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Article

Assessing the Potential for Energy Efficiency Improvement through Cold Ironing: A Monte Carlo Analysis with Real Port Data

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Abstract: Ports in China are facing significant pressure to reduce carbon emissions in alignment with carbon peak and carbon neutrality goals. Onshore power supply (OPS) is regarded as a promising approach to accomplish these targets, necessitating a thorough evaluation of its impact for port authorities to make informed decisions regarding its adoption. This research focuses on Ningbo Zhoushan Port, the largest port globally, as a case study. Two metrics are proposed to quantify the energy efficiency of ships powered by onshore energy while berthed. The installation and connection status of OPS in the port area are analyzed. Subsequently, the energy demand of berthed ships is assessed, and the potential for energy efficiency improvement resulting from OPS implementation is evaluated using Monte Carlo methods. The findings reveal untapped potential in the studied port area, with OPS demonstrating the ability to improve energy efficiency of berthed ships at a rate parallel to the connection rate, excluding indirect emissions. However, considering indirect emissions and energy loss diminishes the effectiveness of OPS. The paper discusses practical implications for enhancing the energy efficiency of OPS, enabling port authorities to make well-informed decisions. These findings are invaluable for Chinese port authorities striving to achieve carbon reduction goals and enhance sustainability in the maritime industry.

Keywords: energy efficiency; onshore power supply; green ports; berthed ships; air pollution

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1. Introduction

In recent decades, there has been a substantial increase in international trade, and water transportation has emerged as a dominant mode for facilitating trade transactions. Within this context of global trade, ports play a vital role in facilitating the efficient transfer of cargo between land and water transportation networks [1,2]. They bear the responsibility of managing approximately 80% of the world's trade in terms of volume and 70% in terms of value [3]. This underscores the vital importance of ports as key components of the global economy.

However, despite the numerous benefits that ports have brought, such as economic growth and increased employment opportunities, it is important to acknowledge the associated energy consumption and carbon footprint resulting from port activities, especially those caused by berthed ships. In 2012, global shipping emissions accounted for approximately 2.2% of global greenhouse gas (GHG) emissions [4,5]. Moreover, if left unregulated, these emissions could increase significantly and potentially reach 17% by the year 2050 [6,7]. The proportion of emissions associated with the port or terminal can exceed 20% at maximum, depending on the type of vessel [5]. The emissions generated by ships have significant environmental and health impacts. Estimates suggest that shipping-related emissions of particulate matter (PM) contribute to an annual toll of around 60,000 cardiopulmonary and lung cancer deaths, primarily concentrated in coastal regions of Europe, East China, and South Asia [8].

In order to mitigate the carbon footprint of shipping, international organizations, governments, and the shipping industry have implemented proactive measures. The International Maritime Organization (IMO) has played a leading role in the development of the Marine Pollution Convention (MARPOL) Annex VI, an international treaty designed to regulate ship emissions and gradually reduce air pollution caused by ships [9]. MARPOL has undergone regular updates since its inception, and in 2005, MARPOL Annex VI was implemented to address the issue of air pollution caused by ships. The primary objective of Annex VI is to reduce air pollution by imposing limits on NOx, SOx, and PM emissions from fuel combustion. In 2010, an amendment was introduced to Annex VI, further tightening the emission limits and introducing the concept of emission control areas (ECA) in which the sulphur cap in fuel was limited to 0.1% in 2015 [10]. China also attaches great importance to the pollution issues caused by the shipping industry. In November 2018, the Ministry of Transport issued the "Implementation Scheme of the Domestic Emission Control Areas for Atmospheric Pollution from Vessels", which sets strict requirements for the emissions of pollutants such as NOx and SOx from ships [11]. In 2019, the Ministry of Transport, in conjunction with other relevant departments, issued the "Guidance on Building World-Class Ports", explicitly stating the need to construct green ports [12]. In 2020, China officially made the promise to achieve carbon peak and carbon neutrality in 2030 and 2060, respectively. Thus, it is urgent for port authorities to take measures to reduce carbon emissions.

When a ship is berthed at ports, auxiliary engines are typically operated to generate electricity for onboard systems and cargo loading/unloading machinery, whereas the propulsion engine is shut down. This practice has been identified as a significant source of emissions from berthed ships [13]. Our previous research has also confirmed that this holds true in the ports currently under study [14]. To mitigate emissions from berthed ships, numerous studies have focused on optimizing the technical parameters, design, and operation of ships to reduce fossil fuel consumption, resulting in a reduction in CO_2 emissions [15]. Among these approaches, an effective approach is the implementation of cold ironing (CI), which is also referred to by various other terms such as alternative maritime power (AMP), onshore power supply (OPS), shore-side electricity (SSE), shore-to-ship power (S2SP), and shore-side power (SSP) [16]. In the present research, we use CI and OPS interchangeably to refer to the same concept. When ships are docked and connected to OPS, they have the capability to turn off their auxiliary engines. This allows the electricity required onboard to be supplied by the onshore power source. As a result, this practice not only eliminates noise pollution but also significantly reduces emissions from the ships [17].

Despite the advantage of OPS, it is acknowledged that the wide application of OPS faces many technical and economical challenges [18,19]. On the other hand, it is noted by many researchers that the port authority (PA) plays important roles in port carbon reduction [20]. Consequently, gaining a clear understanding of how OPS can contribute to emissions reduction becomes crucial for the PA in making informed decisions regarding its usage. Therefore, this study takes the largest port globally, the Ningbo Zhoushan Port, as a case study to examine the current state of OPS installation and utilization and assess the potential increase in energy efficiency resulting from OPS implementation.

The remaining sections of this paper are structured as follows. Section 2 provides a comprehensive literature review, examining prior studies and research relevant to the topic. Section 3 presents the energy efficiency metrics and evaluation methods employed in this study. The findings of the analysis are presented in Section 4. Finally, Section 5 concludes the paper and summarizes the key findings.

2. Literature Review

2.1. Energy Efficiency

Several metrics have been proposed to quantitatively assess the carbon intensity and energy efficiency of ships. Notably, the Energy Efficiency Design Index (EEDI) was introduced in 2011 following the consensus reached at the Marine Environment Protection Committee (MEPC) conference of the IMO. These measures were subsequently incorporated into Annex VI of MARPOL. The EEDI establishes energy efficiency standards that specific new vessels must adhere to. Recognizing the considerable number of operational vessels, the IMO has also proposed the utilization of EEOI as a monitoring tool to evaluate the operational energy efficiency of ships. The EEOI serves as a metric for quantifying and assessing the energy performance of ships during their operational activities [21]. The introduction of EEOI and EEDI has sparked significant research interest in evaluating and enhancing the energy efficiency of ships [22,23]. Interested readers seeking more comprehensive information on these methods can refer to the works of Wang et al. [24] and Duan et al. [25]. These references provide valuable insights and further details on the evaluation and improvement of ship energy efficiency. During the 76th MEPC in 2021, the amendment to Annex VI of MARPOL, known as MEPC.328 (76), was deliberated and approved. This amendment introduced two mandatory emission reduction measures, namely, the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII). The objective of these measures is to achieve the short-term goals of greenhouse gas reduction in the shipping industry by enhancing the technical energy efficiency and operational performance of vessels [26].

