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Carbon emission reduction of shore power from power energy structure in China

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With the construction of China's ecological civilization and the proposal of carbon peaking and carbon neutrality goals, shore power has been vigorously developed as an important technology for the future green development of ports. However, China's electricity is still mostly coal-fired, which produces many carbon emissions. Coupled with regional differences, shore power is by no means certain to lower carbon emissions compared with fuel throughout China. Considering the power energy structure in different regions, this paper establishes a carbon emission correlation model between fuel and shore power during ship berthing, calculates the feasibility and actual emission reduction effect of shore power in coastal ports, and studies the restriction condition of starting time for the use of shore power for ships attached to ports according to the national policy of mandatory use of shore power. The results show that only a small part of coastal provinces and cities are suitable for using shore power, and it is limited by the berthing time of the ship. However, this condition is not related to the size of ships but related to the proportion of power generation. Therefore, the government should develop shore power according to local conditions, and vigorously increase the proportion of clean energy, so that the shore power truly achieve zero carbon emissions.

KEYWORDS
shore power, power source, carbon emissions, power energy structure, actual emission reduction effect

1 Introduction

With the continuous rise of global temperature, greenhouse gases, especially carbon emissions, have attracted much attention from all over the world. In 2020, China pledged to achieve peak carbon emissions before 2030 and to strive to achieve carbon neutrality before 2060 (Sun et al., 2022). The transportation sector has an important role to play in achieving carbon peaking and carbon neutrality goals. As one of the industries difficult to decarbonize (Sharmina et al., 2021), the shipping industry has been attempting to take various measures to reduce the carbon emissions of ships, such as a carbon tax (Ding et al., 2020), ship speed optimization (Cariou et al., 2019), low-carbon fuel and alternative power (Xing et al., 2020), etc. These measures are mainly to reduce the carbon emissions of ships during navigation, but ships also consume fuel and produce CO_2 in the process of berthing operations. Therefore, shore power, as one of the ways to reduce carbon emissions in port operations, has been widely studied and promoted in recent years (Lathwal et al., 2021).

Shore power refers to the power supply that connects to the power supply on the dock and turns off the ship's generator when the ship docks so that the power load on the ship can be transferred to the shore seamlessly. It consists of three parts: the shore power system and infrastructure, the cable management system and the ship-side power system (Chen et al., 2019; Peng et al., 2020). It can not only effectively reduce ship emissions by approximately 48-70% during the ship's stay in port (Zis et al., 2014) but also eliminate the noise and vibration caused by the operation of the ship's generator. It is especially suitable for vessels with relatively fixed routes, large power consumption and high air pollutant emission levels when docking, such as container ships, ferries, cruise ships and medium and large bulk carriers (Dai et al., 2020).

With the attention of environmental protection in China, shore power as an effective way of saving energy and reducing emissions, has been vigorously promoted. By the end of 2021, port power facilities had covered approximately 7,500 berths across the country, with 75 percent coverage of five specialized berths, including container, passenger rolling, cruise, and passenger transport of over 3,000 tons and dry bulk cargo of over 50,000 tons (Zhang, 2022). However, due to the time-consuming connection of shore power and the lack of standardization in various countries (Yin et al., 2020) its utilization rate is less than 20% (Wang, 2022), In this regard, the Ministry of Transport proposed mandatory measures (MOT of the PRC, 2021): "If a ship with power-receiving facilities berths in a coastal port with shore power facilities for more than 3 hours and berths in an inland river for more than 2 hours, it shall use shore power. Otherwise, it will be punished based on the total power of the ship's generator set, combined with the power of the ship's generator set and the length of berthing." However, from the perspective of shore power sources, the power source will also produce carbon emissions in the process of power generation; therefore, whether it is truly low carbon compared with fuel is controversial. At present, thermal power generation accounts for 71.13% of the total in China; hydropower and other new energy sources account for 28.87% (NBS of the PRC, 2021). It can be seen that thermal power generation is still the main source of carbon emissions. In addition, there are certain differences in the power consumption of different areas: hydropower has dominated the central part, the coastal areas have good nuclear power generation, and northwestern and northern China have good resources for wind power and solar power generation, but there is almost no clean energy power generation in the northeastern inland areas. Different provinces with ports also have different proportions of electricity and energy; therefore, mandatory measures may not be applicable to all areas, and the mandatory berthing time also needs to be verified.

