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Shore power management for maritime transportation: Status and perspectives

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ABSTRACT

Due to the gradual increase in maritime cargo volume, exhaust fumes from the maritime industry have become a concern of various sectors of society. In particular, because of their proximity to human habitation, emissions from docked ships are a serious health hazard. Shore power, as a promising approach to reducing ship emissions in port areas, has drawn attention from governments, industries, and academia. This paper reviews studies of shore power's economic challenges from the perspective of ship owners, port authorities, and governments. The basic models roughly summarize the costs of shore power for different interested parties. In addition, some technical reports and governmental studies of shore power are reviewed. This paper provides scholars interested in this area with a systematic review of current research on shore power. Research opportunities that are worth investigating and the potential forces driving the popularization of shore power are identified. We hope that the review helps to increase research on this topic.

1. Introduction

Shipping accounts for over 80% of the cargo volume of all international trade. According to a report by the United National Conference on Trade and Development (UNCTAD, 2019), international maritime trade volumes reached 11 billion tons in 2018, an all-time high record,[1] and the volume is expected to continue to increase over the next 4 years. Studies (Smith et al., 2014; Buhaug et al., 2009) show that shipping emissions, including NO_x, SO_2, CO_2, and particulate matter (PM), account for non-neglectable percentages of the total annual anthropogenic emissions. Environmental concerns, including air pollution, are one of the factors contributing to uncertainty in the maritime industry (UNCTAD, 2019). In the coastal areas in Europe, shipping emissions have contributed a lot to the concentration of air pollutants including NO_2, SO_2, and PM_x (Viana et al., 2014). When berthing at ports, ships often use their auxiliary engines to generate electricity to maintain mechanical operation on board, and thus continually emit exhaust fumes. Therefore, there are large volumes of emissions at ports. According to Ballini (2015), nearly 70% of the maritime emissions occur near port areas, and docked ships are the source of 60% to 90% of port emissions. Port emissions are of particular concern due to their proximity to the population in port cities, and the resulting adverse impacts on the environment and public health. Merk (2014) predicts that by 2050, ships in ports will emit approximately 70 million tons of CO_2, 1.3 million tons of NOx, and 0.16 million tons of SO_2. Therefore, the problem of the exhaust emissions of docked ships will be exacerbated if no effective measures to minimize them are implemented.

Facing the increasingly serious problem of ship emissions, the International Maritime Organization (IMO) has launched an invitation to its member states to call for voluntary participation of multiple shipping sectors in the reduction of Greenhouse Gas from ships

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[1] Accurate data for 2019 has not yet been released.

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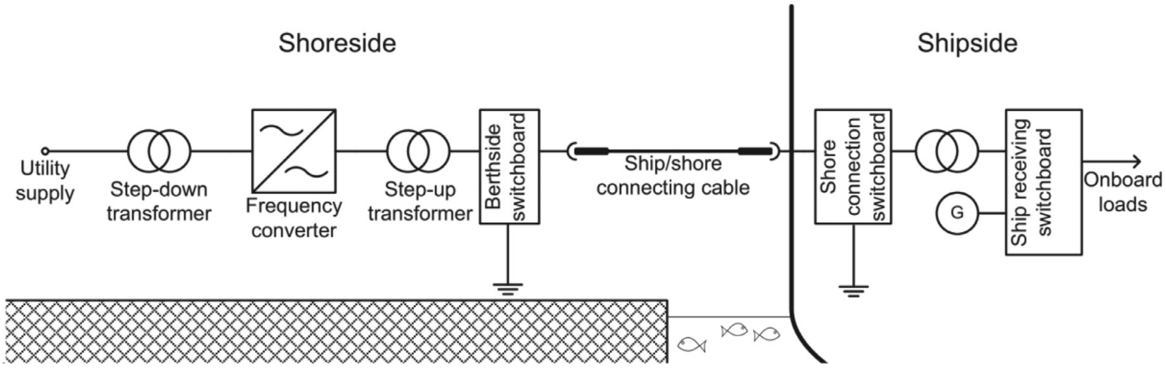

Fig. 1. A generic SP system (Sciberras et al., 2015).