2.2. Emissions Evaluation of Ships

Emissions evaluation has garnered significant research attention as a crucial initial step in reducing emissions in the shipping industry. The calculation methods for ship emissions can be categorized into two main types: energy-based top-down methods and fuel-based bottom-up approaches [27]. A top-down approach in emissions evaluation utilizes fuel sales statistics to estimate the overall fuel consumption of a fleet during a defined timeframe and geographical region. These data are then coupled with emission factors, which represent the amount of pollutants emitted per metric ton of fuel consumed, to calculate the total mass of emitted pollutants. The primary advantage of the fuel-based approach is its minimal data requirements [27]. The fuel-based approach is particularly applicable in scenarios where limited traffic data are available since it uses general fleet information, fuel consumption data, and emissions factors to estimate emissions [28]. However, a key challenge in implementing the fuel-based approach is the difficulty in accessing real energy consumption data as such information is often confidential and not readily available [20,29].

In a bottom-up approach, emissions estimations are calculated for each specific activity by combining engine energy output or fuel consumption with corresponding emission factors and time values. This approach involves breaking down emissions calculations into specific movement types or activities, allowing for more detailed and accurate estimations of emissions [27]. The bottom-up approach provides near-instantaneous emission estimations on a vessel-by-vessel basis, offering high-resolution analysis in both time and space. Researchers have utilized bottom-up methods and movement data obtained from AIS to conduct ship emissions evaluations in various ports and regions, such as Qingdao Port [30], Shenzhen Port [31], the Ningbo Zhoushan area [32], Tianjin [33], and East Asia [34]. The emerging body of research underscores the increasing acknowledgment of the significance of evaluating and mitigating the energy consumption and emissions of ships not only during their active voyages but also while they are in port. However, the data-intensive nature of the bottom-up approach necessitates comprehensive information on ship movement dynamics and technical data, which can be challenging to obtain. The use of AIS data introduces uncertainties to ship emissions calculations due to inherent inaccuracies [5]. Therefore, there is a need for more precise and reliable ship movement data to enhance the accuracy of emissions assessments.

2.3. OPS Adoption

The installation of OPS infrastructure in the port of Gothenburg in 2000 marked the beginning of its implementation, with subsequent developments in ports across Finland, Germany, the United States, and China [35,36]. For instance, the socioeconomic impact of increasing utilization of cold ironing in the port of Genoain is evaluated in [37]. The results show that cold ironing is an effective measure to reduce emissions. In [38], the authors have investigated the emissions reduction in the Port of Santander through the implementation of OPS and demonstrated the potential of the OPS.

However, despite the progress made, there remain numerous challenges hindering the widespread adoption of OPS, as it involves multiple stakeholders such as governments, port enterprises, and liner companies [39]. One of the major obstacles is the high initial construction and maintenance costs, posing difficulties for port and energy companies to overcome [19,40]. To facilitate the adoption of OPS, a comprehensive evaluation of its economic and environmental advantages is crucial, with particular emphasis on assessing its environmental impact. This is of utmost importance for port authorities as they strive to reduce carbon emissions in alignment with carbon peak and carbon neutrality goals. Several studies have indicated that OPS can effectively reduce emissions in ports [18,19,41]. However, the impact of OPS policies can be influenced by various factors, including ship power efficiency, fuel prices, and port efficiency [42]. Furthermore, the extent to which OPS can improve energy efficiency differs among countries with different primary fuel sources for power generation, as highlighted by Dai et al. [35]. Consequently, a critical challenge for port authorities is to assess the energy efficiency improvement brought about by OPS in ports, considering the specific circumstances and conditions of each port.

2.4. Research Gap

Prior research endeavors have exhibited a notable lacuna in the comprehensive assessment of energy efficiency within port operations [43], as well as in the latent opportunities for enhancing energy efficiency through the adoption of OPS systems. Furthermore, a conspicuous dearth exists in the appraisal of OPS utilization patterns. In this study, we examine the installation and connection status of the selected port and assess the potential for energy efficiency improvement resulting from the adoption of OPS in both port and ship operations, focusing on the perspective of the port authority. The findings of this study hold significant value in assisting port authorities in making informed decisions regarding the promotion of OPS adoption and enhancing the energy efficiency of port operations.

3. Methods

In the present research, the energy efficiency of OPS is evaluated. Figure 1 demonstrates the flowchart of the proposed framework. The OPS installation and connection history of the studied port area are analyzed. The bottom-up approach is used to calculate the proposed two metrics and Monte Carlo is used to evaluate the energy efficiency. Detailed descriptions of the proposed framework can be found in the following subsections.

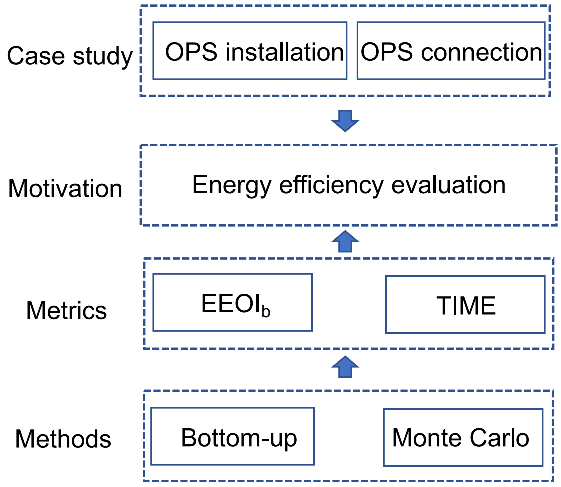


Figure 1. Flowchart of the proposed evaluation framework.

3.1. Cold Ironing

The operational process of utilizing OPS can be categorized into two primary stages: preparations and shore power supply operations. The preparation stage involves several essential steps, including conducting equipment effectiveness checks on the ship prior to its arrival at the port and making the necessary preparations for connecting to the shore power system. This includes deploying the cable using a cable winch and connecting it to the shore power socket at the quay. Furthermore, the ship needs to reduce the number of onboard generators to one and minimize the onboard load.

Once the preparations are completed, the shore power supply operations begin, as illustrated in Figure 2. The process commences by switching from shore power to ship power and connecting to the shore power source after successfully passing the closure test. It is crucial to verify the correctness of the electrical parameters before switching to ship power. After the verification process, the shore power supply can be initiated by switching from ship power to shore power. Once the power supply is successfully established, the ship's power station can resume normal operations. During this phase, dedicated personnel are assigned to monitor the system's status. Finally, before departing from the berth, the ship undergoes a transition process that involves reserving the generator, reducing the grid load, and switching back from shore power to ship power. This restores the power station to its normal operational state.