Therefore, to further study the emission reduction effect of shore power compared with fuel, we verify the feasibility of shore power in different provinces and cities from the perspective of power sources, obtain specific conditions for using shore power, such as berthing time, and propose suggestions on the response strategies of each province and city according to the current shore power policy. This paper establishes a carbon emission correlation model between fuel and shore power during ship berthing and compares the carbon emissions generated using fuel and shore power to provide a reference for the promotion of shore power in different areas. The rest of this paper is organized as follows: Section 2 presents a literature review of shore power sources, emission reduction effects, and promotion optimization. Section 3 describes the methodology, including problem definition, symbolic terminology and mathematical models. Section 4 conducts a case study on the feasibility and conditions of using shore power in coastal port provinces and cities. Finally, Section 5 summarizes the conclusions and policy implications.

2 Literature review

Shore power is one of the important measures to reduce carbon emissions in ports. Current research has mainly focused on the emission reduction effect of shore power and how to promote and optimize shore power in terms of environmental issues.

2.1 Traceability of shore power

The carbon emissions of shore power are closely related to the method of electricity generation; that is, the actual energy mix of the grid, such as coal, nuclear energy, photovoltaic energy, etc., should be considered (Peng et al., 2019). For a cleaner and greener environment, the development of renewable energy is very important to reduce air pollution by using shore power (Kotrikla et al., 2017). Studies have shown that the source of electricity has gradually shifted from thermal combustion to wind energy, tidal energy, and solar energy (Kalikatzarakis et al., 2018). Among them, wind energy, as a clean, natural and abundant renewable energy source, has high global potential. However, according to Kumar et al. (2016), while offshore wind resources are more promising than onshore resources and can compete with fossil-fuel power plants in terms of efficiency and output, there is no advanced technology to fully utilize them. There are also scholars studying wave-power generation for sustainable coastal development, but there are challenges such as high costs (Xu and Huang, 2018). Solar energy is not conducive to the stable operation of the power grid because of its large randomness, intermittency and volatility (Gao et al., 2022). Therefore, renewable energy is still unable to meet the power demand of ships in the short term.

According to the CEC data of the PRC (2020), China's electricity energy is still dominated by fossil-fuel thermal power generation. Although the development of hydropower resources in clean energy has been very high, tidal power generation has long been established as a demonstration project, but it has not been promoted. In the future, China's power generation method will gradually change to new energy sources such as wind energy and solar energy as the core sources and hydropower as the auxiliary source, thereby gradually reducing the proportion of thermal power in the overall power system (Zhang et al., 2015). Therefore, from the perspective of shore power traceability, the widespread use of shore power is an inevitable trend, but it is currently affected by the cleanliness of the power generation energy. The emission reduction effect of shore power needs to be improved.

2.2 Emission reduction effect of shore power

Shipping is increasingly recognized as an important source of air pollutants such as NO_x, SO_2, CO, particulate matter (PM) and the main greenhouse gas, CO_2. Most CO_2 emissions from shipping occur during the time ships spend in port (Styhre et al., 2017). Some scholars taking Guangzhou Port as an example compared the environmental benefits of two emission reduction measures using low-sulfur oil and shore power technology. The results showed that shore power has significant advantages in reducing NO_x emissions (He et al., 2020). In addition, quantitative calculations for Kaohsiung Port have shown the long-term potential of shore power to improve environmental and socioeconomic conditions by reducing port emissions (Tseng and Pilcher, 2015). To reduce air pollution, the Italian government has considered using shore power to reduce air pollution caused by ships and has conducted an economic analysis (Adamo et al., 2014).