(International Maritime Organization, 2019). In addition, multiple projects and initiatives have been proposed by other organizations to deal with the problems brought by ship emissions at berth. The Wuppertal Institute formulates three different pathways for the Port of Rotterdam to becoming a decarbonized port by 2050 (Wuppertal Institute, 2015). The World Ports Sustainability Program is initially set up by the International Association of Ports and Harbors to promote the sustainable development of the shipping industry, and a lot of organizations have signed up as strategic partners, including the American Association of Port Authorities (AAPA), the European Sea Ports Organization (ESPO), the International Association of Cities and Ports (AIVP), and the World Association for Waterborne Transport Infrastructure (PIANC) (World Ports Sustainability Program, 2018). In addition to voluntary programs, stringent regulations have also been imposed, and green technologies and emission control systems have been implemented. Europe and North America have mandated that ships at berth must use fuel with a sulfur content of no more than 0.1%, which significantly decreases the amount of SO_2 emissions from ships (International Maritime Organization, 2014). However, low-sulfur fuels are not the perfect answer. According to Port Authorities (2007), using lower sulfur fuel leads to only marginal reductions in NO_x (10%). Shore-side power is another reliable and effective solution; it allows ships to turn off their engines and plug into an electrical grid while at berth. A shore power (SP) system consists of three parts: a shore-side power supply system, a shore-ship connecting system, and a ship-borne power receiving system (Chen et al., 2019). The shore-side power system is located at a terminal. It receives electricity from the local power grid and then converts the electricity to voltages and frequency suitable for the ships. The shore-ship connecting system consists of cables joining the onshore power supply interface to the power receiving interface onboard. The ship-borne power receiving system receives power transmitted by the connecting system and uses it to power the onboard facilities. The structure of a generic SP system is shown in Fig. 1.

Shore power (SP), also known as “shore-side power,” “shore side electricity,” and “high-voltage shore connections (HVSC),”[2] is a promising approach to controlling exhaust emissions from berthing ships and mitigating air pollution problems in port areas. This approach transfers the power production from dirty onboard sources to much greener large-scale power stations, which are more efficient and more willing to adopt new energy resources that are environment-friendly, such as wind energy, nuclear power, and geothermal energy. Furthermore, central power stations are always located in remote areas to reduce the negative influence of exhaust emissions. As stated in the comments to the New South Wales Environment Protection Authority of Australia (2015), adopting shore-side electricity can reduce SO_2, NO_x, and PM emissions at berth by up to 90%[3] . And compared with the usage of low sulfur fuels, another widely adopted measure to reduce ship emissions at berth, SP performs better in the reduction of NO_x (He et al., 2020).

According to Sofiev et al. (2018), even with cleaner marine fuels, emissions from the maritime industry will still account for up to 250,000 deaths and 6.4 million childhood asthma cases annually. As a promising approach to reducing port emissions, SP should be urgently promoted and applied. Currently, there is a bottleneck in the development of SP. In some countries and regions, such as the United Kingdom (Department of Transport, 2019) and California (California Air Resources Board, 2020), the government has put in place regulations aimed at reducing maritime emissions in ports, and in these areas, SP is frequently adopted as one of the most efficient emission reduction methods. However, in regions that do not have such regulations, the development of SP is slow. Furthermore, the existing SP facilities are not frequently used. In an important study, Chen et al. (2019) identifies the barriers to SP in China, and quantifies the interrelationships among them. Currently, the economy for SP is one of the most important factors to affect the construction proportion and usage rate (Li, 2019; Tang et al., 2020). So, this paper extends the research of Chen et al. (2019) by reviewing the academic research and other relevant literature such as technical reports and governmental studies to identify the economic barriers and management deficiencies that hinder the extensive adoption of SP. It also identifies research opportunities, which may inspire researchers.

[2] Although they are called “high-voltage shore connections (HVSC),” shore power systems can provide electric power at different voltages for different users, such as 0.2–0.5 kV, 6.6 kV, and 11 kV.

[3] The application of SP does not completely eliminate emissions from ships at berth, as auxiliary boilers need to generate steam continually (American Association of Port Authorities, 2007; Wang et al., 2015).

The contribution of this paper is threefold. First, this paper conducts a systematic review of the economic problems in the application of SP, and both academic studies and related reports and regulations are reviewed. Second, based on the cost and benefit structure of different stakeholders, namely the shipping company, the port authority, and the government, economic barriers that hinder the development of SP are recognized. Third, promising solutions to the economic barriers and relevant research opportunities are identified in this paper.

The remainder of this paper is organized as follows. Section 2 summarizes the literature. Section 3 investigates the problem from the perspective of shipping companies. Section 4 considers the perspective of the port authorities. Government perspectives are summarized in Section 5. Section 6 presents the conclusion.

2. Literature review method

Before getting into a detailed review, we present a summary of the literature discussed in this paper. The studies are organized according to the point of view they represent. As the cost of installing and operating SP system varies according to the local situation, technical reports and governmental studies as well as academic investigations are reviewed in this paper.

We searched for relevant studies in various databases, including Web of Science, Science Direct, and Scopus, and found about 300 different academic studies of SP. First, we skimmed through the titles of all the papers, and got to know the field that each paper focuses on. For part of the papers, the main purpose is not to study SP, for example papers that aim to evaluate port emissions or explain the relationship between economy and air pollutions. We went through the abstracts of such papers, and it was revealed that they only have a small part that is related to SP and contains little information about SP other than common knowledge. Therefore, most of them were screened out. Secondly, among all the studies that focus on SP, a few of them investigate the technical details or machine design of SP system, which are not the key point of our paper. Therefore, we also ruled them out. In the rest of the papers, we picked studies that investigate the economic concerns in SP by fast reading. At the same time, we found out that a number of papers investigate SP for electric propulsive ships which consider the environmental benefits as well as economic loss and gain. Because most of the ships focus on the economic aspect while evaluating SP and there are only a small number of electric propulsive ships at present, we selected 3 representative papers and put them in the footnote. We paid attention to the papers that are still on the list, and read them one by one. In order to analyze the current status of SP, we tended to choose recent publications to be reviewed. Moreover, to make the review more comprehensive, the references in papers on SP were also used to identify relevant studies. The final sample included 42 studies investigating SP from different perspectives. Table 1 provides a summary of the publication years and journal titles of the scientific articles. Table 2 summarizes gray literature including 18 reports and governmental studies on SP projects in various countries, which are essential supplements to the academic literature and were found at the websites of the organizations that conducted the research or the government websites.