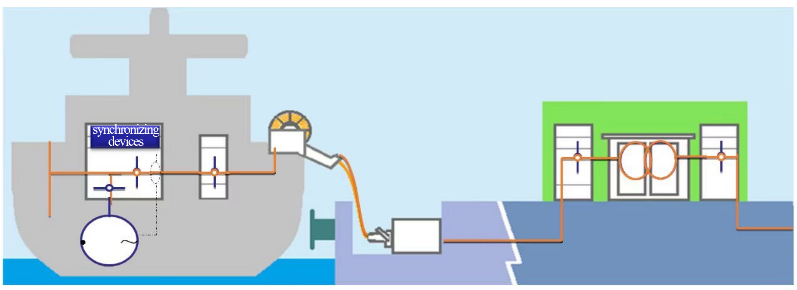


Figure 2. Operation process of OPS.

3.2. The Studied Port Area

In the present study, we take the Chuanshan Port Area of the Ningbo Zhoushan Port (CPANZP) as an example to study the energy efficiency improvement through cold ironing. CPANZP is the second largest single container terminal in the world, with more than 10 million TEU each year since 2017. It is located in the east of Ningbo City, Zhejiang Province, China, as shown in Figure 3. As can be seen from the figure, there are 11 container berths in CPANZP, which is capable of docking the largest container ship in the world.

Figure 3. The location of CPANZP.

Figure 4 illustrates the cargo handling process through the joint operation of ships and ports in a container ternimal. When a ship approaches a port, it typically undergoes an inspection while at anchor and awaits instructions for approach and pilotage. Once inside the port, cargo is loaded and unloaded at the terminal. The port is equipped with quay cranes, yard cranes, and trucks to facilitate the loading, unloading, and transportation of cargo. On the quayside, cargo is initially loaded from the ship onto inner trucks by the quay cranes. Subsequently, the inner trucks transport the cargo to the yard, where it is stacked by the yard cranes. Cargo from the yard cranes is then transported to its respective destinations either by external trucks on the road or by train via the port-rail link. The main sources of emissions in the port area are vessels calling at the port and port machinery, including yard cranes and quay cranes. The energy efficiency of the berthed ships is related to the operation of both ships and ports.

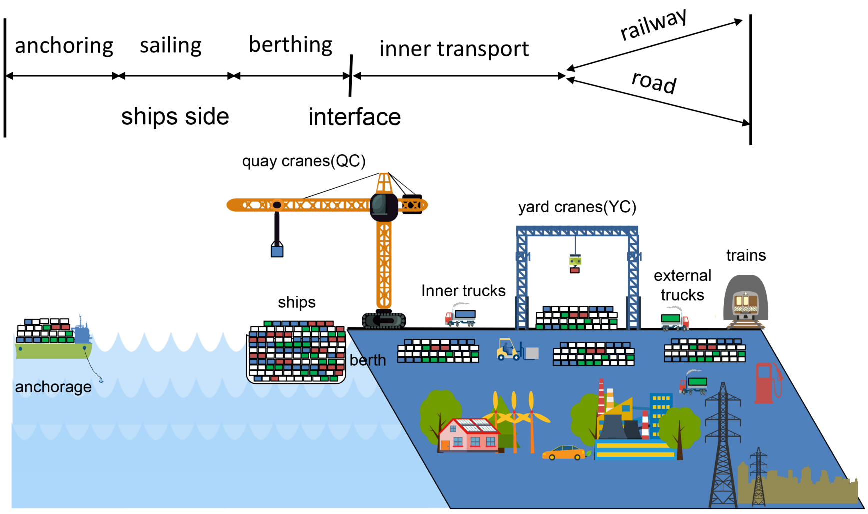


Figure 4. Process of cargo handling in CPANZP.

3.3. Energy Efficiency Index of Berthed Ships

Traditionally, EEOI is an index used to assess energy efficiency and CO_2 emissions of ships during voyage. It is expressed as [44]

$$\mathrm{EEOI} = \frac{\text{actual } CO_2 \text{ emissions}}{\text{performed transport work}}. \tag{1}$$

For a single ship during a voyage, EEOI can be quantified by

$$\text{EEOI} = \frac{\sum_j FC_j \times C_{Fj}}{m_{cargo} \times D_j}. \tag{2}$$

With respect to large number of ships, the average EEOI can be expressed as

$$\overline{\text{EEOI}} = \frac{\sum_i \sum_j FC_{ij} \times C_{Fj}}{\sum_i m_{cargo,i} \times D_j}, \tag{3}$$

where the following definitions apply:

- j: fuel types used;
- i: navigation voyage number;
- FC_{ij}: fuel consumption of fuel type i in voyage j;
- CF_j: fuel mass to CO_2 mass conversion factor with fuel j;
- m_{cargo}: weight of cargo carried on ship;
- D_i: distance of voyage i.

The above EEOI is a measure of the average energy efficiency of ships during a voyage, which is composed of four phase: cruise, at anchorage, at berth, and maneuvering. However, it is not possible to assess the energy efficiency of ships at a single phase, for instance, at berth, as is the interest of the present work, since the distance D of ships during berth phases is not available. Therefore, in the present study, the EEOI is modified as the CO_2 emissions of each unit of handled container and can be expressed as

$$\text{EEOI}_\text{b}^i = \frac{ED_i \times EF}{m_{cargo,i}}. \tag{4}$$

For large number of ships at berth, the average EEOI_b can be expressed as:

$$\overline{\text{EEOI}_\text{b}} = \frac{\sum ED_i \times EF}{\sum m_{cargo,i}}, \tag{5}$$

in which the following definitions apply:

- $EEOI_b^i$: energy efficiency operational index of berthed ship i;
- ED_i: energy demand of a berthed ship i, kWh;
- EF: CO_2 emission factor of auxiliary engine, g/kWh.

Another index used to quantify energy efficiency is TIME, which is calculated by

$$TIME_i = \frac{ED_i \times EF}{t_i}. \tag{6}$$

For the average TIME of large number of ships,

$$\overline{TIME} = \frac{\sum ED_i \times EF}{\sum t_i}. \tag{7}$$

The energy demand ED_i of ships at berth can be calculated via

$$ED_i = MCR_i \times LF \times T_i, \tag{8}$$

where MCR represents the maximum continuous rating power of the auxiliary engine of ship i, and T_i represents the time at berth. LF stands for load factor of auxiliary engines at berth. The load factor of auxiliary engines is different for various types of ships and it is taken as 0.19 for container ships [45]. CO_2 emission factors of auxiliary engines indicate the emission of each unit of energy consumed. It differs depending on the sulfur content of oil consumed and engine types, as is shown in Table 1, in which MSA and HSA represent medium-speed auxiliary and high-speed auxiliary engines, respectively.