However, some scholars are skeptical about the emission reduction effect of shore power. The European Commission has been hoping for a shift to an energy-efficient model for shipping, but research has shown that the implementation of shore power can be challenging. For most EU member states, shore power will help reduce CO_2 emissions, but the proportion of power generation energy varies from country to country; therefore, not all maritime countries can use shore power to reduce CO_2 emissions (William, 2010). In countries with a high carbon content in the electricity supply, the use of shore power from the national grid can lead to increased carbon emissions compared to the use of standard diesel generators (Winkel et al., 2016). In addition, according to the requirement of "connecting shore power first, then loading and unloading operations", it takes time for ships to connect to shore power, which may cause delays. If the carbon reduction effect of shore power is considered from the perspective of the entire voyage, the increase in carbon emissions due to delays caused by shore power can almost be offset by the reduction in shore power (Dai et al., 2020). Therefore, the actual emission reduction effect of shore power needs to be considered and studied in various aspects according to the characteristics of different areas.

2.3 Promotion and optimization of shore power

The research of Chen et al. (2019) shows that the promotion of shore power is subject to 12 constraints in four aspects: technological application, economic cost, operation management, and policy system. The most critical among them are the policy support system, the construction standards for shore power, and the laws and regulations. From the perspective of technical application, Tang et al., (2018) proposed a hybrid energy system including shore power, offshore photovoltaics, batteries, and diesel, considering different shore power prices and emission policies and optimizing them. There have also been discussions on the challenges of shore power technology to the voltage, frequency, power and other technical requirements of ships and onshore ships. By comparing various shore power technologies, it has been recommended to adopt new shore power technologies compatible with TN and IT standards (Kumar et al., 2019; Wu et al., 2013). In response to the high initial investment and operating costs of shore power and the lack of attractiveness, Dai et al. (2019) proposed an environmental and technical–economic analysis framework combined with an emissions trading scheme (ETS) to evaluate the economic feasibility of shore power, because shore power investment in the port is only economically feasible if the port can profit from the sale of electricity. Tan et al. (2021) established a ship selection behavior model for the economics of shore power to assist shipowners in making decisions about using shore power or fuel. The inland river shore power service evaluation system was established to realize an evaluation of the environmental benefits of a shore power system in a designated area.

In addition, the optimization of shore power can mainly be considered from the perspectives of shipowners, ports and governments (Qi et al., 2020). From these three perspectives, economic problems and management defects are the main obstacles to the wider application of shore power. In addition, government subsidies play an important role in the deployment of shore power (Wu and Wang, 2020). Therefore, it is necessary to strengthen the cooperation among shipowners, ports and governments.

At present, the research on shore power has mainly focused on the development and overall promotion and optimization of shore power. Few scholars have considered the inconsistency of the power energy structure in different areas of China from the perspective of shore power sources and the actual emission reduction effect of shore power relative to fuel. There is a lack of research on shore power construction strategies according to local conditions. Therefore, this paper traces the source of shore power, mainly considering thermal power, hydropower, nuclear power, wind power, solar power and other power generation methods. Combined with the power energy structure in different areas, the carbon emission correlation model between fuel and shore power during ship berthing is established, and the calculation of the actual emission reduction effect is completed. Finally, the necessary conditions for the berthing time for ships to use shore power to achieve carbon emission reduction are determined, and pertinent suggestions for realizing the construction of shore power in Chinese ports according to local conditions are proposed.

3 Methodologies

3.1 Problem definition

The purpose of this paper is to study the real emission reduction effect by using shore power instead of auxiliary engine fuel for ships calling at Chinese ports, considering the power traceability of the shore power system. The main issues can be divided into the following two parts:

(1) Under the current power energy structure of coastal provinces and cities in China, how can we determine whether the ports of each province or city are suitable for using the shore power system?

(2) What is the specific emission reduction effect of different ships using shore power? What are the basic conditions for determining that a ship is suitable for using shore power?

