WHITE PAPER

DECEMBER 2015

COSTS AND BENEFITS OF SHORE POWER AT THE PORT OF SHENZHEN

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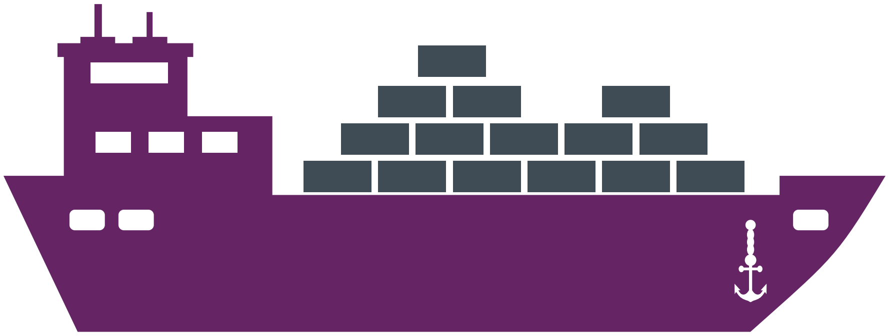

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ACKNOWLEDGEMENTS

This report was commissioned by the China Environment Forum (CEF) at the Woodrow Wilson International Center for Scholars as part of its Choke Point: Port Cities initiative, funded by the Henry Luce Foundation. The authors thank Irene Kwan and Simon Ng for their technical support and Tim Leong for his critical review of the work. The authors also especially thank Shenzhen Human Settlements and Environmental Committee and the Port of Oakland for their review and recommendations for the report.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Seven of the world's 10 largest and busiest container ports are located in China. These booming ports serve as the engines of China's economic growth. While the ports reap economic benefits from oceangoing commerce, their citizens also bear the environmental brunt: shipping-related emissions.

Most energy consumed by international shipping comes from poor quality "bunker oil" with a high sulfur content. Only a few jurisdictions in northern Europe, North America, and most recently Hong Kong are requiring the use of low sulfur fuel by oceangoing vessels. Marine emissions are known to cause cancer and have been linked to respiratory and cardiovascular diseases. Studies conducted in Hong Kong and Shenzhen have found a link between the emissions from the shipping industry and negative health and environmental impacts in port cities.

In China, policymakers are starting to realize the importance of shipping and ports in achieving national and regional air quality standards. The most recent amendments to China's Air Pollution Prevention and Control Law were released on August 29, 2015, and go into effect on January 1, 2016. They require ships at berth to use fuels compatible with emission standards set by the government. Moreover, all new terminals should install shoreside electric power facilities to encourage ships to turn off their diesel engines while at berth. In the wake of mounting public pressure on government and industry to clean up the nation's air and waterways, a recent report from the prominent Hong Kong think tank, Civic Exchange, notes "the global trend for … stakeholders — particularly ships, shippers and ports — is towards cleaner operations." This paper evaluates the potential of one strategy for cleaner operations — shore power, or the use of electricity for ship operations at berth — to control air pollution at Chinese ports.

Shore power has been installed in more than 10 ports worldwide in the past decade, but its life cycle emissions reduction and cost effectiveness have not been examined in depth. This analysis develops an emissions inventory for container ships at the Port of Shenzhen, China, examines the life cycle emissions savings from using onshore power to supplant diesel consumption from ships, calculates the cost effectiveness of onshore power, and compares the results to the cost effectiveness of using fuel switching that can achieve smaller, yet significant, emissions reductions.

Our analysis shows that in 2012 container ships at berth in the Port of Shenzhen emitted 3,400 tonnes of nitrogen dioxide (NO_2), 4,200 tonnes of sulfur dioxide (SO_2), 400 tonnes of particulate matter (PM), and 200,000 tonnes of carbon dioxide (CO_2), comparable to emissions from container ships hoteling at the Port of Hong Kong. By purchasing electricity from Hong Kong to use for onshore power at the Port of Shenzhen in 2020, the port will reduce emissions of SO_2 by 88%, NO_2 by 94%, PM by 95%, and CO_2 by 37%.

On the other hand, onshore power is expensive when compared with fuel switching. The per-tonne costs of reducing NO_2, PM, SO_2 and CO_2 are close to $56,000, $1.4 million, $290,000, and $2,300, respectively, provided 80% of container ships calling at the Port of Shenzhen use onshore power in 2020. The per-tonne cost will be even higher if fewer ships take advantage of onshore power. In comparison, switching from 0.5% (maximum sulfur content) marine diesel oil to 0.1% marine gas oil (MGO) would

lower the cost of reducing PM emissions by 80%, assuming MGO supply is guaranteed. This strategy, however, does not contribute to NO_x reduction.

This research indicates that for Port of Shenzhen, and potentially the rest of the ports in China, fuel switching is generally taking precedence over onshore power because (1) it is cheaper and technologically less challenging, and (2) because PM emissions, for most cities in China, are the largest threat to public health. The onshore power alternative should only take priority if a low sulfur fuel supply cannot be guaranteed, NO_x emissions are dominant concerns, or onshore power infrastructure is already established.

If policymakers choose to prioritize onshore power as the primary emissions reduction option, they should provide incentives to attract ships already equipped with shipside infrastructure. Policymakers should seek to establish alliances with California, for example, where the Air Resources Board (ARB) requires most container ships to use onshore power and where there are close trade ties with the city of Shenzhen and Guangdong province as a whole.

This analysis also highlights the importance of a detailed emissions inventory, without which it is impossible to conduct a cost effectiveness analysis. The Port of Shenzhen still lacks accurate emissions data and inventories for other ship types, which is also an issue for most other Chinese ports. Nevertheless, this research shows that the combination of Automatic Identification System (AIS) data and general ship information for vessels calling at a port can be used as an alternative and are largely available across major ports in China.

1. ONSHORE POWER OVERVIEW

1.1 INTRODUCTION

Onshore power, also known by a variety of names such as Alternative Maritime Power (AMP) or cold ironing, enables ships at dock or in dry dock to use shoreside electricity to power onboard electrical systems, such as lighting, ventilation, communication, cargo pumps, and other critical equipment, while turning off their auxiliary engines. These ships can be connected to onshore power supplies so ship operations can proceed uninterrupted while eliminating diesel emissions resulting from auxiliary engines. The electricity comes from the local power grid through a substation at the port and is plugged into special power connectors in the shore power system on the ship.

Shore power has been installed in more than 10 ports, mostly in North America and Europe. Table 1 provides an overview of ports with shore power systems. More ports in Asia are seriously considering shore power as a viable option to reduce port emissions. Hong Kong, for example, is researching the feasibility of using shore power in its newly built cruise terminal. Shenzhen, the port neighboring Hong Kong, has begun work on shore power infrastructure.

Table 1. Ports using shore power

Year of introduction	Port name	Country	Capacity (MW)	Frequency (Hz)	Voltage (kV)	Ship types using onshore power supply (OPS) [a]
2000-2010	Gothenburg	Sweden	1.25-2.5	50 & 60	6.6 & 11	RoRo, RoPax
2000	Zeebrugge	Belgium	1.25	50	6.6	RoRo
2001	Juneau	U.S.A.	7-9	60	6.6 & 11	Cruise
2004	Los Angeles	U.S.A.	7.5-60	60	6.6	Container, cruise
2005-2006	Seattle	U.S.A.	12.8	60	6.6 & 11	Cruise
2006	Kemi	Finland	N/A	50	6.6	RoPax
2006	Kotka	Finland	N/A	50	6.6	RoPax
2006	Oulu	Finland	N/A	50	6.6	RoPax
2008	Antwerp	Belgium	0.8	50 & 60	6.6	Container
2008	Lübeck	Germany	2.2	50	6	RoPax
2009	Vancouver	Canada	16	60	6.6 & 11	Cruise
2010	San Diego	U.S.A.	16	60	6.6 & 11	Cruise
2010	San Francisco	U.S.A.	16	60	6.6 & 11	Cruise
2010	Karlskrona	Sweden	2.5	50	11	Cruise
2011	Long Beach	U.S.A.	16	60	6.6 & 11	Cruise
2011	Oakland[b]	U.S.A	7.5	60	6.6	Container
2011	Oslo	Norway	4.5	50	11	Cruise
2011	Prince Rupert	Canada	7.5	60	6.6	N/A
2012	Rotterdam	Netherlands	2.8	60	11	RoPax
2012	Ystad	Sweden	6.25	50 & 60	11	Cruise
2013	Trelleborg	Sweden	3.5-4.6	50	11	N/A

[a] RoRo or "roll-on/roll-off" ships carry wheeled vehicles or cargo. RoPax or "roll-on/roll-off passenger" ships are essentially RoRo vessels with passenger accommodation. [b] Information provided by Port of Oakland.
Source: World Ports Climate Initiative (2015).

The growing interest in shore power is driven by a number of factors. Ports are increasingly conscious of emissions generated from port operations that can strain the relationship between ports and nearby communities. As a result, neighboring communities, which are sometimes negatively affected by port emissions, can block port expansion. This then compels ports to voluntarily implement a variety of clean port initiatives to minimize the adverse impacts. Shore power, consequently, has become more attractive as it eliminates emissions from ships at berth, often the biggest polluters at a port. As more ports build shore power infrastructure, the networking effect increases the utilization rate of the shore power equipment by ships, reduces the overall cost, and reinforces the appeal of shore power.

Shore power is also a result of more active policymaking in North America and Europe. The California Air Resources Board (ARB), for example, requires ships in Los Angeles, Long Beach, Oakland, San Diego, San Francisco, and Hueneme to use shore power or equivalent control techniques to reduce at-berth emissions by 80% by 2020 (At-Berth Regulation, 2007). Because there is no other practical equivalent technology commercially available, shore power is likely the technology that most ships will employ in compliance with the ARB regulation.