Equations (7) and (10) indicate that the energy efficiency of berthed ships can be improved by reducing CO_2 emissions, which can be achieved through cold ironing. By supplying shore-side energy to ships, they can shut down their auxiliary engines and thus produce no local emissions. However, shore-side electricity is generally bought from the bulk power system and is mainly generated from traditional energy. Therefore, the indirect emissions should be taken into consideration.

When considering the indirect emissions of OPS, the emissions can be obtained via

$$E_{electricity} = EC^{i}_{electricity} \times EF_{electricity}, \tag{9}$$

where $EC_{electricity}$ is the electricity consumption of OPS, and $EF_{electricity}$ denotes the emission factors of bought electricity, which differ in years, as is shown in Table 2.

Table 1. Emission factors of auxiliary engines, g/kwh [46].

Engine Type	IMO Tier	Model Year Range	CO_2 EF
Using 2.7% Sulfur Fuel			
MSA	Tier 0	1999 and older	707
MSA	Tier I	2000 to 2011	707
MSA	Tier II	2011 to 2016	707
MSA	Tier III	2016 and newer	707
HSA	Tier 0	1999 and older	707
HSA	Tier I	2000 to 2011	707
HSA	Tier II	2011 to 2016	707
HSA	Tier III	2016 and newer	707
Using 0.1% Sulfur Fuel			
MSA	Tier 0	1999 and older	696
MSA	Tier I	2000 to 2011	696
MSA	Tier II	2011 to 2016	696
MSA	Tier III	2016 and newer	696
HSA	Tier 0	1999 and older	696
HSA	Tier I	2000 to 2011	696
HSA	Tier II	2011 to 2016	696
HSA	Tier III	2016 and newer	696

Table 2. Emission factors of electricity in China, g/kwh [47].

Year	EF
2018	610
2019	610
2020	610
2021	581
2022	581

By considering the indirect emissions of OPS, energy efficiency indices in Equations (7) and (10) are modified as

$$\overline{\mathrm{EEOI_b}} = \frac{\sum EC^{i}_{electricity} \times EF_{electricity}}{\sum m_{cargo,i}} \tag{10}$$

$$\overline{TIME} = \frac{\sum EC^{i}_{electricity} \times EF_{electricity}}{\sum t_i}. \tag{11}$$

In the present research, a connection probability p is assumed for a ship to determine whether it connects to OPS, and the Monte Carlo method is adopted to calculate the expected energy efficiency under different connection probabilities.

3.4. Data Resources

Previous studies have commonly relied on Automatic Identification System (AIS) data as a primary source of ship movement information. However, it is crucial to acknowledge the limitations and inaccuracies associated with AIS data [27]. One notable limitation is the potential invisibility or inaccurate tracking of a portion of vessels through AIS. To overcome this limitation and ensure the accuracy of ship movement data, alternative data sources were employed in this study. Specifically, detailed and reliable ship data were obtained from the Information Technology (IT) department, which provided comprehensive information encompassing vessel identification, route details, and timing information pertaining to various ship activities. By leveraging this dataset, the study mitigated the potential inaccuracies associated with AIS data, resulting in more dependable and precise ship movement information for the evaluation of emissions. However, it is important to note that the utilized dataset does not include specific information regarding the rated power of main and auxiliary engines. Such information can be acquired from commercial entities such as the Clarksons database and professional organizations such as the China Classification Society [6].

4. Results

4.1. Analysis of Berthed Ships

This study provides a comprehensive statistical analysis of the quantity of ships that docked at CPANZP from 2018 to 2021. The corresponding data are represented graphically in Figure 5. The graphical depiction reveals that the annual number of docked ships at CPANZP remained relatively stable, hovering around the 5000-ship mark, over the aforementioned four-year period. Furthermore, a trend of an initial increase followed by a decline was observed in this context. It is noteworthy that the highest annual numbers of docked ships were recorded in 2019 and 2020, where the figures were approximately 5300, followed by a subsequent decrease. The reduction could potentially be attributed to the adverse impact of the global COVID-19 pandemic, which led to the imposition of stringent measures such as city lockdowns and traffic controls in many countries and regions, thereby impeding the smooth operation of the shipping market. With respect to the monthly variation of docked ships over different years, a fluctuation between 300 and 500 ships per month was observed in CPANZP from 2018 to 2021, accompanied by a pattern of decrease followed by an increase within a year. Traditionally, the lowest number of docked ships per month occurred in February due to the influence of the Chinese lunar new year. However, the situation changed in 2021, where the month with the minimum number of docked ships was September, possibly due to the COVID-19 pandemic. Additionally, the number of ships that docked each month in 2020 and 2021 was affected to varying degrees by the restrictions on epidemic prevention and control measures.

In order to further analyze the impact of the pandemic on the ships berthing, this paper also presents the berthing time statistics of ships that docked at CPANZP from 2018 to 2021. A comparative analysis was carried out for two different scenarios, i.e., before the pandemic (2018–2019) and after the pandemic (2020–2021), as shown in Figure 6. It can be seen from the figure that the berthing times of ships in the port are mainly distributed between 4 and 18 h, with the distribution peaking at around 10 h. Moreover, by comparing the berthing times of ships before and after the pandemic in CPANZP, it can be found that the berthing times of ships have generally increased to varying degrees. Specifically, the proportion of ships berthing for 0–30 h has decreased, while the proportion of ships berthing for 32–134 h has mostly increased, with the proportion of ships berthing for 60–76 h showing the largest increase.

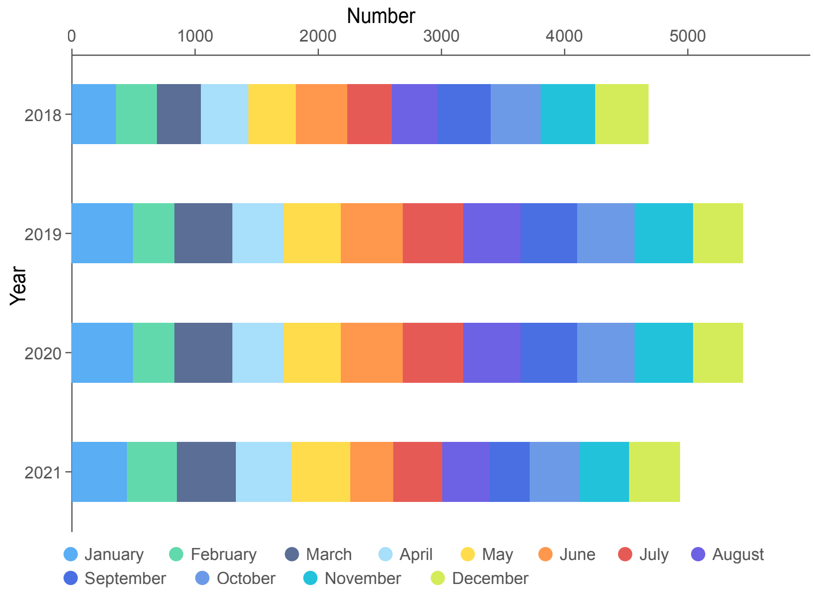
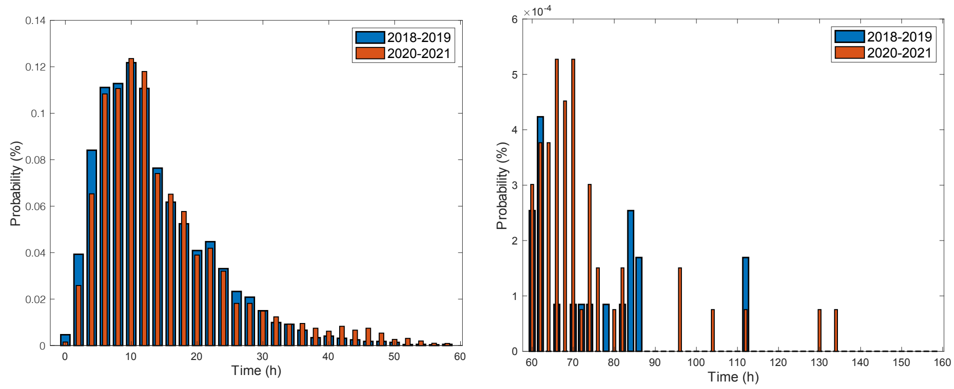