This paper solves the above problems by establishing a mathematical model. The main parameters involved in the model are given below:

where Y_i is the amount of carbon emissions reduced o from ship i using shore power instead of fuel during the berthing operation, g;

Δ is the marginal carbon emission reduction benefit from a ship using shore power, g/kWh;

CE_{Fi} is the carbon emissions from fuel used by ship i at berth, g;

CE_{Ei} is the carbon emissions from the whole process of shore power usage from ship i at berth, g;

CE_{EFi} is the carbon emissions from preparing the shore power for ship i, g;

CE_{EEi} is the carbon emissions from using the shore power by ship i, g;

$FC_i$is the fuel consumption of ship i at berth, g;

EC_i is the total electricity consumption using the shore power by ship i at berth, kW;

EC_{Gi} is the electricity required by ship i when using shore power, kW;

EC_{Ti} is the power loss when ship i uses shore power, kW;

FC_{Ei} is the fuel consumption for preparing the shore power for ship i, g;

P_i is the auxiliary rated power of ship i, kW;

LF is the auxiliary engine load factor of the ships at berth;

SFC is the amount of fuel required per unit of electricity, g/kWh;

T_i is the dwell time during loading and discharging of ship i at berth, h;

t is the time for preparing shore power, h;

$T^*$is the basic berthing time of a ship for carbon emission reduction by using shore power, h;

GT_i is the gross tonnage of ship i, GT or TEU;

DT_i is the deadweight of ship i, t or TEU;

v is the handling efficiency of the port of call, t/h or TEU/h;

Y_{F} is the carbon emission factor of the fuel used by marine auxiliary engines;

Y_{EJ} is the average carbon emission factor of energy j;

η_j is the proportion of power generation of energy j in an area; and

μ is the average power loss factor.

3.2 Mathematical model

In this section, a shore power–fuel carbon emission correlation model is established. It calculates the actual emission reduction effect of ships using shore power instead of fuel. Then, we determine whether the port is suitable for using shore power systems. Finally, we determine the basic conditions for carbon emission reduction by using shore power. The model is described as follows:

$$Y_i = CE_{Ei} - CE_{Fi} \tag{1}$$

The correlation model can be divided into two parts: the calculation of the carbon emissions of ships using shore power and auxiliary engine fuel.

3.2.1 Fuel-carbon emission model

When ships are berthing, only auxiliary engines are used to power the ship; therefore, the ship fuel-carbon emission model can be established based on the ship's auxiliary fuel consumption formula (Moreno-Gutierrez et al., 2018).

$$CE_{Fi} = \gamma_F \times FC_i \tag{2}$$

$$FC_i = P_i \times LF \times SFC \times T_i \tag{3}$$

$$T_i = \frac{DT_i}{v} \tag{4}$$

3.2.2 Shore power–carbon emission model

When a ship uses shore power, its carbon emission sources can be divided into two parts:

(1) The carbon emissions from auxiliary fuel consumption when the ship is waiting to connect to and disconnect from the shore power;
(2) The carbon emissions from the traceability process of power consumption.

Its calculation formula is as follows:

$$CE_{Ei} = CE_{EFi} + CE_{EEi} \tag{5}$$

Among them, the carbon emission calculation formula of the fuel part is basically the same as that of the fuel-carbon emission model, but the berthing time becomes the waiting time for the ship to connect and disconnect the shore power.

$$CE_{EFi} = \gamma_F \times FC_{AEi} \tag{6}$$

$$FC_{AEi} = P_i \times LF \times SFC \times t \tag{7}$$

The carbon emissions of the shore power part need to consider the loss of electric energy in the transmission process. The calculation formula is as follows:

$$CE_{EEi} = \sum_j \gamma_{Ej} \times \eta_j \times EC_i \tag{8}$$

$$EC_i = EC_{Gi} + EC_{Ti} \tag{9}$$

According to the China Energy Statistical Yearbook (Department of Energy Statistics. National Bureau of Statistics, 2013), the average CO_2 emission coefficient γ_{Ej} of each power source is shown in Table 1.

The total power consumed by ships at berth using shore power includes the power required for the ships' operation and the power loss in the power grid. Therefore, the calculation is divided into two parts: the power consumption process and the power transmission and transformation process.

3.2.2.1 Power consumption

$$EC_{Gi} = P_i \times LF \times T_i \tag{10}$$

$$P_i = f(GT_i) \tag{11}$$

The rated power of the ship's auxiliary engine is a key parameter to calculate the ship's electricity consumption. The relationship function between the auxiliary engine rated power of different types of ships and the gross tonnage of the ship obtained by the study has a good fitting effect (Gutierrez et al., 2019). It can be useful for the calculation of P_i , as shown in Table 2.