Although the technology of SP is not fully developed, at present, economic concerns are the main barrier to the extensive adoption of SP. Therefore, this paper focuses on the economic barriers. Different stakeholders are involved in the application of SP, including governments, port authorities, and ship owners/operators. For ships, as they are operated by commercial entities, the main driving force for the adoption of shore-side electric power is economic gain; ship owners mainly focus on the financial returns of their investment. However, port authorities have to consider both the economic and environmental gains and losses. The high installation costs for ports and ships and low popularity of the technology create a dilemma: ports are hoping for a large demand from ships, whereas ships will only embrace the technology when more ports are equipped with SP systems (Ship Technology, 2017). To break the deadlock and promote the implementation of SP, national and regional governments must provide support to both the port authorities and ship owners. In the following sections, we discuss the problem from shipping companies', port authorities', and governments' perspectives.

Among all papers listed in Table 1, Viana et al. (2014), Ballini and Bozzo (2015), and Merk (2014) show the significant environmental impacts of emissions from the shipping industry and explain the necessity of this paper. He et al. (2020) compares the environmental benefits of the application of low-sulfur oil and SP, and Sofiev et al. (2018) shows that the ship industry still account for great social welfare problems if low-sulfur oil is used. Li et al. (2019), Tang et al. (2020), and Song et al. (2017) imply that economic problems are main barriers to the extensive SP application.

Zhu et al. (2018), Fotis et al. (2017), Tang et al. (2018), Wang et al. (2015), Yu et al. (2019), and Winnes et al. (2015) focus on the ship retrofitting of single ships. Meanwhile, Zhen et al. (2020) put strength on the retrofitting decisions of a whole fleet. The principal–agent problem between shipping companies and captains is reflected by Zis et al. (2016), Feng and Li (2017), and Zis (2019).

A bunch of papers investigate economic problems in the SP application from the perspective of single port (Hall, 2010; Theodoros, 2012; McArthur and Osland, 2013; Wang et al., 2015, 2019; Ballini and Bozzo, 2015; Tseng and Pilcher, 2015; Winkel et al., 2016; Vaishnav et al., 2016; Innes and Monios, 2018; Cheng and Li, 2018; Peng et al., 2018a, 2018b,2019; Radwan et al., 2019; Hossain et al., 2019; Yang et al., 2019; Dai et al., 2020). Because relevant policies and costs vary largely, most of these papers choose a port or ports in a specific area to be analyzed. Cannon et al. (2015) and Wang et al. (2015) give examples of ports cooperating to promote the application of SP on board.

In the perspective of government, most studies focus on the government subsidies, which are the main approaches applied by governments to promote the SP application. Song et al. (2017), Li et al. (2020), and Dai et al. (2019) analyze the influence of the subsidy rate on the government's benefits. Wu and Wang (2020) propose a mathematical model to develop a subsidy program that

Table 1
Academic papers reviewed.

Journal/conference	Number of papers	Publication year (Number)
Applied Energy	1	2018(1)
Atmospheric Environment	1	2014(1)
Clean Technologies and Environmental Policy	1	2019(1)
Electric Power Systems Research	1	2017(1)
Energy	1	2018(1)
Energy Policy	2	2016(1), 2020(1)
Environmental Science and Technology	1	2016(1)
IEEE	2	2017(1), 2020(1)
In Foundations of Insurance Economics	1	1992(1)
International Academic Exchange Conference on Science and Technology Innovation	2	2020(2)
International Conference on Advances in Energy and Environment Research	2	2018(1), 2019(1)
International Conference on Advances in Energy Resources and Environment Engineering	1	2020(1)
International Conference on Transportation Information and Safety	1	2017(1)
International Council for Clean Transportation	1	2015(1)
International Transport Forum	1	2014(1)
Journal of Cleaner Production	2	2019(2)
Journal of Renewable and Sustainable Energy	1	2015(1)
Marine Policy	1	2019(1)
MEng thesis	1	2012(1)
Nature Communications	1	2018(1)
Ocean and Coastal Management	1	2019(1)
Ocean Engineering	2	2018(1), 2019(1)
Research in Transportation Business & Management	3	2015(3)
Resources, Conservation and Recycling	1	2010(1)
Sustainability	1	2018(1)
Transportation Research Part A	1	2019(1)
Transportation Research Part B	1	2020(1)
Transportation Research Part D	6	2013(1), 2015(1), 2018(1), 2019(2), 2020(1)
Transportation Research Record	1	2016(1)

Table 2
Reports and governmental studies reviewed.