Figure 5. Number of ships berthed at CPANZP during 2018–2021.



(**a**) Within 60 h (**b**) Beyond 60 h

Figure 6. Distribution of the ships berth time before and after COVID-19.

The increased stay time at berth might cause a higher demand of energy for ships. In order to evaluate the electricity demand of berthed ships at different connection rates, this study considered the cases where the probability of each berthed ship in CPANZP connecting to shore power was 20%, 40%, 60%, 80%, and 100%, respectively. Using the Monte Carlo method, the expected shore power demand of berthed ships in CPANZP was calculated through a large number of simulations. Technical information such as the berthing time, ship type, and auxiliary engine power of berthed ships in CPANZP from 2018 to 2021 was collected, and the expected shore power demand under different connection probabilities was calculated. The results are shown in Figure 7.

From the figure, it can be seen that under the same year and shore power connection probability, the energy demand of berthed ships in CPANZP generally shows a trend of decreasing first and then increasing. Among them, due to the relatively small number of berthed ships in February and March, the corresponding shore power demand is also relatively small. Although the number of berthed ships in 2021 decreased compared to previous years due to the impact of the pandemic, it can be seen that the shore power demand of berthed ships in 2021 is still higher than that in 2018–2020 because the berthing time of berthed ships has increased due to the pandemic. Specifically, with probabilities of 20%, 40%, 60%, 80%, and 100% for each berthed ship to connect to shore power, the monthly shore power demand of berthed ships is around 2.4×10^6 kWh, 4.8×10^6 kWh, 7.1×10^6 kWh, 9.1×10^6 kWh, and 1.2×10^7 kWh, respectively. It can be seen that as the probability of each ship connecting to shore power increases, the monthly shore power demand of berthed ships also increases accordingly, with a large increase. When each ship connects to shore power with a probability of 100%, the monthly shore power demand of berthed ships reaches about 15% of the total electricity consumption in the CPANZP area in 2021.

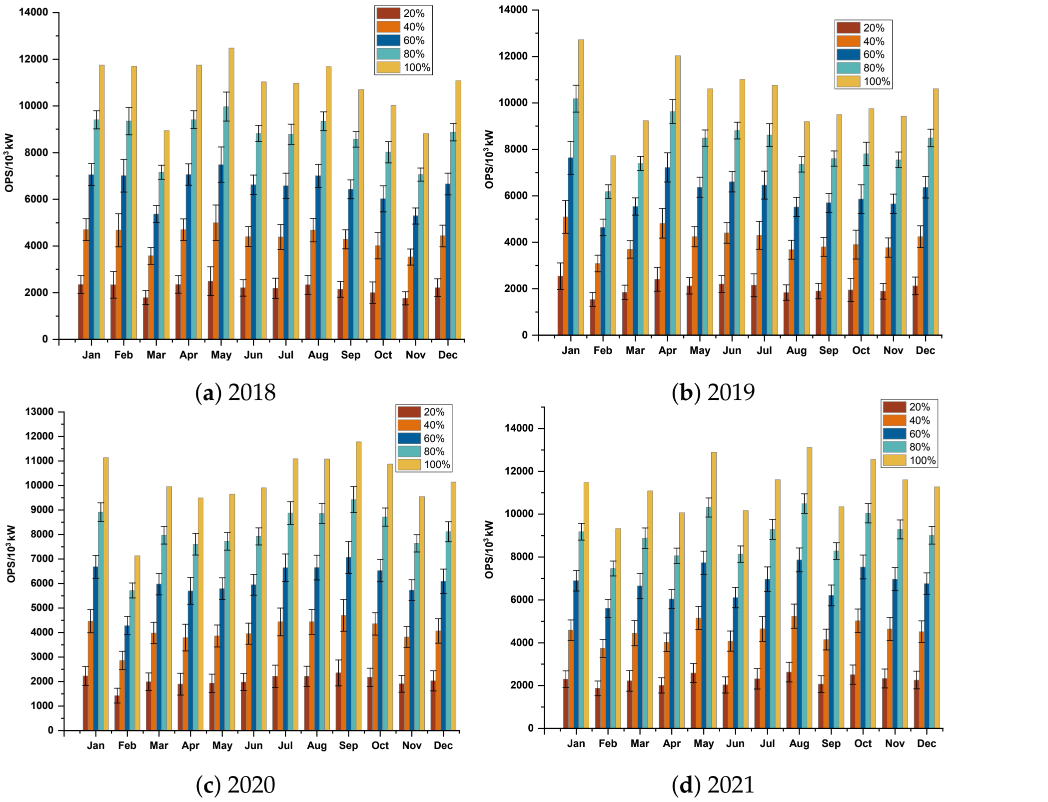


Figure 7. Energy demand from OPS of berthed ships in CPANZP under different connection probabilities in (**a**) 2018, (**b**) 2019, (**c**) 2020, and (**d**) 2021.

4.2. Analysis of OPS Connection

There are 14 sets of low-voltage OPS (LVOPS) equipment and 5 sets of high-voltage OPS (HVOPS) equipment in CPANZP at present. The specific distribution is shown in Figure 8. Among them, five sets of LVOPS equipment were constructed in 2020 and completed in 2021, and nine sets of LVOPS equipment were constructed and completed in 2022, all of which have been completed. The capacity of LVOPS equipment is 200 kVA, except for two sets of LVOPS equipment at Berth 1, which are 800 kVA. One, one, two, and one set(s) of HVOPS equipment was constructed in 2015, 2016, 2018, and 2020, respectively, and completed in 2016, 2017, 2019, and 2020, respectively. Among them, Berths 3 and 4, 5 and 6, 8 and 9, and 10 and 11 share one set of HVOPS equipment, respectively. The capacity of HVOPS equipment includes 3000 kVA, 4000 kVA, and 5000 kVA.