The penetration of shore power is also aided by other regulations that target marine pollution. Ships entering the Emission Control Areas (ECA), which include the 200 nautical miles from the coasts of the US and Canada, the Baltic Sea, and the North Sea, are required to burn fuel with a maximum sulfur content of 0.1% (1,000 ppm) as of January 1, 2015 (International Maritime Organization, 2015). The higher cost of lower sulfur fuels will alleviate cost concerns about using shore power.

In recent years shippers have shown a growing interest in managing the environmental impact of the logistical chain. For shipping companies whose fleets are already equipped with shore power systems, the growing network of shore power does not pose a threat to their cost structure but presents an opportunity to distinguish themselves. Ports that take part in the Environmental Shipping Index, which rewards ships that voluntarily reduce their emissions, offers incentives for ships to use shore power as well.

1.2 TECHNICAL CONSIDERATIONS OF SHORE POWER

The shoreside electrical and infrastructure requirements include an industrial substation to receive power transmitted from the local grid, normally at 34.5 kilovolts (kV) and a transformer to bring the voltage down to be compatible with the ship's electrical specifications (i.e., 6.6 kV or 11.0 kV 3-phase, 60 Hz). A nonexhaustive list of onshore infrastructure requirements includes: distribution switchgear, circuit breakers, safety grounding, underground cable conduits, electrical vaults, and power and communications receptacles and plugs. An existing berth must be modified to accommodate the installation of shore power cables and accessories. For the construction of a new berth, technical requirements and specifications of shoreside electrical and infrastructure can be included in the design phase.

Ships participating in a shore power electrification program will require the installation of shore power cable receptacles and an associated electrical management system. Retrofits can be made to the existing fleet without the capacity of shore power. For new builds, the ship owner can request an onboard shore power ready system be included as part of the ship's electrical system design. An onboard shore power system consists of receptacle panels, a voltage switching board, circuit breakers, and a control and monitoring system. Depending on the frequency and voltage of the shore power supply and a ship's electrical systems, a second transformer to bring voltage down further from the shoreside power system and/or an electrical frequency converter (i.e., 50 Hz to 60 Hz or vice versa) may be needed.

In addition to shoreside and shipside systems, there are tremendous variations in power, voltage, and frequency levels in different parts of the world. The low-voltage systems (typically 400 to 480 V) that have been applied earlier required numerous connection cables, while high-voltage systems (6.6 to 11 kV) are easier to handle. The difference in electrical frequency between North America and parts of Japan compared to the rest of the world is also a factor that needs to be considered.

In addition, the frequency and voltage of onboard electrical systems may differ among various vessel sizes and categories. Oceangoing vessels (OGV) calling at European ports tend to have more 60 Hz electrical systems onboard, while smaller vessels have 50 Hz systems. The latter are primarily smaller vessels not sailing to other continents.

The average power demand and peak power demand of various vessel types and sizes differ as well. Indeed, they vary significantly. The difference has a significant impact on the cost of the shore power system and it is therefore important to pursue energy reduction options and assess peak power demand in advance. Table 2 reports the power requirement for different ships.

Table 2. Specifications of shore power

Vessel type (length)	Average power demand (MW)	Peak power demand (MW)	Peak power demand for 95% of vessels (MW)
Container vessels (< 140 m)	0.17	1	0.8
Container vessels (> 140 m)	1.2	8	5
Container vessels (total)	0.8	8	4
RoRo and vehicle vessels	1.5	2	1.8
Oil and product tankers	1.4	2.7	2.5
Cruise ships (< 200 m)	4.1	7.3	6.7
Cruise ships (> 200 m)	7.5	11	9.5
Cruise ships (> 300 m)	10	20	12.5

The shore power infrastructure also varies by ship types. For vessels such as tankers, cruise ships, and RoRo vessels that commonly berth at the same dock and do not use cranes, shoreside connection is easier. At container terminals where vessels do not always dock at the same position, there is a need for more connection points.

The International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO), and the Institute of Electrical and Electronics Engineers (IEEE) jointly publish a voluntary standard for shore power systems. The standard, IEC/ISO/IEEE 80005-1, covers onshore, onboard, and shore-to-ship connection and interface equipment. It describes how to design, install, and test high-voltage shore power systems, addresses safety aspects such as emergency shutdowns, and makes additional requirements for Ro Ro passenger ships, cruise ships, container ships, tankers, and LNG carriers. Notably, it does not address frequency issues and low voltage systems.

1.3 THE COSTS AND BENEFITS OF SHORE POWER

The cost of a shore power system consists of both fixed investment and operational costs. Fixed investment constitutes shoreside and shipside investment in shore power infrastructure, including installing high-voltage power, transformers, switchboard and control panel, electrical distribution system, cable reel system, and the frequency converter. The two largest expenses associated with shoreside infrastructure are frequency conversion equipment and quayside supply of high-voltage power, accounting for about half of total fixed investment. Costs for shipside modifications can range from $300,000 to $2 million, depending on vessel type and size and the need for an onboard transformer. There is also a significant difference between retrofit and new-build projects, with retrofits sometimes costing up to twice as much as incremental new-build investments. The operational cost is primarily related to electricity costs and taxes, both of which vary by region. Some countries, such as Sweden, reduce taxes for electricity used by shore power systems; however, some electricity suppliers also charge connection fees.

The main benefit of using shore power is the improvement in local air quality. Emissions at berth are replaced by emissions from electricity generation elsewhere that provides the shore power; emissions from electricity generation are usually lower and occur further from population centers. However, actual emissions reductions must be evaluated carefully and are influenced by three key factors. First and most important is the emission factor of marine diesel. For countries with coastal ECAs, the net reduction from shore power is lower than for countries with less stringent sulfur regulations because the sulfur level of marine diesel consumed within the ECA is 80% lower than that consumed outside the ECA. Second, the actual emissions reduction will also depend on the emission factors of the power plants feeding the local or national grid. Power sourced from wind turbines and hydropower plants causes no pollutant emissions at all. Third, the actual impact on human health has to do with where emissions are generated. In most circumstances, both ports and power generating stations are far from city centers. But in cities such as Hong Kong, where the port is located close to residential areas, moving emissions from ships to power stations may yield more benefits.

The purpose of this report is to examine the net emissions reduction benefit of using shore power in Shenzhen and to evaluate key factors that influence the potential for reducing emissions. The structure of this report is as follows. Section 1 provides a review of existing shore power systems around the world. Section 2 discusses the proposed shore power in Shenzhen. Sections 3 and 4 discuss the electricity generation mix in Hong Kong, the neighboring city from which the Port of Shenzhen purchases electricity, and the life cycle emissions reduction achieved by switching from marine diesel to electricity. Section 5 discusses the methodology used to quantify the total emissions reduction of using shore power at the Port of Shenzhen by 2020 and Section 6 provides the findings. Finally, Section 7 offers conclusions from this work.

2. SHORE POWER IN SHENZHEN

2.1 THE PORT OVERVIEW

The Port of Shenzhen is one of the busiest and fastest growing ports in the world. Spread across the coastline of Shenzhen, which was the first city designated as a Special Economic Zone (SEZ) in China in 1984, and the hallmark of China's "reform and opening up." Since 1984 the Port of Shenzhen has ridden the wave of economic growth to become the third largest container port in the world as measured by container throughput in twenty-foot equivalent units (TEU) (Figure 1).

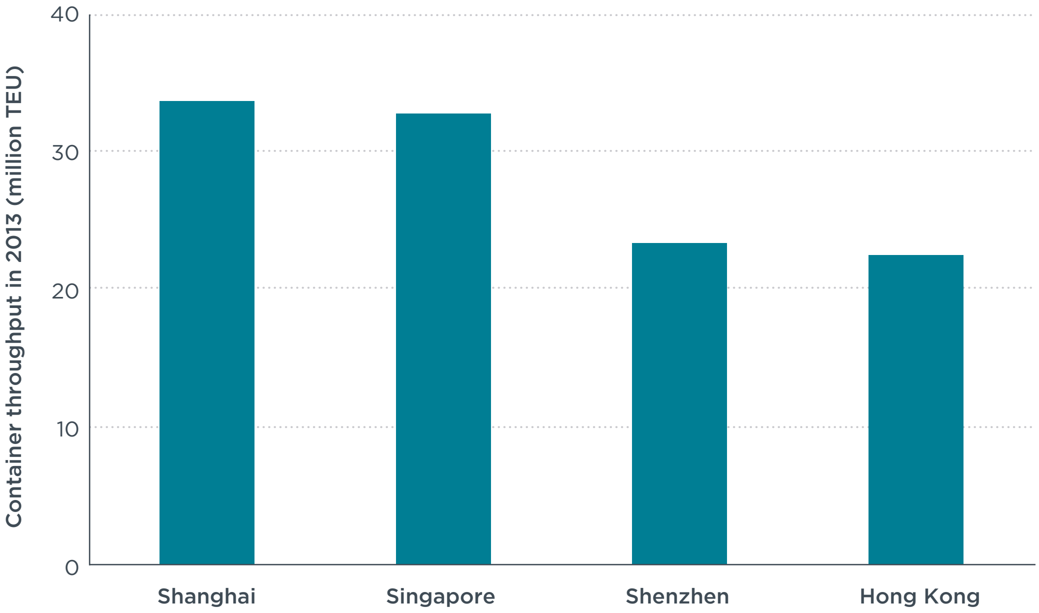

Figure 1. Container throughputs at the largest ports in the world in 2013.
Source: World Shipping Council (2014).