Country or region of the institution/organization	Number of literature	Publication year (Number)
Australia	1	2015(1)
Canada	1	2017(1)
European Union	1	2015(1)
Hong Kong Special Administrative Region of the People's Republic of China	1	2015(1)
International	6	2009(1), 2014(2), 2016(1), 2017(1), 2018(1),
The People's Republic of China	3	2014(1), 2017(1), 2019(1)
The United Kingdom	1	2019(1)
The United States of America	4	2007(1), 2014(1), 2019(1), 2020(1)

maximizes the reduction of at-berth emissions from ships, considering the interrelationship between the implementation of SP at ports and no ships.

3. Shipping companies' perspective

3.1. SP retrofitting for a single ship

Ship owners' main concern is their economic profits, so their decision to install an SP facility and use shore-side electric power when berthing depends on the potential cost savings of this technology. In this section, we develop a basic model of a ship's annual energy costs at berth. After comparing the costs with and without an SP facility, a ship owner would choose the most economical method. The cost of fuel consumed by boilers and facilities other than auxiliary engines while berthing is unchanged by the application of SP, so it is omitted in the model. At present, only a limited number of berths can provide electric power to ships, so ships can only use SP at certain ports. Therefore, we introduce α to represent the proportion of berths with SP among all of the berths that are visited by a ship. Our equations calculate the basic energy source costs of berthing with and without an SP facility.

We list the notations before giving the concrete expression of a ship's annual cost of energy at berth with and without an onboard SP system:

α	The percentage of berths with SP among all the berths that are visited by the ship
β_E	Shore side electricity price (USD/kW·h)
β_F	Traditional fuel price (USD/ton)
C_{Fuel}	Annual cost of energy source at berth when traditional fuel is the only energy source (USD/year)
C_{In}	The average annual installation cost of shipside SP facility (USD/year)
C_M	The annual maintenance cost of ship-side SP facility (USD/year)
C_{SP}	Annual cost of energy source at berth when the ship is equipped with SP facility (USD/year)
Q_E	The power required by the ship for an hour at berth (kW)
Q_F	The fuel consumed by the ship for an hour at berth (ton/hour)
T	The average time of berthing (hour)
V	The number of berths the ship visits each year

The annual energy source costs to berth a ship with and without SP facilities are calculated as follows:

$$C_{SP} = C_{In} + C_M + \beta_E \times Q_E \times \alpha T \times V + \beta_F \times Q_F \times (1-\alpha) T \times V \quad (1)$$

$$C_{Fuel} = \beta_F \times Q_F \times T \times V. \quad (2)$$

In general, when $C_{SP} < C_{Fuel}$, the ship owner will choose to equip the ship with SP facilities. Otherwise, the ship owner will not install SP facilities.[4] It is assumed that SP is more economical than auxiliary engines, namely, $\beta_E \times Q_E < \beta_F \times Q_F$. Otherwise, the ship operator will decide to use auxiliary engines on all visits. Various studies and reports have demonstrated that all of the parameters in the above functions directly affect ship owners' decisions. The cost function we propose is close to the model proposed by Song et al. (2017). However, in our calculation, the percentage of berths visited by the ship that provide SP is considered. The parameter α reveals that only a limited number of ports are equipped with SP facilities. It also indicates that the decision to install an SP facility is influenced by the berths a ship visits. For ships that visit fixed berths, e.g., liner ships, α is especially influential.

[4] There are studies that focus on electric propulsive ships take ship emissions into consideration while deciding on the shore power system installation or management. Zhu et al. (2018) propose a model to optimize the design of ships' hybrid electric propulsive systems, which includes the SP system. Fuel consumption, greenhouse gas (GHG) emission, and lifecycle cost are considered in the objective function. Fotis et al. (2017) and Tang et al. (2018) focus on the management method for ship's energy system, which includes the SP facility, to minimize the operation cost, with the limit of GHG emission.

Installation and maintenance costs. Among the costs required to make use of SP, the installation cost (C_{In}) and maintenance cost (C_{M}) are the largest and most widely discussed. The ship-side investment for an SP system is very costly and varies significantly ($50,000[5] to $2 million), depending on vessel type (Wang et al., 2015; IMO, 2018), ship size (City of Los Angeles Harbor Department Environmental Management Division, 2014), and the need for an onboard transformer (American Association of Port Authorities, 2007). However, the popularization of the technology and the development of manufacturing technology has led to a decreasing trend in the cost of ship retrofitting. This is a positive development, as a lower installation cost increases the annual cost saving ($C_{\mathrm{SP}} - C_{\mathrm{Fuel}}$), increasing ship owners' motivation to adopt SP. Yu et al. (2019) make decision on whether to install SP onboard and when to install, considering the payback period of the project.