LVOPS equipment and HVOPS equipment have been basically arranged on each berth of CPANZP for use by berthing ships. However, as of August 2022, only four sets of LVOPS equipment at Berths 1 and 2 and two sets of HVOPS equipment at Berths 5 and 6 , as well as 8 and 9 , have been used, as shown in Figure 9. Among them, the number of ship berths in July and August 2022 amount to 405 and 410, respectively, and there are only 14 and 38 OPS connections, respectively, in July and August 2022, and both are LVOPS. It can be seen that for LVOPS equipment, compared with the usage before July 2022, there is a significant increase in July 2022 and August 2022, but the utilization rates of shore power are only 3.46% and 9.27%, respectively. The utilization rate of LVOPS is still very low, and most LVOPS equipment has not been used. Compared with LVOPS equipment, HVOPS equipment has relatively high electricity consumption, but its connection times are only 7, and it is only being used before July 2022. The utilization rate of shore power has been low, and most HVOPS equipment has not been used either.

To sum up, OPS equipment in CPANZP still has a lot of room to use. Making full use of the OPS equipment and improving the utilization rate of OPS equipment are of great significance to energy conservation and emission reduction in the port industry and the realization of the national “carbon peaking and carbon neutrality” goal.

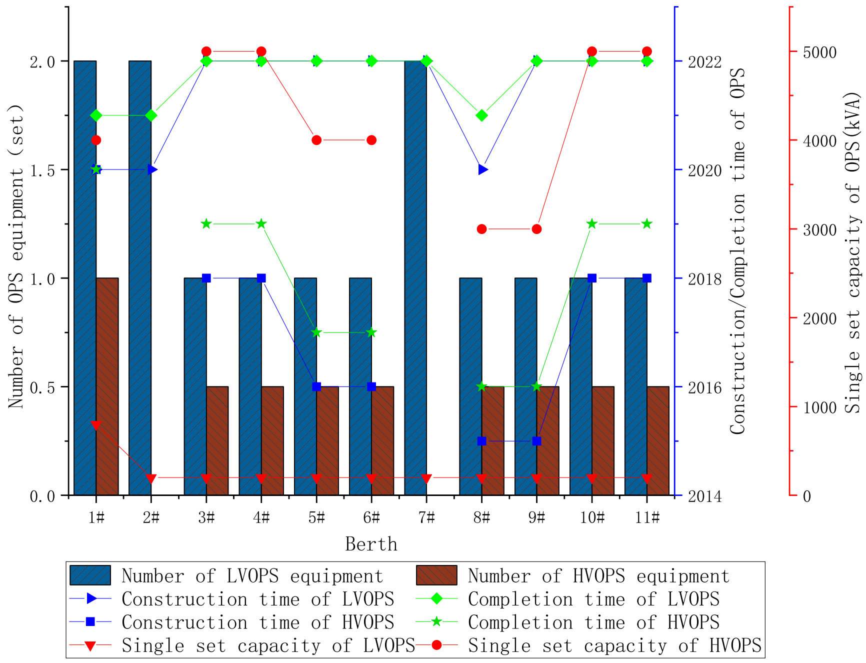


Figure 8. The installed OPS in CPANZP.

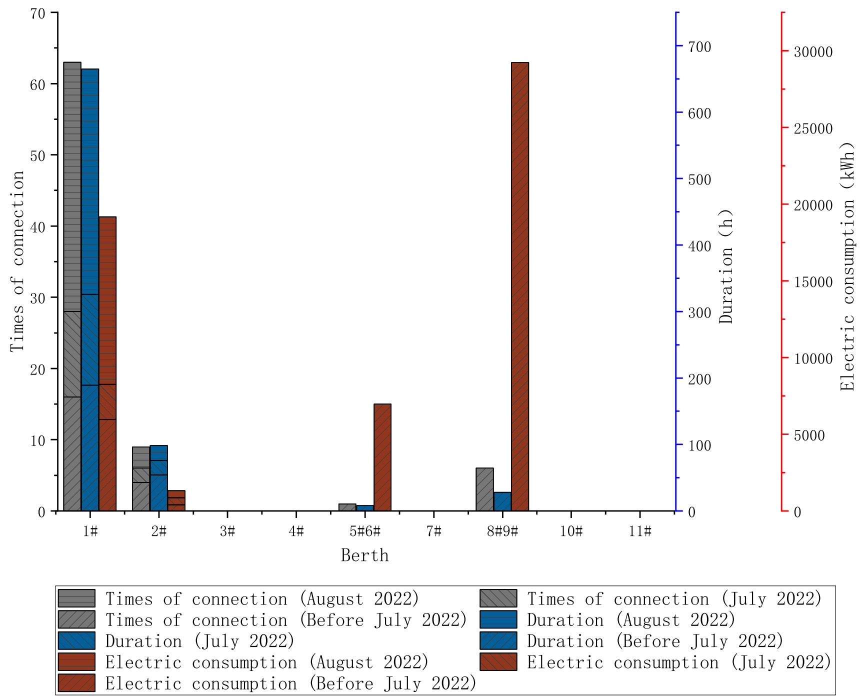


Figure 9. The connection history of OPS in CPANZP.

4.3. Analysis of Energy Efficiency

In order to further analyze the energy efficiency of berthed ships, the Monte Carlo method is used to calculate the expected values of $EEOI_b$ and TIME under different shore power connection probabilities, as shown in Figures 10 and 11, respectively.

4.3.1. Energy Efficiency without Indirect Emissions

Figure 10 shows the monthly average of $EEOI_b$ for vessels using 2.7% sulfur heavy fuel oil (HFO) without considering indirect emissions in the Ningbo-Zhoushan Port Chengshan Port Area from 2018 to 2021. In these four years, the average monthly $EEOI_b$ when the shore power connection probability was 0 was 9535.03 g/TEU, 8976.69 g/TEU, 8597.87 g/TEU, and 9625.16 g/TEU, respectively. The overall trend of $EEOI_b$ in the Chengshan Port Area was decreasing, indicating the continuous improvement of the port's energy efficiency. However, in 2021, $EEOI_b$ increased significantly, reaching the highest level in four years. This was due to the significant increase in emissions per TEU container caused by the COVID-19 pandemic.

Comparing the energy efficiency of vessels at different shore power connection probabilities, it can be seen that when vessels do not use shore power, the monthly $EEOI_b$ emissions are generally between 6000 g/TEU and 12000 g/TEU. With the increase in shore power usage, the emissions per TEU decrease gradually, and the unit emissions of TEU can be reduced by roughly the corresponding percentage for every 20% increase in shore power usage. Therefore, providing shore power for vessels calling at ports is of great significance to promoting emission reduction and achieving carbon peak and carbon neutrality.