The Port of Shenzhen is situated in the Pearl River Delta in China's Guangdong province adjacent to Hong Kong. The port is separated by the Kowloon Peninsula into east and west areas, consisting of facilities in Da Chan Bay, Shekou, Chiwan, Mawan, Yantian, Dongjiaotou, Fuyong, Xiadong, Shayuchong and Neihe, with a total of 135 berths (Wikipedia, 2015). Yantian and Shekou are the two most important port areas in the port. The port is home to 39 shipping companies serving 131 international container routes with more than 20 feeder routes to other ports in the Pearl River Delta region (Wikipedia, 2015).

Table 3. Areas that constitute the Port of Shenzhen

Area	Quay length (m)	Berths	Largest berth (deadweight tonnage)
Yantian	5,090	20	100,000
Shekou	7,388	48	100,000
Chiwan	4,406	26	70,000
Mawan	4,298	16	50,000
Xiadong	1,898	9	50,000
Dongjiaotou	391	5	3,000
Shayuyong	704	6	5,000
Fuyong	442	5	5,000

Source: China Ports & Harbours Association (2008).

With a population of 15 million and a GDP totaling $237 billion, the city itself is a huge import market and an important export base in Guangdong province (Wang, 2012; Shenzhen Municipal Bureau of Statistics, 2012). The city is about 20 nautical miles (37 km) north of Hong Kong and 60 nautical miles (110 km) south of Guangzhou, the capital of Guangdong province, enabling Shenzhen more economic influence on international trade. The city also has an airport that serves as UPS' Asian-Pacific cargo hub, a railway system that extends to the rest of Guangdong province, and a highway that links Shenzhen to Hong Kong, Macao, and other cities of Guangdong province, all contributing to the growth of the port.

The Port of Shenzhen competes with the Port of Hong Kong and the Port of Guangzhou, both of which are among the world's top 10 ports. Ports in Taiwan and Singapore are also potential competitors. Any action made by Shenzhen that adds costs to shipping companies may have unintended consequences on the city's economy and employment. Meanwhile, as Hong Kong pioneered the use of shore power and low sulfur fuel to reduce air pollutants in the Pearl River Delta region, the city has exerted influence on Guangzhou and Shenzhen to take parallel action. As a result, Shenzhen must strike a balance between reducing port emissions and strengthening the port's competitiveness.

2.2 SHORE POWER AT THE PORT OF SHENZHEN

In response to the concern over air pollution in the city, the Shenzhen government in September 2013 released the Shenzhen Air Quality Enhancement Plan. The plan set out target timelines for various ship emission control measures, most of which need to be achieved no later than 2015. It called for reducing concentrations of $PM_{2.5}$, particulate matter with an aerodynamic diameter less than 2.5 micrometers, in the city from 35 mg/cm^3 in 2013 to 33 mg/cm^3 by 2015, 32 mg/cm^3 by 2016, and 30 mg/cm^3 by 2017. Accordingly, the Port of Shenzhen plans to have eight berths supplying shore power by 2014 and 15 berths by 2015, with at least 15% of container ships using the shore power. By 2014, the cruise terminal under construction should be installed with shore power that supplies electricity to all berths. The Human Settlement and Environment Commission will oversee the implementation of the plan and provide shore power. It also will set subsidies for the electricity used to lower costs. The municipal government is also providing fiscal incentives for shoreside infrastructure (Shenzhen Municipal Government, 2013).

The first shoreside shore power infrastructure has been built in Shekou. Two voltage options, 440 and 6,600, are provided to ships that may be equipped with different shore power equipment. They can now serve three container ship berths in Shekou. Figure 2 shows an example of the available shoreside infrastructure.

Figure 2. An example of shoreside shore power infrastructure in Shekou.
Source: used with permission by Dr. Liang from Shenzhen Academy of Environmental Sciences.

The Port of Shenzhen will purchase electricity from Hong Kong due to the physical proximity to its neighboring city. Hong Kong currently has four power stations in addition to a small wind farm. The electricity from these stations is distributed by CLP Power Hong Kong Limited (CLP) and The Hong Kong Electric Company Limited (HKE).

By the end of 2013, CLP Power had 218 primary and 13,692 secondary substations in its transmission and distribution network. The company's power system has been interconnected with the Guangdong power system since April 1979 and electricity is exported to Guangdong province.

HKE has 51 switching/zone substations and 3,776 substations. The interconnection between the company's transmission system with that of CLP Power by a cross-harbor link has an installed capacity of 720 MVA, enabling the provision of joint emergency support during generator failure, reducing potential loss of supply to customers (Hong Kong Special Administrative Region Government, 2015).

To alleviate concerns about the cost of shore power and the erosion of the competitiveness of the Port of Shenzhen, the government hopes the network effect — more ports with shore power infrastructure leading to reduction in its overall cost — will hold. To accomplish that, the port is actively seeking collaboration with ports in California and attracting ships with shipside shore power infrastructure already onboard to visit the Port of Shenzhen. The government is also developing a plan to establish Sino-US Green Shipping Lanes that will appeal to not only shippers, but also companies and consumers who can provide extra incentives for ships to install more shore power systems.

3. THE ELECTRICITY GENERATION MIX IN HONG KONG

3.1 CURRENT GENERATION MIX

The electricity demand in Hong Kong amounted to nearly 43 billion kWh in 2012 with an annual growth rate of about 1%. Of the two companies supplying electricity in the area, HKE represents about 25% of the market while CLP claims the rest. In 2012, HKE had a total installed capacity of 3,757 MW, including coal-fired and gas-fired generators as well as a small number of oil-fired and renewable-energy generators. CLP has an installed capacity of 8,888 MW in total for gas-fired, coal-fired, and oil-fired stations along with imports of electricity from Daya Bay Nuclear Power Station (DBNPS) and Guangzhou Pumped Storage Power Station.

In 2012, the generation mix in Hong Kong was dominated by coal, representing 53% of total electricity, followed by nuclear (23%) and natural gas (22%). Oil and renewables constituted the remaining 2% of the generation mix (Figure 3).

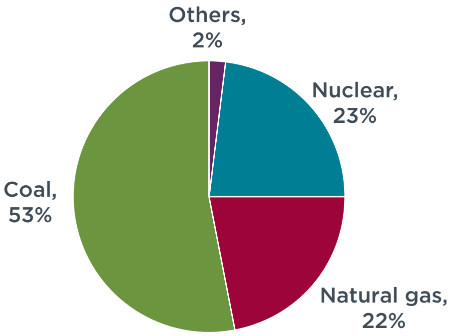

Figure 3. Electricity generation mix in Hong Kong in 2012 (Hong Kong Environment Bureau, 2012).

The coal-fired power units have the highest share of emissions, accounting for 50% of total SO_2, 22% of NO_X, 14% of respirable suspended particles (RSP), and 50% of greenhouse gas (GHG) emissions. Natural gas has been used in Hong Kong for electricity generation since the 1990s. The emissions of SO_2, NO_X, RSP, and CO_2 per unit of electricity generation from using natural gas compared to burning coal are about 98%, 77%, 79%, and 45% less, respectively. Hong Kong purchased nuclear energy from DBNPS under a 20-year contract that ended in 2014. Nuclear constituted about 23% of overall fuel mix in Hong Kong in 2012. Under the power purchasing agreement with DBNPS renewed in 2014, the share of nuclear will decline to around 20% by 2020.

Renewable energy, such as wind, does not emit GHGs or other air pollutants during the electricity generation process. But, given the intermittent nature of renewable energy and the natural and geographical constraints, the reliability of electricity from renewable energy poses challenges. Hong Kong's average wind speed is approximately 3 m/s, whereas the typical wind turbine functions properly only at wind speeds over 6 m/s. Urbanization and density of buildings further affect the availability of sites with strong, reliable wind patterns. The Lamma Winds, which began operating in 2006, was the first commercial-scale wind turbine in Hong Kong and remains its most visible renewable energy project. The overall capacity is 0.8 MW with a capacity factor of 13%.

Additionally, exposure to sunshine in Hong Kong while consistent across the territory, is only within the medium range for solar irradiance. Thus, while the Hong Kong government has adopted solar technologies in a number of government projects and the power companies in Hong Kong also use solar to generate electricity, the application is limited. Hong Kong is also building waste-to-energy projects that will contribute about 1% of total electricity generation by 2020.

3.2 THE GENERATION MIX IN 2020

Due to environmental concerns, the Hong Kong government has not permitted construction of any new coal-fired power plants since 1997. Most coal-fired power plants were built in the 1980s and are scheduled to be retired by 2017, subject to their operating conditions. Because it takes years to plan and build a power generator and such a decision will have a lasting impact over the next three decades, Hong Kong has been careful and deliberate in planning the future generation mix, taking into consideration both demand and environmental protection.

In 2012, Hong Kong consumed 43 billion kWh of electricity and is forecast to consume 48 billion kWh of electricity by 2020, representing about 1% annual growth. Because the planning of generation capacity is based on maximum load rather than an overall consumption basis, a reasonable reserve capacity has to be ensured as well.

To reduce air emissions from power plants, Hong Kong has set statutory emissions caps for SO_x, NO_x, and RSP in 2017 and a range of emissions from power plants in 2020. The emissions levels from power generators in 2010 and the emissions caps for 2017 are shown in Table 4, along with Hong Kong's emissions reduction targets by 2020. In addition to air emissions, the government proposed to reduce the CO_2 intensity of power generators by 50%-60% by 2020, based on 2005 levels, through fuel switching. In 2005, the power sector generated about 28.6 million tonnes of CO_2 emissions (Hong Kong Environmental Protection Department, 2014).