Demand for SP. In addition to the initial installation cost and the maintenance costs, the operations of ships, such as the berthing time $V \times T$ and power demand Q_{E}, also affect the potential economic benefit of an SP system. Winkel's (2015) systematic review of SP benefits in Europe reveals that SP is most attractive to ships with high energy demands while berthing, because with the same bunker fuel and SP price, they enjoy more significant economic benefits than other ships. For similar reasons, SP is most popular among cruise ships, container ships, and RoRo ships (Roll On–Roll Off cargo ships and ferries), which have high energy demands (American Association of Port Authorities, 2007; Winnes et al., 2015). These three types of ships are the main consumers of shore-side power.

Most existing studies consider ship retrofitting the best way for ship owners to use the SP technology, but this ignores the influence of the length of the remaining service lives of ships. In fact, building new ships with SP facilities rather than retrofitting is another option for ship owners. In practice, ship owners operate ships in various conditions with different remaining service lives. For ships nearing retirement, reconstruction has a high annual average installation cost and this reduces the potential benefits. However, constructing a new ship with SP facilities requires a long lead time, usually two to three years. Retrofitting ships helps ship owners take advantage of SP as soon as possible, but ordering new ships with SP facilities lowers the annual average installation cost. Therefore, ship owners' decision to either retrofit the ships they already have or to save the investment for new ships is a key factor in the uptake of SP.

3.2. SP retrofitting for a fleet of ships

Large shipping companies operate fleets of ships. The ships in a fleet are deployed in a number of cargo trades in a holistic manner that minimizes the total cost. A company can retrofit a portion of the fleet with SP facilities, and then deploy these ships on cargo trades that require ships to frequently visit ports with an SP infrastructure. Zhen et al. (2020) examine the optimal installation of SP and/or scrubbers (a cleaning system that removes SO_2 from ship exhaust gases) on ships and consider the deployment of ships, sailing speed determination, and cargo routing in a holistic model. They find that it is preferable for either all of the ships deployed on the same route to install SP or for none of them to install it.

In practice, a certain period is required to retrofit ships; ships cannot be deployed for the duration of the retrofit, and ship owners will suffer from income reduction. As the ships adopted in the liner shipping industry sail on a predetermined schedule, managing the retrofitting work to minimize income loss is challenging for ship owners. This problem deserves more attention from academia.

3.3. Using SP at ports: the principal–agent problem between shipping companies and captains

Ships with existing ship-side facilities do not always use SP at berths that have an available SP source. The traditional fuel price (β_{F}) influences this decision (Zis et al., 2016; Feng and Li, 2017; Zis, 2019), and when $\beta_{\mathrm{E}} \times Q_{\mathrm{E}} \geq \beta_{\mathrm{F}} \times Q_{\mathrm{F}}$ the operator will choose to use auxiliary engines. Even when the cost of using SP is lower than the cost of using bunker fuel, ships equipped with SP facilities are still reluctant to use the SP. According to the practitioners we talked to, the main reason for this hesitation is as follows. Captains,[6] to a large extent, have the authority to decide whether to use SP; captains must also supply the labor (e.g., manpower for SP connection and disconnection, monitoring the SP system). However, the cost savings of using SP accrue only to the shipping company. This is a typical principal–agent problem (Grossman and Hart, 1992): the captain (the agent) acts on behalf of the shipping company (the principal) but the captain is motivated to act in his own best interests, which in this case are contrary to those of the shipping company.

The principal–agent problem hinders the extensive adoption of SP. Due to the nature of ship operations, the captain's attitude has a great influence on the ship-side SP system utilization rate. Shipping companies could adopt the following basic rules to address the principal–agent problem and motivate the captain to use SP whenever it saves costs: (i) stop using SP when the electricity price is above a certain threshold; and (ii) compensate the captain for each time SP is used. These rules could drive improvements in SP facility use ratio and the benefits to shipping companies of retrofitting their ships. Studies of the factors that affect policy determination, including the SP price threshold and the amount of compensation, would be of high value to researchers and practitioners.

[5] We use '$' to represent US dollars, unless otherwise specified.

[6] Here we use "captain" to refer to the captain and crew.

4. Ports' perspective

4.1. Single ports

4.1.1. Cost-benefit analysis of installing SP infrastructure

In this subsection, we analyze the cost and benefits of SP infrastructure installation for a single port. As power stations that supply the national grid with electricity are always located in remote areas, their emissions have less influence on port environments. Therefore, in this section, we ignore the exhaust emissions that result from generating the extra electricity for ships.[7]

We list the notation before giving the concrete expression of the benefit of SP installation to a port:

α_{SP}	The percentage of ships visiting the port that use SP at berth
β_E	Shore side electricity price (USD/ kW·h)
β_G	Electricity price of power grid (USD/ kW·h)
B	The annual economic and environmental benefit for the port by installing the SP infrastructure (USD/year)
B_{Env}	The environmental benefit of reducing a tonnage of fuel (USD/ton)
C_{InP}	The annually average installation cost of shore-side SP infrastructure (USD/year)
C_{MP}	The annually maintenance cost of shore-side SP infrastructure (USD/year)
N	The number of ships that visit the port each year
Q_E	The power required by the ship for an hour at berth (kW)
Q_F	The fuel consumed by a ship for an hour at berth (ton/hour)
T	The average berthing time of ships (hour)