3.2.2.2 Power loss

In the process of power supply, the power system will inevitably have some power loss, including the energy loss caused by transmission lines and the power loss caused by transformers and other power(Sundaram, 2022). In addition, there is also the loss of transmission from the grid to the onshore power supply. The power consumption formula in the power consumption process is as follows:

$$EC_{Ti} = \frac{EC_{Gi}}{1-\mu} \times \mu \tag{12}$$

3.3 Judgment rules based on the correlation model

By analyzing the constructed correlation model, the criteria for determining whether the ship calling at a port is suitable for using shore power can be obtained. When Y_i <0, the ship is suitable for using shore power at this port; otherwise, it cannot achieve carbon emission reduction by using shore power. In addition, the correlation model can determine the cleanliness of shore power from two perspectives: port and ship.

TABLE 1 Average carbon emission coefficient of each power source.

Power source type	γ_{Ej} (g/kWh)	Power source type	γ_{Ej} (g/kWh)
Coal power	1001	Hydroelectric power	4
Fuel power	840	Nuclear power	16
Gas power	469	Photovoltaics power	48
Wind power	12	Photothermal power	22

(Source: Department of Energy Statistics, 2013).

TABLE 2 Relation function of auxiliary engine-rated power and gross tonnage of various types of marine auxiliary engines.

Types of ship	f(GT)	R^2
General cargo ship	$1.328(GT)^{0.7321}$	0.7986
Cruise	$-1.119\times10^{-6}(GT)^2+0.3692(GT)$	0.8488
Reefer ship	0.2073(GT)+587.4	0.5953
LNG ship	$2.597\times10^{-11}(GT)^3-4.131\times10^{-6}(GT)^2+0.2040(GT)+422.6$	0.9005
Bulk Carrier (Grain)	$2.786\times10^{-11}(GT)^3-3.609\times10^{-6}(GT)^2+0.1506(GT)+99.97$	0.8662
Bulk Carriers	0.06610(GT)+335.2	0.8937
Oil tanker	$70.86(GT)^{0.3317}$	0.6467
Container ship	$4.217\times10^{-6}(GT)^2+0.1331(GT)$	0.7697
Container ship (TEU)	0.0003(TEU)2+1.562(TEU)	0.7494
Chemical tanker	$108.6(GT)^{0.3062}$	0.8441

(Source: Gutierrez-Romero et al., 2019).

By deforming the judgment rule (Y_i <0), the marginal carbon emission reduction benefit of port shore power can be obtained, and the cleanliness of shore power can be determined from the perspective of the port.

$$T \times P_i \times \left(\frac{\sum_j \gamma_{Ej}\times\eta_j}{1-\mu} - \gamma_F \times SFC\right) + P_i \times \gamma_F \times SFC \times t < 0 \quad (13)$$

$$\Delta = \gamma_F \times SFC - \frac{\sum_j \gamma_{Ej}\times\eta_j}{1-\mu} \quad (14)$$

According to the above judgment rules, when the proportion of thermal power generation in the area is low, Δ>0, then the marginal carbon emission reduction benefit of using shore power at the port is positive, and the shore power system can achieve carbon emission reduction; and when the proportion of thermal power generation in the area is high, Δ≤0, then the port is not suitable for using shore power.

Determining from the perspective of the ship, when Δ>0, Y_i =0; then, the solution equation for the basic berthing time is as follows:

$$T^* = \frac{f(GT_i)\times\gamma_F\times SFC\times t}{f(GT_i)\times\gamma_F\times SFC - f(GT_i)\times\frac{\sum_j \gamma_{Ej}\times\eta_j}{1-\mu}} \quad (15)$$

For a port with positive marginal carbon emission reduction benefits of shore power, the port is suitable for using shore power systems; when the berthing time of the ship exceeds the basic berthing time, the ship is suitable for using shore power at this port.