Table 4. Emissions caps for power stations in 2017 and 2020

Pollutant	2010 emissions (tonnes)	2017 emissions cap (tonnes)	2020 emissions change from 2010 level (lower bound)	2020 emissions change from 2010 level (upper bound)
SO_x	17,800	10,399	-35%	-75%
NO_x	27,000	25,950	-20%	-30%
RSP	1,010	750	-15%	-40%

In 2008, the Government of Hong Kong and the National Energy Administration signed a Memorandum of Understanding (MoU) to ensure a continuous supply of natural gas. Under the MoU, the Hong Kong branch line of the mainland's Second West-East Gas Pipeline is being constructed and will provide Hong Kong with a new source of natural gas. The contract for nuclear electricity supply to Hong Kong was also renewed for 20 years, until 2034. Despite the renewal, the amount of nuclear electricity purchased will be largely unchanged from the current amount. The total share of electricity from nuclear will decline due to the growth of electricity consumption in Hong Kong.

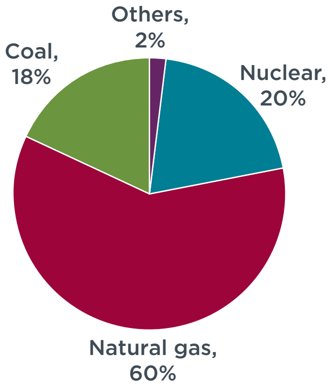

Figure 4. Projected electricity generation mix in Hong Kong in 2020.

With the share of nuclear energy declining and renewable energy representing a small share of total fuel mix, electricity from natural gas needs to be increased significantly in order to replace coal. To achieve the targets shown in Table 4, the share of electricity from natural gas has to increase to 60%, while the share of electricity from coal has to decrease to less than 20%. Figure 4 shows the projected generation mix in Hong Kong in 2020 (Hong Kong Environmental Protection Department, 2014).

4. EMISSIONS FROM SHORE POWER AND MARINE DIESELS

4.1 EMISSIONS INTENSITY FROM POWER PLANTS IN HONG KONG

The life cycle emissions reduction from using shore power in place of marine fuel relies partly upon the generation mix of power stations that supply ports with electricity. This is especially the case in Shenzhen where power stations in Hong Kong are located near the city.

Hong Kong's generation mix is much cleaner than that of other places in China, with 23% of its electricity coming from nuclear and 20% from natural gas. The city has rather low emissions intensity in its power stations. Figure 5 shows the emissions intensity of CO_2 and several pollutants. The data for total emissions in 2012 was obtained from the Hong Kong government and was adjusted by a transmission loss of 3%. The annual electricity consumption amounted to 43 billion kWh in 2012.

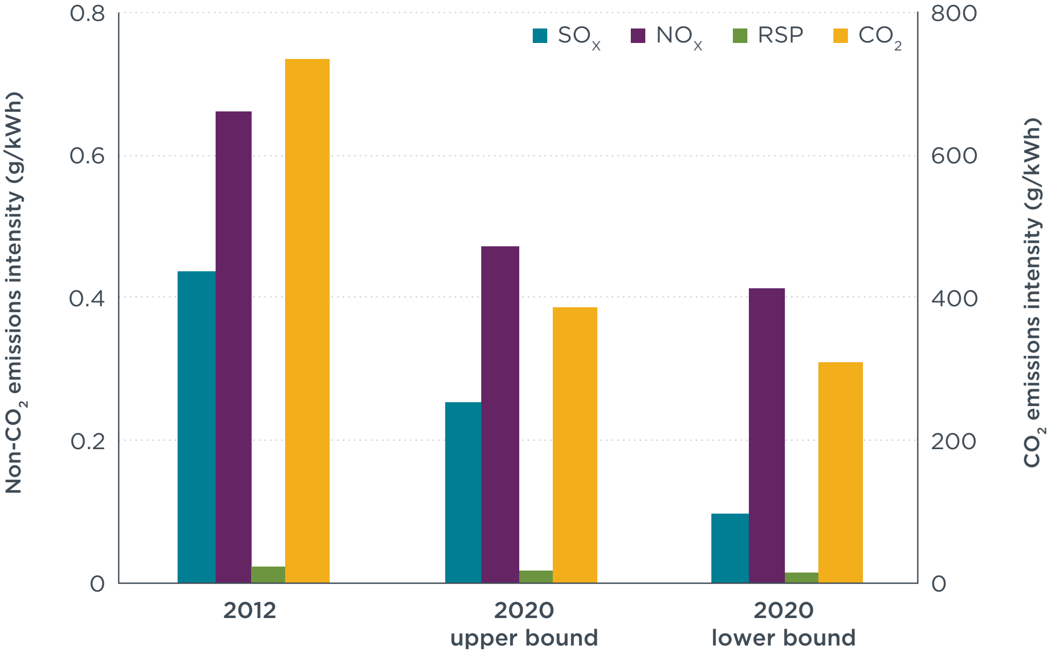

Figure 5. Emissions intensity of power stations in Hong Kong in 2012 and 2020.

Additionally, the Hong Kong government has been moving away from coal due to environmental concerns. As gas-fired power plants replace the coal-fired power plants that are scheduled to retire after 2017, the generation mix will be much cleaner and in line with the government's plan to cap emissions at 2012 levels and reduce them gradually over time (Table 4). As the electricity consumption grows to 48 billion kWh and emissions decline, the emissions intensity from power generators in Hong Kong will continue this downward trend after 2020. Figure 5 also illustrates the emissions intensity from power generators in Hong Kong by 2020.

4.2 EMISSIONS INTENSITY FROM MARINE DIESEL ENGINES

The diesel fuel used by OGVs is often called heavy fuel oil or residual oil. As its name suggests, marine diesel is at the bottom of the refinery process, and therefore rich in sulfur but low in price. The International Maritime Organization (IMO), the regulatory body for international shipping, has been working to tighten the sulfur level permitted in marine diesel fuel. The current IMO regulation requires OGVs to use fuels with a sulfur level no more than 35,000 parts per million (ppm). The global average sulfur level is 27,000 ppm, lower than the statutory requirement. After 2020, the allowable sulfur level in marine diesels will be lowered significantly, to 5,000 ppm, subject to a review in 2016 that may postpone the regulation to 2025. In this analysis, we assume ships will use marine diesel fuel with a maximum sulfur level of 27,000 ppm in 2012 and 5,000 ppm in 2020.

Together with fuel quality standards, IMO also set up regulations for engines and energy efficiency. These are Tier I through Tier III for NO_x and Energy Efficiency Design Index, or EEDI, for CO_2, NO_x, and CO_2 emissions per unit transport should fall under the new IMO regulations. For NO_x, we used the emission factor of Tier I marine engines in 2012 and the emission factor of Tier II marine engines in 2020. For CO_2, we applied the emission factor used in the IMO Third GHG Study (International Maritime Organization, 2014) in 2012 and lowered it in 2020 to reflect the penetration of EEDI-compliant ships. Table 5 illustrates the emissions intensity of SO_x, PM, NO_x and CO_2 of OGVs used in this study.

Table 5. Emissions intensity of marine diesels

Pollutant	2012 (g/kWh)	2020 (g/kWh)
SO_x	12	2.1
NO_x	10	9.8
RSP	1.4	0.38
CO_2	620	610

Figure 6 compares emissions reductions from producing one kWh of energy via electricity generation with operation of a marine auxiliary engine at berth. It reveals that shore power is a promising means of reducing marine pollution even in 2020 when the sulfur level of marine diesel is significantly lowered. In 2012, the emissions intensity of marine diesel was lower only for CO_2 (as shown by the positive value in percent change), reflecting the greater thermal efficiency of current marine diesel engines. That advantage will disappear by 2020 as Hong Kong's generation mix switches to natural gas. On average, switching from marine diesels to onshore electricity will reduce emissions of SO_x by 88%, NO_x by 94%, PM by 95%, and CO_2 by 37% in 2020.

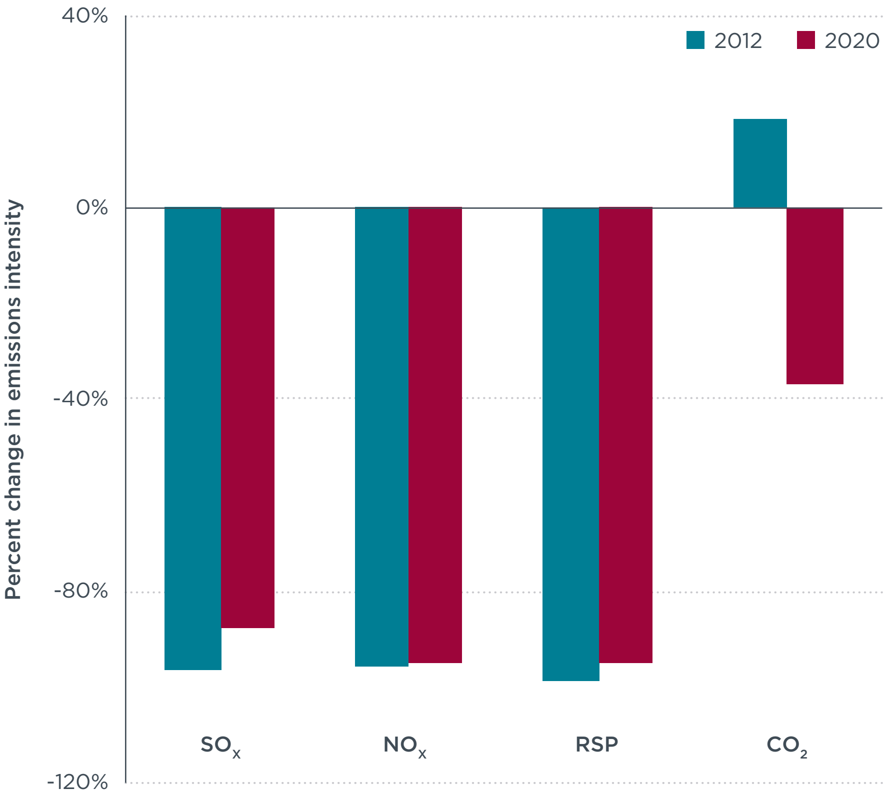

Figure 6. Emissions reduction by switching from marine diesels to electricity via shore power.