The annual benefit to a port of providing SP to ships can be calculated as follows:

$$B = \alpha_{SP} N \times \left[Q_F \times T \times B_{Env} + Q_E \times T \times \left(\beta_E - \beta_G \right) \right] - C_{InP} - C_{MP}. \quad (3)$$

As indicated by Eq. (3), providing electric power to ships requires investment in infrastructure, maintenance costs, and extra payments to the power company for the electricity. The benefits of this service include emission reduction and revenue from selling SP to ships. Port authorities tend to invest in SP only if they will gain from the project ($B > 0$). Due to the differences in SP capacity and existing port infrastructure, the investment and costs (C_{InP}, C_{MP}, β_G) vary between ports, but the environmental benefits of reducing fuel consumption at berth (B_{Env}) is closely related to port location. A series of studies have been conducted to examine this issue for different ports or regions. We extract the model from Song et al. (2017), but make slight changes. In our model, the environmental benefits of SP are included in the port's profit, as port authorities are always guided by their local governments, which are concerned about environmental pollution and air quality. In the remainder of this section, we focus on the elements that affect revenue and costs.

Potential environmental and health benefits. The environmental benefits of emission reduction ($\alpha_{SP} N \times Q_F \times T \times B_{Env}$) have a strong influence on the decision to supply SP. The greater the environmental benefit, the more willing the port authority is to invest in SP. To analyze these benefits, it is essential to know the volume and economic effect of the emissions. A number of studies investigating these issues are reviewed here. Studies of different ports or regions have been conducted, including studies of the Port of Shenzhen (Wang et al., 2015), the Port of Bergen (McArthur and Osland 2013), the Port of Aberdeen (Innes and Monios 2018), and other European ports (Winkel et al., 2015, 2016). Dai et al. (2020) innovatively discuss the environmental effects of SP including the influence of the extra berthing time, which is one consequence of the use of SP. To match their predetermined schedules, ships sometimes need to speed up and discharge more emissions, which has a strong influence on the overall environmental benefits of SP. Tseng and Pilcher (2015) roughly estimate and compare the cost of installing SP system and the potential pollutant emission reduction, and study the potential of SP for the port of Kaohsiung, Taiwan.

Percentage of visiting ships that use SP. The percentage of visiting ships that adopt SP (α_{SP}) is a crucial factor in calculating the overall benefit of SP adoption (Cheng and Li, 2018). Given a constant number of visiting ships, a port's benefits increase with α_{SP}. Vaishnav et al. (2016) compare the economic costs of SP systems and their benefits in US ports. They find that when a quarter to two thirds of the ships calling at US ports use SP instead of auxiliary engines while berthing, namely, $\alpha_{SP} \in [25\%, 67\%]$, environmental benefits equal to $70–150 million can be achieved, depending on the assumed social cost of pollution. According to Ballini and Bozzo (2015), 60% of ships using SP the system will bring €2.97 million (approximately $3.3 million) external health savings for the Port of Copenhagen.

Installation and maintenance costs. The influence of installation costs (C_{InP}) and maintenance costs (C_{MP}) on port authorities' decision to build an SP facility is straightforward. According to official statistics from the Government of Canada (2017), the installation of SP facilities by ports (C_{InP}) varies from $347,477 to $5,000,000. A note published by the World Ports Climate Initiative (WPCI, 2016) gives the methodological framework for calculating the cost structure of SP usage. In this note, the annual maintenance cost (C_{MP}) is calculated as approximately 5% to 10% of the initial investment (C_{InP}). According to the survey (Electrical and Mechanical Services Department, 2015), installation investment for the Kai Tak Cruise Terminal in Hong Kong is HK$315 million (approximately $40.5 million), and the annual maintenance and operation cost is estimated to be HK$14 million (approximately $1.8 million) per year. Peng et al. (2018b, 2019) make an investigation of the allocation and the power capacity of a port's SP system, balancing

[7] Some papers consider power station emissions when evaluating an SP. Hall (2010) and Theodoros (2012) find that not all countries accrue environmental benefits from providing power to ships, and that the benefits depend on the national energy source structure. Peng et al. (2018a) state that the emission reduction volume of SP will decline if the emissions of power generation is considered.

between the installation as well as maintenance costs of the SP facilities and emission reduction volume. Building a two-stage model, Wang et al. (2019) propose a framework to design a hybrid renewable energy system for seaports, which includes the wind energy, energy storage, and on-shore power supply systems. And the installation and maintenance costs of SP system are contained in the objective function.