4 Case analysis

4.1 The power energy structure of coastal ports

According to the shore power–fuel carbon emission correlation model, the power energy structure has a significant impact on whether the ports are suitable for using shore power. This section first collects data from various provinces and cities in China in 2021 (see Appendix A for detailed data). Among them, the provinces and cities where Chinese coastal ports are located are currently dominated by thermal power generation, but there are certain differences in the power energy structure in different provinces and cities.

In addition, the power grid is usually used between the provinces in China for power transmission. At present, the six regional power grids belonging to the State Grid in China have basically achieved interconnection and interoperability. Therefore, the Chinese power distribution and transmission network can be divided into two parts: the State Grid and Southern Power Grid (Abhyankar et al., 2020). According to an assumption (Chen et al., 2022), the power generation of each province or city first meets its own electricity demand. If there is surplus electricity, it will be transmitted to other provinces and cities through the grid market, as shown in Table 3.

The remaining electricity consumption in Guangdong, Guangxi, and Hainan is provided by the Southern Power Grid, and that in the other eight provinces and cities is provided by the State Grid (Abhyankar et al., 2020). According to each area's own power generation and grid distribution (this study ignores the loss rate of cross-provincial distribution), the actual power energy structure of 11 coastal port provinces and cities is shown in Figure 1 (see Appendix A for detailed data):

4.2 Model Input

The important parameters of the model are set, as shown in Table 4.

In addition to the above parameters, the dock-loading efficiency is affected by the operation efficiency of the quay crane and the number of quay cranes, and the number of quay cranes is related to the length of the ship. Therefore, the dock-loading efficiency needs to consider the actual terminal

TABLE 3 Grid power energy structure.

Grid name	Proportion of thermal power generation (%)	Proportion of hydroelectric power generation (%)	Proportion of wind power generation (%)	Proportion of nuclear power generation (%)	Proportion of solar power generation (%)
The State Grid	69.88	17.23	9.78	0	3.11
Southern Power Grid	27.38	64.93	6.09	0	1.60

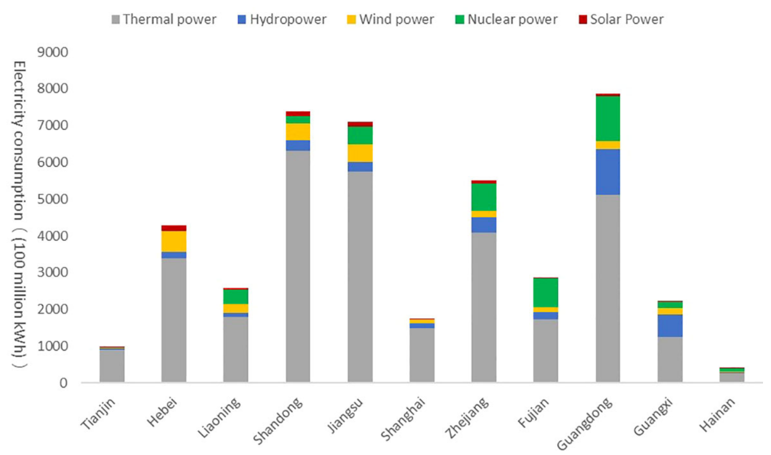

FIGURE 1
The actual power energy structure of 11 coastal port provinces and cities. (Source: NBS of the PRC, 2021).

equipment and ship conditions. In addition, to set the loading efficiency, the study determines the revised content of the container ship design ship size in the "Code for General Plane Design of Seaports" issued by the Ministry of Communications and the actual situation of Xiamen Port's container terminal, as shown in Table 5.

4.3 Feasibility analysis of port shore power

Solving the relational model, if $\Delta>0$, for some ships that meet certain conditions, the use of shore power can achieve carbon emission reduction, and the larger the value of Δ is, the better the carbon emission reduction effect of using shore power. Therefore, regarding Δ as an indicator for determining the cleanliness of port shore power, combined with the current situation of the actual power energy structure in China, a reasonable assumption is made for the case.

Chinese statistics in 2021 show that coal power accounts for nearly 90% of thermal power generation, oil power accounts for a very low proportion, and photovoltaic power generation accounts for more than 99% of solar power generation. Therefore, in this case study, assuming that coal power and gas power account for 90% and 10% of thermal power

TABLE 4 Model parameter value.