5. METHODOLOGY: ACTIVITY-BASED APPROACH

Shore power is the provision to supply ships at berth with shoreside electric power while their main and auxiliary engines are turned off. Without shore power, ships need to keep auxiliary engines running during hoteling to provide electricity onboard the ship. In addition to auxiliary engines, most OGVs have one or more boilers that are used for heating fuel and producing hot water. Boilers typically are not used during transit at sea because many vessels are equipped with exhaust gas recovery systems, or “economizers,” that use the heat of the main engine exhaust for heating fuel or water. However, boilers are operated when ships are hoteling at berth even when shore power is substituted for auxiliary engines.

In this study, we quantify the SO_X, NO_X, PM, and CO_2 emissions from auxiliary engines and boilers from container ships in 2012 as the baseline. We also analyze emissions from auxiliary engines and the emissions reduction potential of auxiliary engines from using shore power. We assume three different scenarios for the percentage of ship owners adopting shore power by 2020 — 10%, 20%, and 50% — and evaluate the potential emissions reduction for each scenario. We also investigate how providing shore power will influence the peak demand of the electricity supply and stability in Hong Kong.

5.1 AUXILIARY AND BOILER EMISSIONS FROM SHIPPING

The best practice for estimating global fleet emissions is through an activity-based approach where the emissions are estimated for individual categories of ships (International Maritime Organization, 2014). The estimates of emissions are then added together to obtain the total emissions of ships in the port. The activity-based approach to calculating emissions for ships at berth can be summarized in Equation 1.

$$E_j = \Sigma_i(AE_i \times Hour_i \times EF_j \times LD_{i\text{-}AE} + Bo_i \times Hour_i \times EF_j \times LD_{j\text{-}B}) \times \frac{1}{10_6} \qquad \text{[Equation 1]}$$

where E_j is the total tonnage of emission j; AE_i represents the auxiliary engine power of ship i (kW); $LD_{i\text{-}AE}$ is the load of the auxiliary engine; Bo_i represents the power used in the boiler of ship i (kW); $Hour_i$ is the total hours a ship stays at the port; and EF_j is the emission factor (grams per kWh) for emission j, $LD_{i\text{-}B}$ is the load of boilers. Adding the emissions from auxiliary engines and boilers yields the total emissions from a ship in hoteling mode.

The total emissions reduction from switching to shore power can be determined using life cycle analysis and depends mainly on emissions from auxiliary engines and the emissions reduction rate from shore power. Boilers have to operate during the hoteling period regardless. In addition, connecting and disconnecting shower power with ships takes about three hours, during which auxiliary engines are running to produce electricity. Equation 2 summarizes the relationship.

$$E_j = \Sigma_i(AE_i \times (Hour_i - 3) \times EF_j) \times \frac{RR_j}{10_6} \qquad \text{[Equation 2]}$$

where RR_j is the reduction rate of emission j from shore power, as identified at the end of Section 4.2 (i.e. 88%, 94%, 95%, and 31% for SO_X, NO_X, PM, and CO_2, respectively in 2020).

5.2 DATA AND ASSUMPTIONS

The most important components in Equation 1 are the total number of ships and their hoteling hours in Shenzhen. Unfortunately, high-resolution data similar to that for the Port of Los Angeles or Port of Long Beach are unavailable. We used ships in the Automatic Identification System (AIS) data to calculate emissions from container ships in Shekou and assumed these ships were representative of total container ship activities in the Port of Shenzhen. The AIS data, however, were incomplete as there were only 450 container ship arrivals at the Port of Shekou. The AIS data also provide the IMO number, a unique ship identifier. With the IMO number, we were able to link ships in the AIS data with the Clarkson data containing ship-specific information such as deadweight tonnage (DWT) and twenty-foot equivalent unit (TEU). Because auxiliary engine power in the Clarkson data is sparsely populated, we used default values for auxiliary engine and auxiliary boiler power from Ng et al. (2013), who assessed the shipping emissions inventory in Hong Kong. The default values assume certain auxiliary engine power for each ship size category, shown in Table 6.

Table 6. Auxiliary engine and boiler default values

Ship size (TEU)	Auxiliary engine (kW)	Boilers (kW)
0-1,000	300	136
1,000-2,000	388	232
2,000-3,000	650	232
3,000-4,000	913	313
4,000-5,000	643	393
5,000-6,000	1,307	534
6,000-7,000	1,307	393
7,000-8,000	1,320	586
8,000-9,000	1,488	586

In addition, AIS data also provide the hours of hoteling. The emission factors of SO_X, NO_X, PM, and CO_2, in grams per kWh, are obtained from different sources. We calculated the emission factors of SO_X and PM based on the 2.7% sulfur level in marine fuels used by ships in 2012. We used the emission factor associated with a 0.5% sulfur level standard, assuming that it will come into effect by 2020. The emission factor for NO_X is taken from Ng et al. (2013), which is based on a 2007 emissions inventory. Ships built between 2007 and 2012 generally meet higher NO_X engine standards. However, because ships complying with the engine standard penetrate the market slowly, we used the same emission factor for NO_X that Hong Kong had used for our comparison and validation. By 2020, the port may see more ships complying with newer, Tier III-compliant engine standards. We applied the average NO_X emission factor in the global fleet to calculate NO_X emissions in 2020 based on the Third IMO GHG Report (International Maritime Organization, 2014). The CO_2 emission factor is assumed to be 620 grams per kWh, the same as that used by the Port of Long Beach (Starcrest Consulting Group, 2014). As the EEDI phases in, the average emission factor of CO_2 is assumed to drop to 610 grams per kWh by 2020. The emission factors used in this analysis are shown in Table 7.

Table 7. Emission factors used

	Engine emission factor (g/kWh), 2012	Engine and boiler emission factor (g/kWh), 2020	Boiler emission factor (g/kWh), 2012
SO_x	12.0	2.1	16.1
PM	1.4	0.4	0.8
CO_2	620	610	620
NO_x	15	9.8	2.0

We used sample ship activity data (500 ship arrivals) and emission factor values as inputs to Equation 1 to determine the baseline emissions for the Port of Shenzhen in 2012. To estimate the emissions reduction achievable through switching to shore power, we eliminated data for ships that stayed at port fewer than five hours because shore power is expected to be used only for longer periods of time. We also excluded emissions from boilers because they continue to run when ships are connected to shore power. Armed with detailed analysis of emissions from the sample ships, we extrapolated the results to the container ship fleet calling at the Port of Shenzhen. The total number of container ships calling at the Port of Shenzhen was about 20,000 in 2012, according to the Shenzhen Human Settlement Environment Commission. Our sample represents 2.5% of total ship arrivals in Port of Shenzhen in 2012.

To project the emissions in to 2020, we assumed a 1% annual growth rate for container ships calling at Shenzhen, corresponding to the compounded annual growth rate between 2011 and 2013. To validate our analysis, we also compared the emissions from container ships in Shenzhen with those of Hong Kong.

6. FINDINGS

6.1 EMISSIONS AT BERTH FROM CONTAINER SHIPS IN SHENZHEN

Applying Equation 1, we estimated SO_X, PM (or DPM, diesel particulate matter), NO_X and CO_2 emissions in 2012 from container ships in Shenzhen to be about 4,200, 390, 3,400, and 200,000 tonnes, respectively. This is within 5% of estimated emissions from Hong Kong in 2007 (Figure 7).

Figure 7. Emissions from container ships at berth in Shenzhen (2012) and Hong Kong (2007).

Without further regulations, SO_X and PM emissions are estimated to drop to about 700 and 130 tonnes, respectively. This is due to the IMO regulation that mandates the sulfur level of marine fuels drop from 2.7% to 0.5% globally by 2020. NO_X and CO_2 emissions will increase to about 3,300 tonnes and 210,000 tonnes in 2020, respectively, despite having lower emission factors. This is because higher emissions from ship activity growth outweigh the emissions reductions from declining emission intensities. Emissions from container ships in Shenzhen in 2012 and 2020 are illustrated in Table 8.

Table 8. Emissions from container ships in Shenzhen in 2012 and 2020

Emission	2012 Shenzhen (tonnes)	2020 Shenzhen (tonnes)
SO_X	4,161	714
DPM	390	129
NO_X	3,397	3,333
CO_2	195,000	207,000

6.2 EMISSIONS REDUCTION FROM SHORE POWER IN 2020

In addition to calculating the emissions baseline in 2020, we also calculated emissions reduced from container ships in the hoteling mode via shore power. In order to do so, we took into consideration (1) the time it takes to connect and disconnect ships using shore power, and (2) that boiler emissions will not be reduced by shore power. Applying Equation 2 and the emissions reduction factors identified in Section 4.2, we estimated that switching from diesel to electricity will reduce SO_X, PM, NO_X and CO_2 emissions by 330, 66, 1,700, and 40,000 tonnes, respectively, on a life cycle basis. These are about 46%, 51%, 51%, and 2% lower than the 2020 baseline for SO_X, PM, NO_X, and CO_2, respectively.

However, it is unlikely that 100% of container ships will adopt shore power at berth by 2020. The California Air Resources Board's shore power regulation, the most stringent to date, requires affected fleets to use shore power for at least 80% of their visits by 2020 (California Air Resources Board, 2012). Because of the voluntary nature of the shore power system in Shenzhen, we assumed 50% as the highest penetration rate Shenzhen could achieve. We also examined the emissions reduction potential if Shenzhen achieves 10% and 20% penetration rates by 2020. Figure 8 shows the emissions reduction potential of SO_X, NO_X, PM, and CO_2 based on different penetration rates.