Electricity price of power grid. In addition to the cost of installation, the ports' increased electricity cost (β_G) is another crucial factor, as the selling price of SP must be relatively low to encourage ships to use SP. If the local power grid charges a high electricity price (β_G), the port will not be able to make a profit by selling power to ships; sometimes, to encourage ships to use SP, the SP price (β_E) is set to be lower than β_G. This will definitely lessen port authorities' enthusiasm for the system. A series of papers have considered this effect. Dai et al. (2019) examine the case of the Port of Shanghai, and Radwan et al. (2019) examine the case of the Port of Djibouti.

In practice, the installation cost varies, and models that consider this variability can help port authorities to choose the optimal time to invest in SP. Further research on this topic has practical value because it could help to further decrease the SP port-side costs.

4.1.2. Compulsory SP usage and incentive measures

California has compulsory requirements for the use of SP. The state government has imposed regulations to reduce the air emissions from ships docking at berth. Fleet operators have to turn off auxiliary engines and connect to some other source of power, most likely a grid-based SP; or use alternative control technology that can achieve an equivalent emissions reduction. According to the California Air Resources Board (2020), beginning on January 1, 2020, a fleet visiting a California Port should 1) assure that at least 80% of the fleet's visits to the port meet the onboard auxiliary diesel engine operational time limits; and 2) reduce the onboard auxiliary-diesel-engine power generation while docking at the berth by at least 80% from the fleet's baseline power generation. To the best of the authors' knowledge, California is currently the only jurisdiction to implement compulsory SP usage.

In addition to compulsory measures, incentives can be adopted to encourage ships to access an SP grid. China has stipulated that, from February 1, 2020, ship visits that use SP will be provided with a higher berthing priority and will get a reduced SP service fee; furthermore, ships that actively use SP at local ports will be given right of way when sailing through the area (Ministry of Transport of The People's Republic of China, 2019). In Canada, the incentive measures in some ports, including the Port of Vancouver and the Port of Prince Rupert, are in the form of reduced port fees and certificates of environmental performance (Hossain et al., 2019). To a certain extent, these incentives sacrifice the economic revenue, the port service level and navigational channel resources to improve the SP utilization rate, but they are more moderate than compulsory rules.

Incentives to improve the utilization of existing portside SP facility have direct effects on environmental benefits. As ship operators are the decision makers on SP utilization, regulations and policies that encourage them to adopt SP are promising methods to increase port authorities' benefits. Relevant research helps port authorities to determine the optimal subsidies for maximizing their benefits. The compulsory usage regulation adopted by ports in California might get instant results, but such strong regulations may not be suitable for ports in a weak position in fiercely competitive environments and could become a disadvantage (Yang et al., 2019). Economic awards or subsidies are a promising approach, but a compensation-only approach is costly. Therefore, a policy that combines rules and financial rewards is much needed; studies on the optimal balance would be very helpful to port authorities.

4.2. Port collaboration to promote SP

Port collaboration is an efficient way to contribute to the environmental protection. For example, the European Sea Ports Organization leads the program "EcoPorts", which aims to improve environmental management through cooperation and knowledge sharing among ports (European Sea Ports Organization, 2020). There are some successful implications of such collaboration in the promotion of SP. As mentioned, the percentage of berths that a ship visits that provide electric power is a critical factor in ship owners' decision to retrofit their fleet. Naturally, when two ports collaborate and install compatible SP systems, this will greatly encourage ships that visit both ports to invest in an SP facility. Therefore, ports can improve the SP usage by cooperating with larger SP programs. This is called the ripple effect or network effect of port collaboration in SP implementation. Collaboration also allows ports to share information on technology, strategy, and policy.

One example of ports cooperating to maximize the utility of SP systems is the cooperation between Shanghai Municipal Transportation Commission (SMTC, formerly Port of Shanghai) and the Port of Los Angles (POLA) (Cannon et al., 2015). Another example is the collaboration of the Port of Shenzhen with ports in California (Wang et al., 2015). To reduce concerns about the high installation costs of SP systems and to benefit from the network effect, the Shenzhen government is collaborating with ports in California and developing shipping lanes between Shenzhen and California. Expanding this bilateral collaboration to multilateral co-operation might further improve the network effect and contribute to increases in SP utility. The different forms of cooperation among ports and their influence on SP implementation deserve further investigation.

5. Governments' perspective

To reduce barriers and promote the implementation of SP, national and regional governments have subsidized interested parties, including ports and ship owners. This section focuses on studies of the use of subsidies. There are two main types of subsidies provided by governments: subsidies for SP system installation, which are discussed in Section 5.1, and subsidies for SP utilization, which are discussed in Section 5.2.

5.1. Subsidies for SP installation

National and regional governments have provided subsidies for ship operators and ports that install SP systems. According to the notice of the Ministry of Transport of China (2017), port authorities and ship owners that finished SP projects in 2016, 2017, and 2018 can receive subsidies covering a maximum of 60%, 50%, and 40% of the equipment purchase costs, respectively. In Shenzhen (Shenzhen Transportation Commission et al., 2014), the government subsidizes ports for up to 30% of the SP construction cost. The Canadian Government has invested up to C$5 million (approximately $3.8 million) into SP projects such as retrofitting the Port of Montreal, the Port of Halifax, and the Port of Vancouver Fraser (The official website of the Government of Canada, 2017). The European Commission's European Marco Polo Program to reduce traffic congestion subsidizes up to 20% of the eligible cost of SP infrastructure construction. Furthermore, the European Union subsidizes 20–50% of the SP implementation cost for private operators (Ship Technology, 2017).