Parameter name	Value	Unit	Sources and remarks
γ_F	3.114	g CO_2/g	(Ji and El-Halwagi, 2021)
LF	0.19	–	(Nguyen et al., 2022)
SFC	213.7	g/kWh	(Moreno-Gutierrez et al., 2018)
t	1	h	(Tseng and Pilcher, 2015)
μ	6.6	%	(CPNN, 2022)

TABLE 5 Loading efficiency value.

Vessel size (TEU)	Length of ship (Meter)	Number of quay cranes used	Quay crane operation efficiency (TEU/h)	Loading efficiency (TEU/h)
≤200	≤80	1	30	30
201-1050	81-160	2	30	60
1051-3500	161-240	3	30	90
3501-6630	241-320	4	30	120
6631-12500	321-400	5	30	150

generation, respectively, and photovoltaic power generation is used for solar power generation, the correlation model solution results can be obtained (see Appendix A for detailed data). Through the analysis of the solution results, under the current power energy structure, the marginal carbon emission reduction benefits of Tianjin, Hebei, Liaoning, Shandong, Jiangsu, Shanghai and Zhejiang are all negative. Among the 11 coastal port provinces and cities in China, only the ports in Fujian, Guangdong, Guangxi and Hainan are suitable for using shore power.

Although China is still dominated by thermal power generation, with the development of clean energy, the proportion of coal power and even thermal power will gradually decrease in the future. Therefore, in the case of widespread use of clean energy in the future, it can be foreseen that the promotion of shore power is imperative. However, the current national policy of mandatory use of shore power is not applicable to provinces and cities whose current power energy structure is biased toward thermal power.

4.4 Carbon emission reduction effect and condition analysis of shore power

The feasibility analysis of shore power in provinces and cities with coastal ports shows that the power energy structure of Fujian, Guangdong, Guangxi and Hainan is suitable for the use of shore power. Therefore, this case study selects Haikou Port and Xiamen Port as cases, taking the container ship Taking as the object (assuming that the ship is fully loaded). Considering the relationship between the loading efficiency and ship size, the relationship between the specific carbon emission reduction effect of the shore power and the size of the ship is analyzed, and the results are shown in Figure 2.

In Figure 2, under the same loading efficiency, the reduction in carbon emissions of ships using shore power is positively correlated with the size of the ship. Overall, large ships are more suitable for using shore power than small ships. In addition, for ships of the same size, the cleaner the power energy structure at the port of call is, the better the carbon emission reduction effect of using shore power.

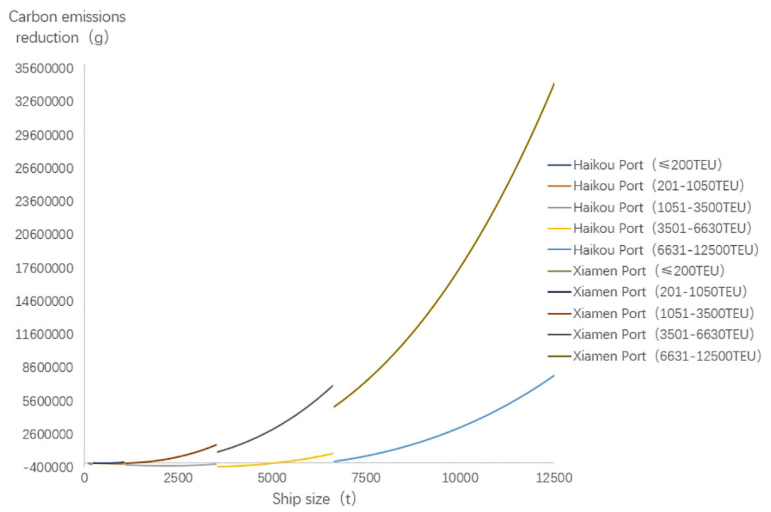

FIGURE 2
The relationship between carbon emission reduction and ship size.