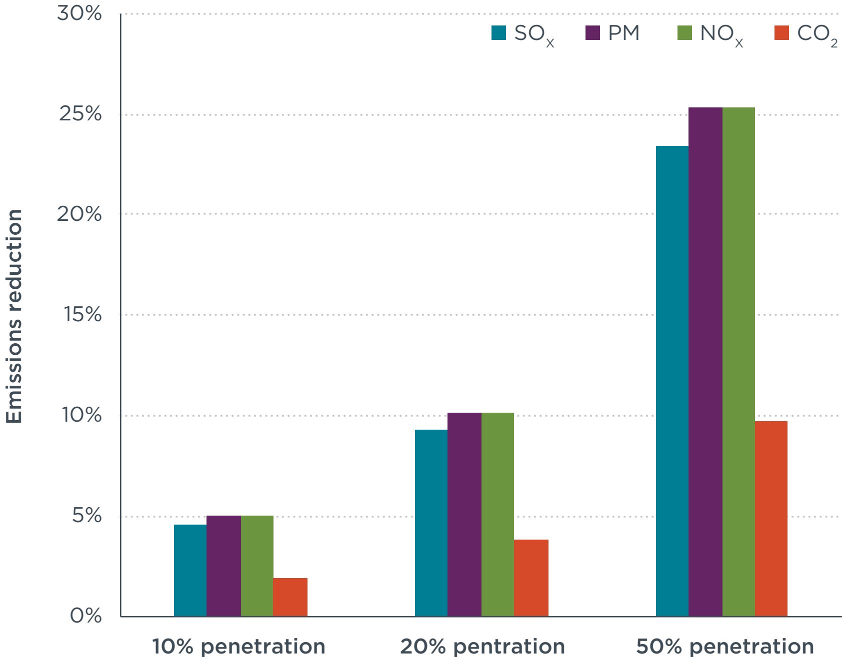

Figure 8. Emissions reduction for different shore power penetration rates.

6.3 PEAK DEMAND

Peak demand or peak load is a period in which electrical power is provided for a sustained period of time at a significantly higher level than the average supply level. For an electric utility company, the actual point of peak demand is a single half hour or hourly period, which represents the highest point of customer electricity consumption. The daily peak demand usually occurs around 5:30 p.m. At this time, there is a combination of office and residential demand and at some times of the year, shorter daylight time.

Operating reserve is the generating capacity available to the system operator within a short interval of time to meet demand in case a generator goes down or there is another disruption to the supply. Most power systems are designed so that under normal conditions, the operating reserve is always at least the capacity of the largest generator plus a fraction of the peak load. Usually, the risk-neutral, economically optimal planning reserve margin of 9%-11% is used to balance expected marginal costs of additional reserves against the marginal costs of unserved load (The Brattle Group, 2014). One parameter by which to measure the operating reserve is the reserve margin, which is expressed in Equation 3:

$$RM = \frac{C - D}{D} \qquad \text{[Equation 3]}$$

where *RM* is the reserve margin; *C* represents the expected maximum available supply; and *D* is expected peak demand.

As Figure 9 shows, utility companies in Hong Kong maintained 10-16 GW of reserve capacity between 2006 and 2011, or 15%-20% of the reserve margin, ensuring 99.9997% of supply stability (Hong Kong Environment Bureau, 2012).

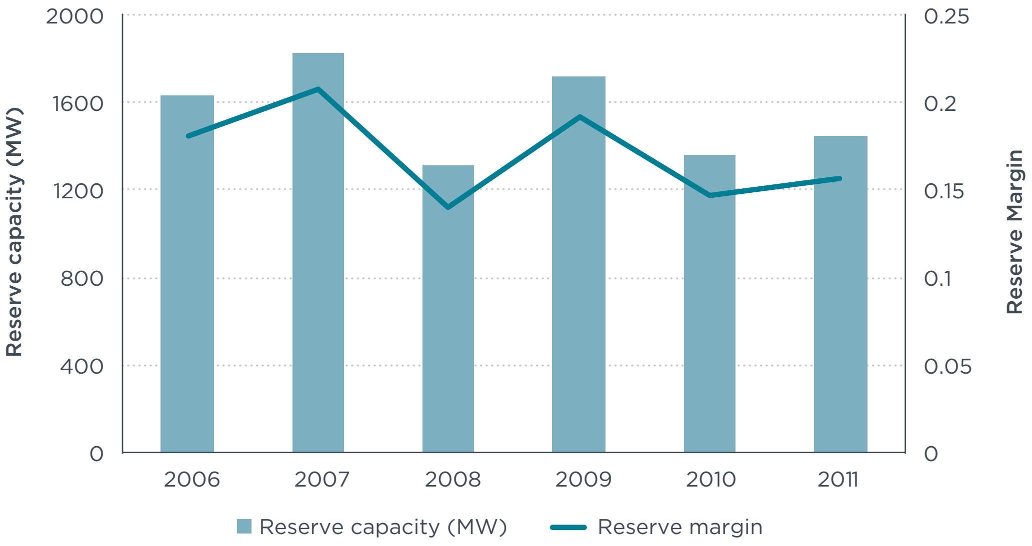

Figure 9. Reserve capacity and reserve margin of the electricity supply in Hong Kong. *Source: Hong Kong Environment Bureau (2012).*

In this section, we examined the power demand of shore power from container ships and evaluated whether the power demand would impact the peak load and reserve power in a significant way.

We started by examining the ships at the Port of Shekou in the AIS database and matched them to auxiliary engine power default values (as in Table 6) because the engine power is more important than ship numbers in this analysis. The AIS data documented the arrival time of the ship. We rounded arrival times to the nearest hour and tallied the total ship power by every hour of the day. The average power of each hour is about 16 MW and the standard deviation is 3.0 MW.

We assume a normal distribution of all container ships calling at the Port of Shenzhen over each hour of the day, with a 1% annual growth rate between 2012 and 2020. The average hourly power demand at the Port of Shenzhen in 2020 is estimated at 164 MW with a standard deviation of 205 MW. Assuming a 20% penetration rate of shore power by 2020, about 860 MW is needed to maintain a 99.9997% stability rate. We then calculated the reserve capacity, assuming the total capacity of power generation in Hong Kong grows 1% per year between 2011 and 2020 and the reserve margin is an average of the reserve margins between 2006 and 2011. We estimated the reserve capacity to be about 2,000 MW. In other words, to supply shore power in Shenzhen, the reserve margin will decline to 9.7%.

We also ran a sensitivity analysis that evaluates the influence of shore power on the grid in Hong Kong. If 10% of ships adopt shore power, the reserve margin in Hong Kong will dip below 13%. The influence on the electricity grid in Hong Kong is minimal because the reserve margin is still close to what it was between 2006 and 2011. If the penetration rate increases to 50%, the reserve margin will drop to 6% and begin to strain the city's electrical system.

An additional consideration is the shore power in the newly built cruise terminal in Hong Kong, which is to be completed by 2015. If 50% of container ships in Shenzhen and all cruise ships in Hong Kong use the shore power supplied by the Hong Kong electricity grid, the electricity supply and stability would be seriously tested. Figure 10 shows results from a sensitivity analysis for various penetration rates of shore power.

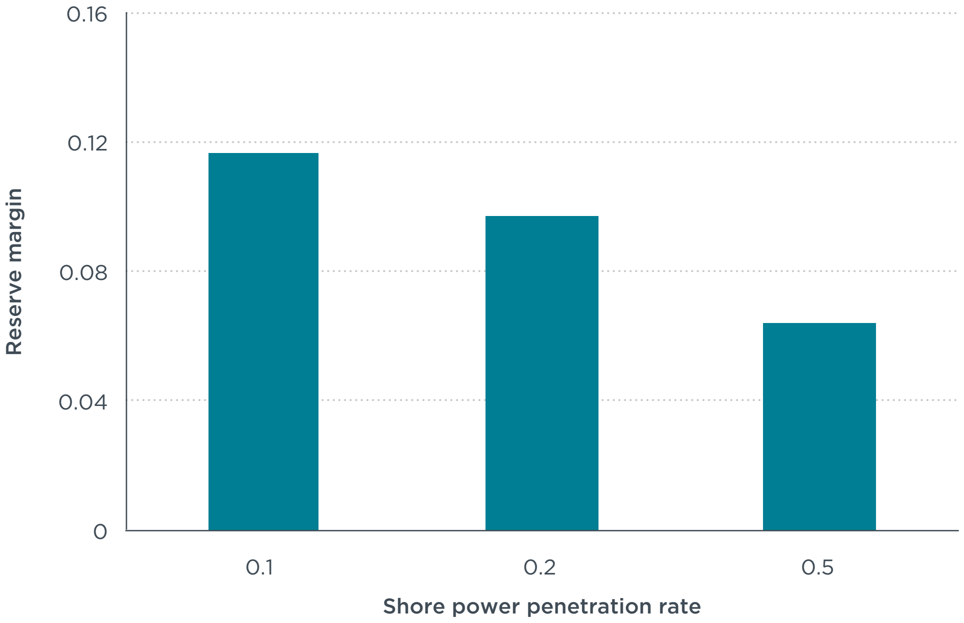

Figure 10. Shore power penetration rates and estimated reserve margin of the Hong Kong electricity grid in 2020.

