectories under the different scenarios (thousand tonnes of emissions)

Year	Announced Ambitions		LNG-bridging		Partial Decarbonization		Full Decarbonization	
	CO_2e100	CO_2e20	CO_2e100	CO_2e20	CO_2e100	CO_2e20	CO_2e100	CO_2e20
2020	62	62[a]	62	62	62	62	62	62
2025	66	67	66	69	62	63	56	56
2030	84	86	84	91	73	75	59	59
2035	159	167	157	175	123	130	82	82
2040	216	226	201	225	144	153	79	79
2045	205	213	158	175	113	120	33	34
2050	174	182	104	116	66	72	0	0

[a] When rounded to the nearest tenth, CO2e20 is 61.82 thousand tonnes and CO2e100 is 61.69 thousand tonnes.

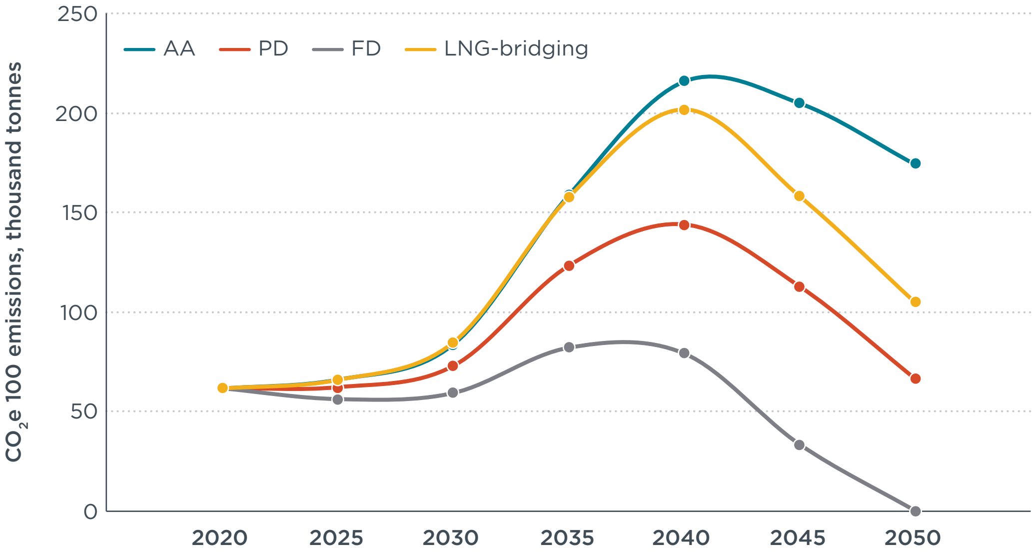

Figure 2. Technological roadmaps to a zero-emission port for Port of Yangpu

The technological pathways presented incur different costs for the port. As demonstrated in Meng, Sturrup, and Zhang (forthcoming), these costs will be reduced as technology matures and zero-emission fuel production ramps up. Although cost might be a key concern, the benefit of integrating decarbonization ambitions with development plans, including direct economic benefits and indirect environmental and climate benefits, could outweigh the cost and put the port at a strategically more important position in the coming years. Because cost is outside of the scope of this study, our proposed technological roadmaps (PD and FD) could be integrated into port decarbonization plans and refined by prioritizing emission sources that are more cost-effective. Future studies should evaluate the cost-effectiveness of port decarbonization measures. Apart from the FD scenario, all other scenarios show remaining CO_2e emissions by 2050. Carbon removal technology could be used to remove these remaining emissions, although the cost could be prohibitively high. Even if the cost barrier is addressed, there are other concerns surrounding the disposal of stored CO_2. It is thus wiser to explore technologies to achieve deep cuts in emissions, rather than relying on carbon removal technology alone.

CONCLUSIONS

In this study, we designed potential technological roadmaps for Port of Yangpu to become a zero-emission port by 2050. We focused on three major groups of port emission sources: vessels, cargo handling equipment, and on-road vehicles. We primarily considered two types of decarbonization technologies: electrification and zero-emission fuels. The decarbonization potential of electrification relies on the WTW CO_2e emissions of electricity to be used by the port. The decarbonization potential of zero-emission fuels relies on the stringency of sustainable alternative fuel standards and the penetration rates for using these fuels. We found that for the Port of Yangpu to become zero emission by 2050, electric powertrain systems need to dominate the on-road and off-road transportation sectors and ships need to be able to run on zero-emission fuels. Renewably sourced electricity also needs to be available and affordable. Using fossil LNG as a bridging solution for achieving zero emissions was found not to be effective even if low methane slip is assumed. Although this roadmap may seem challenging to achieve, some Chinese ports have initiated pilot projects using these technologies. The roadmap shown to be effective in leading to a zero-emission port relies on electrification and zero-emission fuels. Thus, ports should consider the climate impact of economic development plans, as early planning is key to achieving decarbonization goals.

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