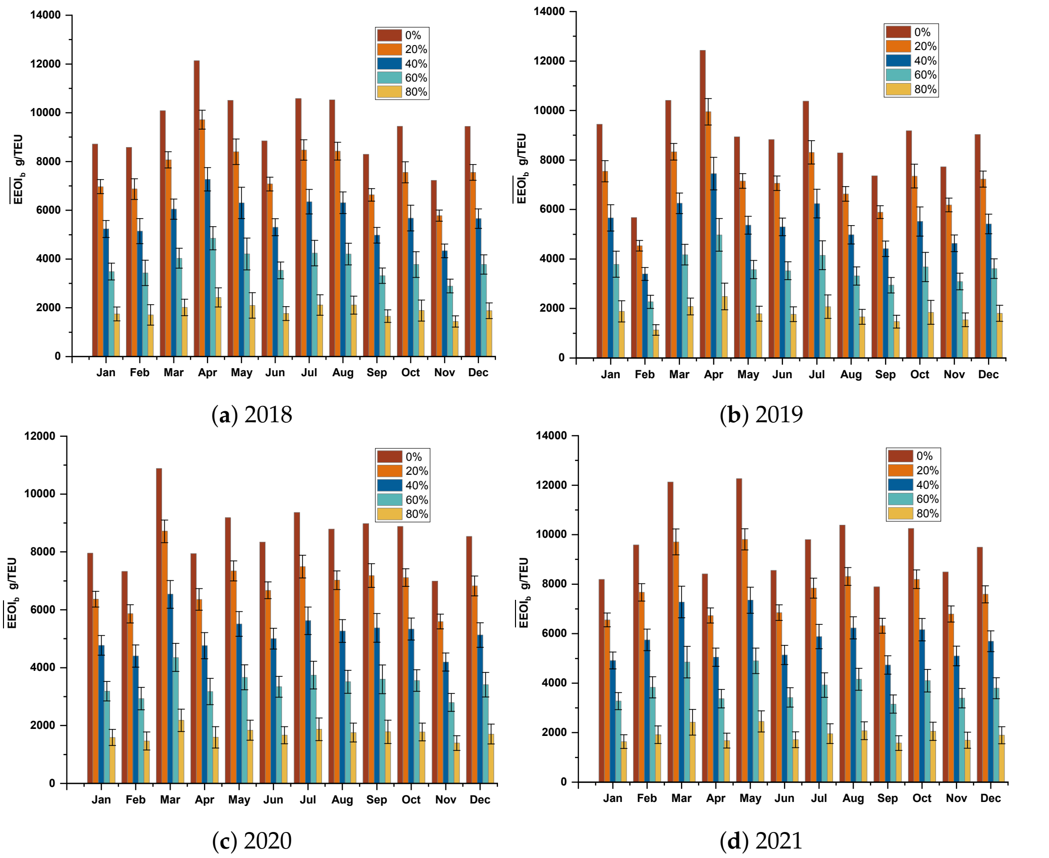
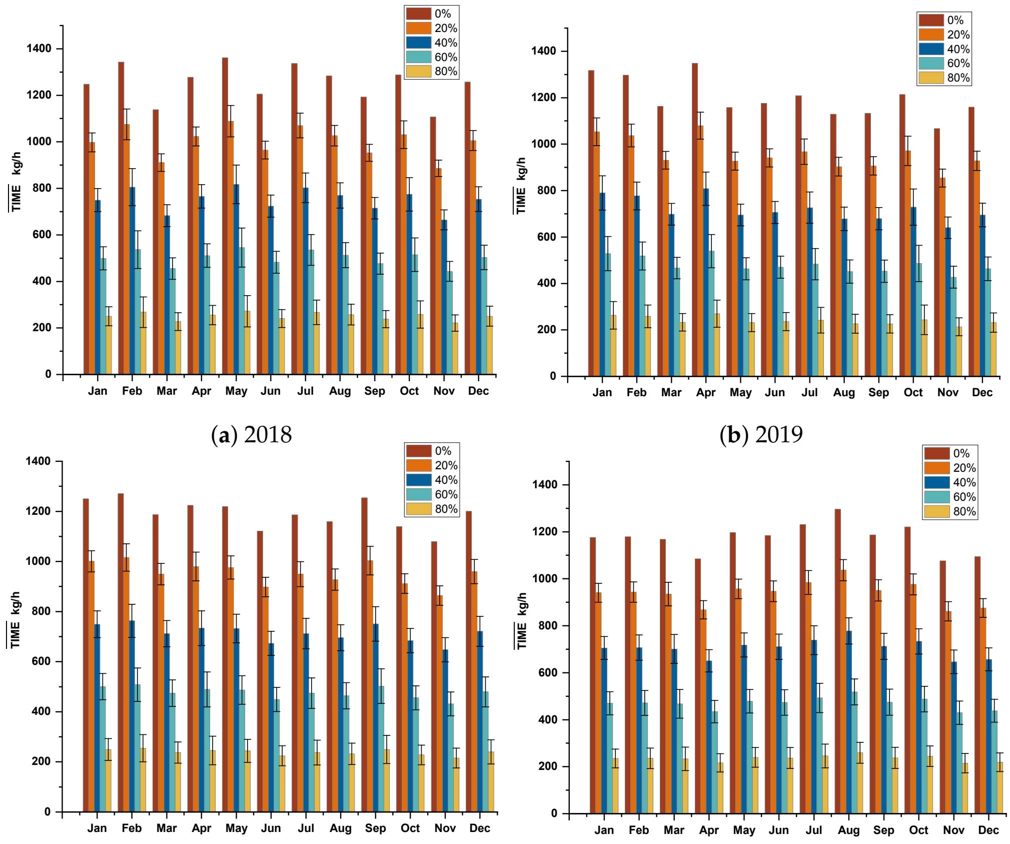


Figure 10. $EEOI_b$ of berthed ships in CPANZP with 2.7% sulfur HFO fuel under different OPS connection probabilities without indirect emissions in (**a**) 2018, (**b**) 2019, (**c**) 2020, and (**d**) 2021.

Similarly, Figure 11a–d shows the monthly expected values of TIME for vessels using 2.7% sulfur heavy fuel oil without considering the indirect emissions caused by not using shore power from 2018 to 2021. From the perspective of emissions per unit time of vessels calling at ports, the average monthly TIME from 2018 to 2020 was 1253.50 kg/h, 1197.66 kg/h, 1191.00 kg/h, and 1174.80 kg/h, respectively. This indicates that the emissions per unit time of vessels calling at Chengshan Port Area have been decreasing year by year. Even under the impact of the pandemic in 2020, the efficiency improvement of the port was still achieved, albeit at a slower pace.

Similarly, comparing the emissions of vessels with equal probabilities of using shore power of 0%, 20%, 40%, 60%, and 80%, it can be seen that if each vessel does not use shore power, the monthly CO_2 emissions are between 1100 kg/h and 1300 kg/h. With the increase in shore power usage, CO_2 emissions decrease gradually, and the emissions per vessel can be reduced by approximately 220 kg/h–290 kg/h for every 20% increase in shore power usage.