7. COST-BENEFIT ANALYSIS

7.1 DATA, ASSUMPTIONS, AND METHODOLOGY

7.1.1 Introduction

The cost data in this analysis come primarily from two sources: the cost-benefit analysis of onshore power by Environ, which was commissioned by the Port of Long Beach (POLB), (Environ International Corp., 2004), and an analysis conducted by California Air Resource Board (At-Berth Regulation, 2007). We also referred to other studies to cross-check and validate cost estimates used by Environ and CARB (Yorke Engineering, 2007; Starcrest Consulting Group, 2011). The cost of reducing emissions through onshore power includes capital investment in retrofitting ships and redesigning terminals, recurring costs in operating and maintaining terminal infrastructure, and extra costs in purchasing electricity over diesel to power ships onshore. The fixed and variable costs were discounted over the lifetime of the onshore power infrastructure and calculated using the discounted cash flow (DCF) approach. The total net present value (NPV) of the cash outflow was divided by the total life cycle emissions reduction from the lifetime of the onshore power implementation to derive the overall costs and benefits.

7.1.2 Data and assumptions

Capital costs for vessels

For onshore power to be implemented, ships need to be equipped to receive power from an outside source. Existing ships usually need to be retrofitted with specific electrical equipment—wiring, connectors, transformers, and switchgear—while many new ships are being built with this equipment as part of their naval architecture. Environ and CARB estimated that the cost to modify a ship to receive onshore power ranges from $500,000 to $2 million. Environ examined the total capital investment for each of the four container ships analyzed in its study. We assumed that the vessel-side capital investment is a function of the size of the ship. Based on data provided by Environ, we calculated that the average cost for the capital investment is around $172 per TEU capacity.

As shown in Section 1, several ports around the world have implemented incentives or mandates for ships to use onshore power. Notably, California, one of the most popular destinations for ships originating from Shenzhen, will require 80% of container ships to use onshore power by 2020. Some European ports encouraging ships to use onshore power are major destinations for trade from Shenzhen as well. The retrofit costs to these ships were not counted in this analysis, either because they are already installed with vessel-side equipment or will install it regardless. Our baseline cost-benefit analysis assumed 40% of ships visiting the Port of Shenzhen each year come from ports in Europe and North America that already require ships to use onshore power.

Capital costs for berths and terminals

The necessary shoreside infrastructure may include cables, plugs, underground wiring, substations, transformers, and switchgear. Based on information provided by various ports, CARB estimated the cost to modify each berth at a terminal to be about $5 million. We used this as the baseline cost for each berth. This figure does not take into account other infrastructure investments that may be needed, including costs related to improving existing electrical infrastructure. We then adjusted the cost downward by 20%

because relatively low labor and raw material costs in China, along with the experience learned from onshore power projects elsewhere, should reduce capital overlays.

There are 44 berths for container ships at the Port of Shenzhen, according to the Transport Commission of Shenzhen Municipality (2013). We assumed 60% of them will be equipped with shoreside infrastructure. We further assumed the investment in shoreside infrastructure is fixed, meaning the port will not be able to scale back the investment even if it turns out that only 10% of shoreside onshore power capacity would be utilized.

Electrical infrastructure outside ports
Electrical infrastructure, such as distribution lines and substations, may be required in order for the local utility company to supply the ports with sufficient electricity for shore power projects. The necessity and the level of investment vary from port to port. CARB reported that the Ports of Los Angeles and Hueneme were not expected to need significant additional outside electrical infrastructure; the Port of San Diego had required as much as $32 million of additional investment, but that was later scaled down. We do not have enough data to evaluate if the Port of Shenzhen needs electrical infrastructure outside the port. To be conservative, we applied a $5 million adjustment in total cost for electrical infrastructure outside the Port of Shenzhen in this study.

Operations and maintenance cost
The recurring cost of operations and maintenance (O&M) for shore-side infrastructure is also taken into account. Based on the Environ study, for this analysis we assumed annual O&M costs of 12% of total capital investment in shoreside infrastructure.

Energy costs
The electricity tariff in Shenzhen is based on electricity usage, classified as industrial, commercial, or residential, and demand (100 KVA, 3,000 KVA, and 5,000 KVA) (China Merchants (Shenzhen) Power Supply Co., Ltd., 2014; Shenzhen Local, 2007). In this study, we assumed the electricity cost for ships falls into the category of industrial usage and above 5,000 KVA so the cost is $0.15 per kWh (0.92 yuan per kWh). Using onshore power eliminates the need to burn marine diesel oil (MDO), which by 2020 will have a maximum sulfur content of 0.5%. We used $700 per tonne as the fuel cost, which is equivalent to about $0.14 per kWh. The net cost of electricity over MDO is a recurring cost over the lifetime of onshore power.

7.1.3 Methodology: discounted cash flow (DCF)

In this study, we applied the DCF approach to model the cost effectiveness of onshore power per Equation 4. Under this approach, the starting year is 2017 and the capital investments are made in equal amounts in three years between 2017 and 2019. The costs would be fully depreciated by 2035. The 15-year lifetime is in line with assumptions made by Environ and CARB. In addition to capital investment, the recurring costs include terminal O&M costs and extra costs of replacing diesels with electricity. We used a 10% discount rate in this analysis.

Consistent with the prior sections, we assumed the onshore power would begin to operate in 2020. The benefits of applying onshore power to reduce emissions accrue between 2020 and 2035. The emissions reduction due to onshore power is based on the calculation from Section 4. It includes emissions reductions of NO_X, SO_X, PM, and CO_2

that result from turning off the auxiliary engine during hoteling net of emissions from the power plant in Hong Kong by 2020. The emissions savings grow as the throughput of Port of Shenzhen increases 1% annually.

$$\text{Cost Benefit} = \frac{\text{Net Present Value of Net Cash Outflow}}{\text{Emissions Savings}} \qquad \text{[Equation 4]}$$

Equation 4 represents the average cost effectiveness of onshore power for all container ships visiting the Port of Shenzhen, but the cost of reducing one tonne of pollutant from each individual ship may vary. Frequent callers, defined as ships that arrive at the Port of Shenzhen 10 times or more per year, may incur lower costs than their infrequent peers. In this analysis, we used a 6,000 TEU container ship as an example for a case study to demonstrate the effectiveness of a policy that encourages frequent callers to use onshore power to reduce overall compliance costs.

The methodology of the case study follows Equation 1 with a few important adjustments. First, we assumed the ship would share the berth infrastructure cost and O&M costs in proportion to its share of total port TEU throughput. For example, if the ship visits the Port of Shenzhen 10 times a year, the total throughput of this ship (60,000 TEU assuming the full utilization rate) to Shenzhen's 23 million TEU throughput is 0.26%. As such, the container ship will share 0.26% of total terminal infrastructure investment and O&M costs. The ship will incur more costs if it visits the port more frequently. Secondly, we assumed the ship has to be retrofitted for shore power at the cost of $172 per TEU, for a total of about $1 million, in 2020. Lastly, we assumed the only variable that changes the cost effectiveness of using onshore power for this ship is the frequency of calling at the port. Visiting the Port of Shenzhen more frequently will increase the cost of sharing terminal infrastructure and O&M, but also will lead to more emissions reductions, while the vessel-side investment is fixed.

In this case study, we used the emission factors introduced in Section 4 to calculate savings of NO_X, SO_X, PM, and CO_2 between 2020 and 2035. The auxiliary engine power is also the same as the default value for a 6,000 TEU ship. We assumed the container ship uses 20 hours of onshore power per visit and the fuel cost is $700 per tonne.

7.2 RESULTS

With the aforementioned data, assumptions, and methodology, we calculated the cost effectiveness of using onshore power for the container ship fleet visiting the Port of Shenzhen. Table 9 shows the average costs of reducing one tonne of pollutants through onshore power at the Port of Shenzhen. The costs of reducing one tonne of NO_X, PM, SO_X and CO_2 are close to $56,000, $1.4 million, $290,000, and $2,300, respectively. The estimates fall within the range of costs estimated by CARB (Table 10), which assessed the cost effectiveness of reducing only NO_X and PM through using onshore power.

Table 9. Cost of reducing pollutants using onshore power in Shenzhen (80% penetration rate)

Pollutant	Cost per tonne
NO_X	$56,000
PM	$1,400,000
SO_X	$290,000
CO_2	$2,300

Table 10. Cost of reducing pollutants using onshore power in Los Angeles, Long Beach, and Oakland estimated by CARB with an 80% compliance rate

Pollutant	Cost per ton — POLA and POLB	Cost per ton — Oakland
NO_x	$11,000-$32,000	$15,000-$71,000
PM	$400,000-$1,100,000	$400,000-$2,500,000

Source: California Air Resources Board (2007)

Two important variables influencing the cost-benefit analysis are the adoptability of onshore power by ships visiting a given port and the number of ships already equipped with vessel-side onshore power infrastructure due to similar initiatives elsewhere. Higher penetration rates will result in greater reduction of emissions and thus improve cost effectiveness. Higher percentages of ships already equipped with vessel-side infrastructure will reduce the investment requirements directly attributable to a given port's shore power initiative and result in lower total costs as well. Figures 11 and 12 show the cost and benefit of NO_x and PM reduction under different penetration rates and shares of ships originally equipped with onshore power visiting the Port of Shenzhen. Under the best scenario where 60% of ships are already equipped with vessel-side equipment and the shore-side infrastructure is 50% utilized, the average cost of reducing one tonne of pollutant is only a quarter that of the worst scenario, defined as 40% of ships already with vessel-side equipment and 10% utilization rate. Both figures point to an important policy insight: policies that are designed to attract ships already equipped with onshore power will significantly boost the cost effectiveness of onshore power in Shenzhen. Attracting these ships may not only forgo the need for fresh investment in vessel-side onshore power equipment, but also improve the utilization rates of onshore power at the Port of Shenzhen.