According to the analysis of the carbon emission reduction effect, only ships that meet certain conditions are suitable for using shore power. For the policy of mandatory use of shore power, this case study also examines the basic berthing time (when the actual berthing time of the ship exceeds this value, the carbon emission of the ship using shore power begins to be lower than that of using fuel).

According to the calculation formula of T^* , the basic berthing time is not related to the size of the ship. Under the same power energy structure, the basic berthing time is a fixed value. In addition, ports in each area have different basic berthing times for shore power use due to their different power energy structures. The cleaner the power energy structure of a port is, the lower the requirements for its basic berthing time. In the case study, in Haikou Port, ships with a berthing time of more than 42.99 hours are suitable for using shore power; in Xiamen Port, ships with a berthing time of more than 16.41 hours can use shore power.

5 Conclusion and policy implications

5.1 Conclusion

This paper focuses on the emission reduction effect of shore power from the perspective of power traceability. Although shore power is an effective means to reduce ship-berthing carbon emissions, it is not applicable to all areas. The study establishes a shore power–fuel carbon emission correlation model and studies the feasibility of using shore power in the ports of coastal provinces and cities under the current traceability of power sources. In addition, we analyze the carbon emission reduction effect from shore power of specific ports. Finally, according to the national policy of compulsory use of shore power, the conditions and restrictions for ships calling at ports to use shore power are examined. The paper draws the main conclusion as follows: At present, most provinces and cities in coastal cities mainly rely on thermal power generation, but the proportion of clean energy varies. Among them, Guangxi accounts for almost half of the clean energy; Guangdong has a certain proportion of hydropower and nuclear power generation; Fujian and Hainan account for approximately 1/5 of nuclear power generation; and other coastal provinces and cities still have more than 70% thermal power generation. The feasibility calculation through the carbon emission correlation model shows that the marginal carbon emission reduction benefits of shore power in most ports are negative. Only four ports, Fujian, Guangdong, Guangxi and Hainan, are suitable for using shore power because of their relatively clean power energy structure. However, it is also related to the berthing time of the ship; that is, only when the berthing time of the ship exceeds the basic berthing time of using shore power at the port of call is the use of shore power related to lower net carbon emissions. Therefore, the basic berthing time of shore power use can be used as a condition for determining whether a ship is suitable for using shore power at the port of call, which has nothing to do with the size of the ship. In addition, the cleaner the power energy structure of the port area is, the higher the marginal carbon emission reduction benefit of the shore power system, and the lower the berthing time requirements for ships suitable for using shore power.

5.2 Policy implications

At present, most policies for shore power in China are methods of encouragement and support. Mandatory measures on berthing time ignore the differences in the power energy structure of ports in various areas. Therefore, this paper proposes suggestions for the promotion of shore power according to local conditions from the perspective of power traceability:

Different laws and policies should be formulated and implemented in accordance with the power energy structure, economic development level, port resources, etc., of different areas. Compulsory measures should be implemented for coastal ports in Fujian, Guangdong, Guangxi and Hainan. When the size of the ship and the loading and unloading time exceed a certain value, the responsible subject and reward and punishment measures for using shore power are clarified. Relevant laws and regulations should be formulated and improved according to the actual situation. At the same time, financial subsidies and support should be increased, the idle rate of shore power berths should be reduced, and the development of shore power should be ensured. For areas where the current use of shore power is still not clean enough, the use of shore power should not be mandatory for the time being.

Finally, there are some limitations in this paper. For example, the model does not fully consider the influence of practical factors and only studies the single ship type of coastal area and container. And to achieve China's carbon peaking and carbon neutrality goals, the promotion of shore power is the inevitable trend of port development in the future, the future can be from inland areas and other ship form further in-depth study, but also to realize the energy revolution is a long process, each region should fully consider its electricity clean degree to shore power promotion policy and planning, at the same time, our country should actively develop new energy technologies, gradually increase the proportion of clean energy, so as to fundamentally make the shore power to achieve zero emissions, create a green, safe, economical and new port environment.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

LS:Conceptualization, Writing - Review & Editing. PD: Conceptualization, Investigation, Writing - Original Draft. YX: Methodology, Formal analysis, Investigation. WL:Supervision. ZH: Resources. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.1077289/full#supplementary-material

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