A few studies of government roles have identified subsidies as the best approach for government involvement. Song et al. (2017) examine the application of SP to a single port from the point of view of system design and investigate the detailed benefits for all of the interested parties. Unlike other papers focusing on this topic, Song et al. (2017) treat the port and government as two separate parties connected by government subsidies. The port is interested in its economic gain, whereas the government is providing ports that are installing SP facilities with substantial subsidies to gain environmental benefits. Song et al. (2017) also analyze how subsidy rates, shore-side power and on-grid power prices, and the annual utilization of shore-side and ship-side facilities affect the distribution of benefits among the stakeholders. Li et al. (2020) investigates the governmental SP subsidy mechanism and its effect on the SP promotion.

A government has to allocate its limited subsidy budget to maximize the total benefits and will be influenced by the characteristics of the potential recipients. The interaction between the installation of ship-side facilities and shore-side facilities that was mentioned above makes this allocation problem more complex. For instance, equipping a port (P) with SP facilities will improve the potential environmental benefits gained from retrofitting ships that service the shipping line (G_P) that visits the port, and creates incentives for the government to subsidize G_P. In turn, a shipping line that has ships with SP systems increases the potential benefits of subsidizing the ports they visit. Wu and Wang (2020) study a SP deployment problem in a container shipping network from the perspective of the government. They develop a subsidy program that maximizes the reduction of at-berth emissions from ships in the network. A two-stage optimization model is used to describe the problem, and it is solved by a tailored labeling algorithm. Adding ships that operate in international shipping lanes further complicates the problem, as they visit foreign ports that are governed by other countries with other policies. Further research on this problem must take SP regulations and SP system implementation in multiple countries into account. This expansion is necessary, as ships operating in international shipping lanes constitute a high proportion of the traffic in large ports.

5.2. Subsidy for SP utilization

At present, the utilization rate of SP system at port is low, especially in areas without stringent regulations about the ship emissions reduction. Data show that in China a large number of existing SP facilities at ports have high idle rates, and one of the main reasons is the low demand. Only 11.5% of the ships that have SP system choose to connect to SP while berthing (Port Technology and Green Port, 2018). Subsidies to improve the SP facility utilization rate is a feasible solution to this problem. To make the SP price attractive, a government can subsidize the port authority's electricity cost. Dai et al. (2019) conclude that, for the Port of Shanghai, subsidizing electricity prices is more effective than just financing the facilities' implementation, and helps to avoid great financial losses at ports. In Shenzhen (Shenzhen Transportation Commission, 2014), the port authorities with SP infrastructure supply ships with electricity at the price of CNY0.7/kW·h (approximately $0.1/kW·h). The gap between the SP price and the price of electricity from power grid will be covered by government subsidy. In addition, a subsidy will be given to cover part of the annual maintenance cost, and the amount should not exceed 10% of the annual electricity cost.

Apart from a competitive SP price, other subsidies that encourage ships to use SP could be implemented. For instance, the government could cover part of the port charges and taxes for ship visits that take advantage of shore electricity. To determine the best subsidies, optimization models must be developed that balance the environmental benefits and costs. Studies that focus on this topic will benefit policy makers and help them to achieve a remarkable effect at the lowest cost.

6. Conclusion

Shore power, a promising approach to reducing emissions from docked ships, is drawing increasing attention from scholars around the world. Studies have investigated problems related to SP from different stakeholders' point of view. Economic concerns and management deficiencies are the major barriers to the wider application of SP. This paper reviews studies of these problems from three perspectives, ship owners/operators, ports, and governments. Basic models that demonstrate the costs and benefits of SP equipment installation for port authorities and ship owners are presented. Studies of the regulations and policies adopted by ports to raise the utility rate of their SP facilities are also reviewed. As most governments' involvement has been focused on providing subsidies to other participants, i.e., port authorities and ship owners, the subsidy standards in various countries are listed as well as academic research on optimizing subsidies. In addition to reviewing the literature, this paper identifies valuable research opportunities in the field of SP.

Reviewing the literature and analyzing the cost and benefits structure of different stakeholders reveals that the low utilization of existing SP systems is one of the main barriers to increasing SP implementation. Removing the obstacles requires joint action from all three interested parties. Port authorities, with the support of their governments, could encourage ship operators to use SP by implementing regulations and providing subsidies. The shipping companies, given the principal–agent problem, could obtain higher benefits by compensating captains for using SP.

We hope that this paper provides a foundation for future research in the area and some direction for scholars interested in this issue. It would be an honor if this paper were helpful to others.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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