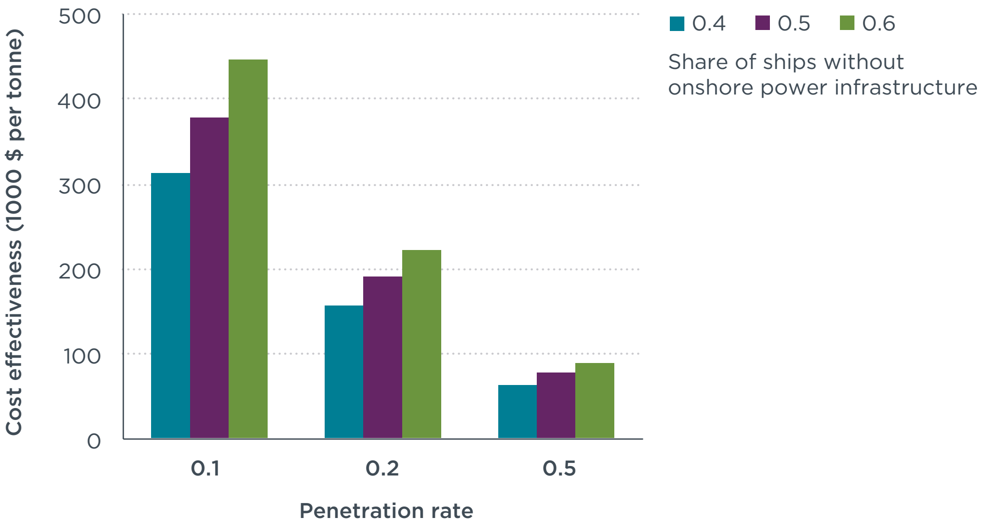

Figure 11. Cost effectiveness of reducing NO_x at the Port of Shenzhen by using onshore power.

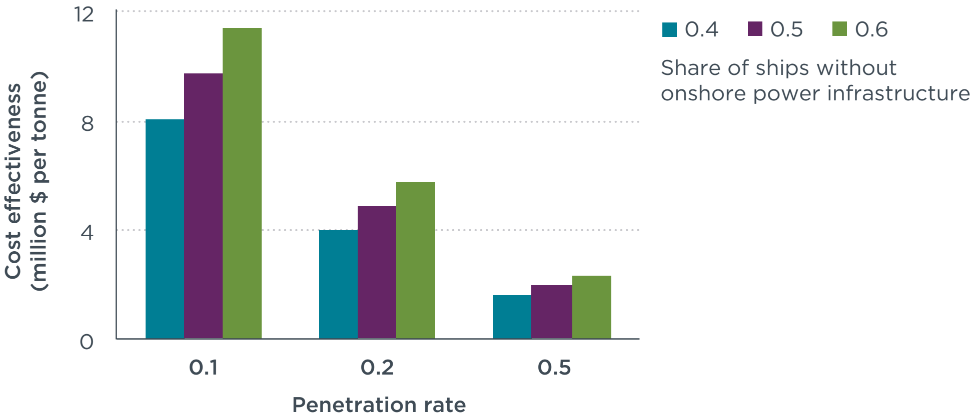

Figure 12. Cost effectiveness of reducing PM at the Port of Shenzhen by using onshore power.

Table 11 shows the results of a case study on a single 6,000 TEU ship. As expected, more frequent visits to the Port of Shenzhen spreads the fixed cost for retrofitting the vessel over multiple calls, and thus significantly reduces the average cost of mitigating one tonne of pollutants. For example, doubling the visits from 10 to 20 improved the overall cost and benefit by a third. From a policy perspective, the Port of Shenzhen should use innovative policies to encourage ships already equipped to receive onshore power to visit the port more frequently. These policies may include discounting port fees for ships with vessel-side equipment calling at the Port of Shenzhen and greater recognition for shipping companies using onshore power. Another benefit of such a policy is to increase the use of shoreside infrastructure and improve the return on investment at the port.

Table 11. Per-tonne cost-benefit of reducing various emissions for a 6,000 TEU container ship

Frequency	NO_x	PM	SO_x	CO_2
1	$153,000	$3,928,000	$711,000	$3,000
5	$37,000	$954,000	$173,000	$600
10	$23,000	$583,000	$106,000	$400
15	$18,000	$459,000	$83,000	$300
20	$16,000	$397,000	$72,000	$250

7.3 THE COST EFFECTIVENESS OF EXISTING ONSHORE POWER

Because the Port of Shenzhen has already installed three sets of onshore power system at three berths, this cost for initial investment in infrastructure becomes a sunk cost and the only additional cost becomes electricity over fuel, and the ship-side retrofit cost. We further assume that most ships with ship-side infrastructure will be routed to these berths as a result of incentives and government policy. About 80% of ships that visit these berths already have ship-side infrastructure installed.

Table 12 shows that the cost effectiveness of existing berths is much better than the newly built berths. It also reiterates the need to attract ships with onshore power infrastructure already installed.

Table 12. Cost-benefit of berths already installed with onshore power

Pollutant	Cost per tonne
NO_x	\$23,000
PM	\$600,000
SO_x	\$115,000
CO_2	\$950

7.4 COMPARISON WITH LOW SULFUR FUEL STRATEGY

Another strategy to reduce pollution at ports is to switch to lower sulfur fuels while at berth. In this section, we compared the cost-benefit of using onshore power to that of switching to lower sulfur fuel. We assumed ships are required to use 0.1% marine gas oil (MGO) instead of using the MDO that contains 0.5% sulfur and is the base fuel in this study.

Ships pay a premium for MGO because it is less available and of higher quality than MDO. Data from Bunkerworld, however, shows little difference in price between the two fuels (Bunkerworld, 2015). In this study, we assumed MGO has a \$100/tonne premium over MDO. We also assumed ships will only change fuel for its auxiliary engines but continue using 0.5% MDO in the boilers, consistent with the assumption made for the onshore power.

Table 13 shows the reduction of SO_x and PM by switching to MGO and the cost-benefit. It shows that switching to MGO reduces emissions less than using onshore power but the cost is much lower. Policymakers thus face a potential tradeoff between a deeper cut in emissions and a heftier price tag of reducing more emissions.

Table 13. Emissions reduction from switching to MGO

	Reduction (tonnes 2012 to 2020)	Cost per tonne
SO_x	280	\$13,000
PM	12	\$310,000

8. CONCLUSION

This analysis develops the emissions inventory from container ships at the Port of Shenzhen, which lays the foundation to better understand total emissions from the Port of Shenzhen. We calculated that container ships at berth in the Port of Shenzhen emitted 3,400 tonnes of NO_x, 4,200 tonnes of SO_x, 400 tonnes of PM, and 200,000 tonnes of CO_2 in 2012, comparable to emissions from container ships hoteling at the Port of Hong Kong. Total emissions will grow by 10% by 2020 as shipping activity in the port continues to climb.

This research also offers a novel analysis that examines the life cycle emissions savings from using onshore power to supplant diesel consumption from ships, the cost effectiveness of onshore power, and its comparison with fuel switching that can achieve smaller but still equally significant emissions reduction. The analysis shows two faces of onshore power. It nearly eliminates NO_x, PM, and SO_x emissions in port areas due to a cleaner electricity generation mix. Such is the case in Hong Kong, where electricity for the Port of Shenzhen is purchased.

It also provides the Port of Shenzhen with an opportunity to leverage the network effect of onshore power — as more ports take up onshore power, the per-tonne mitigation cost will drop precipitously. Our assessment shows that if 60% of container ships visiting Shenzhen each year have already installed shipside equipment and 50% of them opt to use shore-side electricity, the cost of reducing one tonne of pollutant is only a fifth of what it is when only 40% of ships have the shipside equipment and 10% of them use shore-side electricity by 2020.

On the other hand, the cost effectiveness of shore power is less appealing than other emissions reduction methods. Reducing one tonne of PM through onshore power, even if the market penetration is 50%, is still nine times the cost of fuel switching, although fuel switching does not address NO_x and CO_2 emissions.

This analysis lays forth policy options to reduce emissions from the Port of Shenzhen, and potentially the rest of the ports in China. Our study found that fuel switching is generally taking precedence over onshore power because it is cheaper and technologically less challenging. Investments currently marked for onshore power infrastructure and subsidies to incentivize ships to use onshore power may be better utilized to encourage ships to switch to low sulfur fuels. Only if a low sulfur fuel supply cannot be guaranteed or NO_x emissions are dominant concerns should onshore power be prioritized.

In the event that policymakers decide to implement onshore power, they should focus on attracting ships that are already carrying shipside onshore power equipment and increase the utilization of the onshore electricity supply system. They may consider forging an alliance with ports in California where trade ties with Shenzhen are close and most container ships must use onshore power by law. Developing shipping lanes between Shenzhen and California in which container ships are encouraged to use onshore power drives down the average cost of using onshore power in Shenzhen.

This research did not take into account technologies other than onshore power and fuel switching to reduce air emissions in ports. Exhaust gas scrubbers and selective catalytic reduction, for example, have great potential to reduce NO_x and SO_x emissions from marine engines. Regulators in California are also approving new technologies to control hoteling emissions, including the use of barge-based bonnets to vacuum up and then treat stack emissions from ships at port. Future research may consider the merits of these technologies; this study mainly focused on comparison between onshore power and fuel switching because these are the two mainstream options for reducing air polluting emissions from ports like Shenzhen right now.

This research also highlights the importance of a detailed inventory in allowing us to examine emissions from different operating cycles and focus specifically on ship hoteling. Most ports in China, barring Hong Kong, Shanghai, and to a lesser extent, Shenzhen, do not have such capacity, which hinders effective policymaking.

This research is only the first step to help shed light on emissions reduction in the Port of Shenzhen. Greater acknowledgement of and transparency about ship activities around and within the port will enable us to better grasp the state of emissions in the Port of Shenzhen and help policymakers create relevant policies. As the city government continues to tighten its environmental standards and the International Council on Clean Transportation enters the next stage of fulfilling the goals laid out in the Memorandum of Understanding with the Shenzhen Habitat and Environment Committee, a clear picture about emissions from the port and how to reduce them is within sight.

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