(**a**) 2018 (**b**) 2019

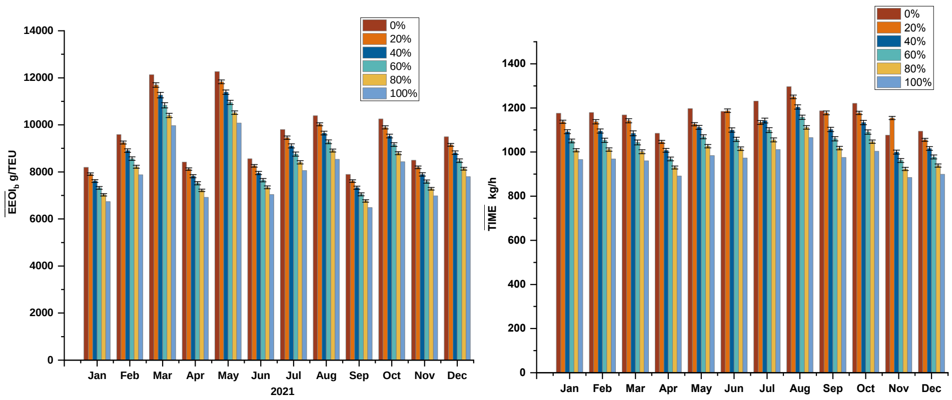
(**c**) 2020 (**d**) 2021

Figure 11. TIME of berthed ships in CPANZP with 2.7% sulfur HFO fuel under different OPS connection probabilities without indirect emissions in (**a**) 2018, (**b**) 2019, (**c**) 2020, and (**d**) 2021.

4.3.2. Energy Efficiency Considering Indirect Emissions

In practice, the electricity required for ships to use shore power is not obtained through green energy, resulting in indirect emissions when using shore power. The monthly expected values of $EEOI_b$ and TIME in CPANZP for 2021, taking into account the indirect emissions of shore power, are shown in Figure 12. When considering the emissions per TEU container, the monthly emissions fluctuate significantly, as shown in Figure 12a. When the probability of using shore power is zero, the monthly emissions per TEU container are between 8000 g/TEU and 12,200 g/TEU, with the highest emissions occurring in March and May when completing unit container operations, which may be related to the large volume of port operations and longer waiting times for ships. When considering emissions from a TIME perspective, as shown in Figure 12b, the monthly CO_2 emissions produced per unit time are relatively stable at around 1180 kg/h, as the port operation speed is relatively stable.

Compared to the energy efficiency without considering indirect emissions under the same conditions, the consideration of indirect emissions from shore power significantly increases both the emissions per unit TEU container and the CO_2 emissions per unit time. Although using shore power can still reduce emissions to a certain extent, the degree of reduction is greatly reduced, and the effectiveness of shore power is greatly weakened. For every 20% increase in the shore power usage rate per ship, emissions can only be reduced by around 300 g/TEU or 45 kg/h, and if losses in the shore power connection are taken into account, the emission reduction effect will be further reduced.

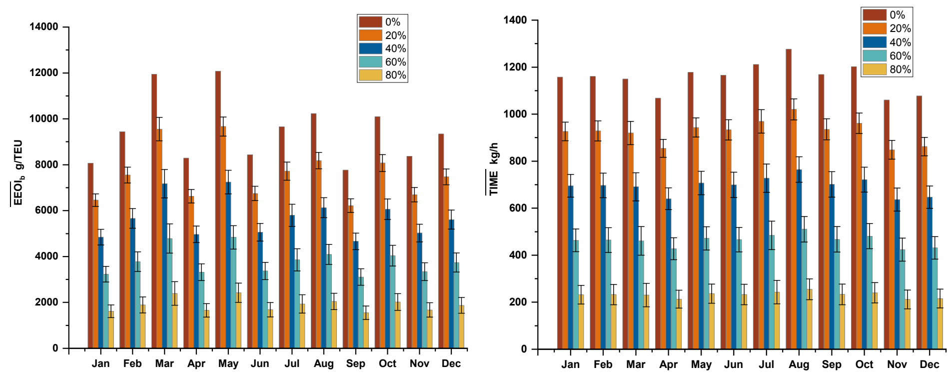


(**a**) $EEOI_b$ (**b**) TIME

Figure 12. $EEOI_b$ and TIME of berthed ships in CPANZP with 2.7% sulfur HFO fuel under different OPS connection probabilities and considering indirect emissions in 2021.

4.3.3. Energy Efficiency Considering Low Sulfur Fuel

With the increasing attention to the coastal environment in China, there may be further restrictions on the sulfur content of ships' fuel within emission control areas in the future. It is expected that the fuel sulfur content will be further limited to 0.1% by 2025. Therefore, this study evaluated the monthly $EEOI_b$ and TIME values considering the indirect emissions from ships using marine fuel with a sulfur content of 0.1% while berthed, as shown in Figure 13a,b, respectively.



(**a**) $EEOI_b$ (**b**) TIME

Figure 13. $EEOI_b$ and TIME of berthed ships in CPANZP with 0.1% sulfur HFO fuel under different OPS connection probabilities without indirect emissions in 2021.

The results show that, similar to the use of marine fuel with a sulfur content of 2.7%, an increase of 20% in the probability of ships using shore power can reduce emissions by approximately 2000 g/TEU or 230 kg/h. Moreover, the sulfur content in the fuel used by ships can also have an impact on CO_2 emissions. Compared with the use of heavy fuel oil with a sulfur content of 2.7% under the same conditions, the use of heavy fuel oil with a sulfur content of 0.1% can reduce CO_2 emissions by 120–190 g/TEU or 16–20 kg/h per month.

4.4. Implication Inspiration

The findings of this study hold significant implications for understanding the challenges and opportunities associated with the practical implementation of OPS in ports. Addressing these challenges and opportunities is crucial for the successful implementation of OPS in ports, enabling enhanced energy efficiency and reduced carbon emissions. Governments, port authorities, and relevant stakeholders should collaborate to develop strategies, policies, and infrastructure improvements that support the increased adoption and connection of OPS, ensuring the efficient and reliable operation of power systems within ports.

First, while the installation of OPS infrastructure in CPANZP is abundant, the actual connection of OPS remains rare, particularly for ocean-going ships. Consequently, there exists substantial untapped potential for energy efficiency improvement, with ample room for increasing the adoption and connection of OPS. Measures to incentivize and promote OPS connection, such as government subsidies, are necessary. Secondly, the connection of OPS poses challenges for the existing power systems in ports. As the connection rate increases, there is a sharp rise in the power demand of berthed ships, surpassing the capacity of the power system by several times. This significant increase in power demand may potentially strain or overload the power system, leading to hidden failures or disruptions. Therefore, improving and upgrading the existing power systems are imperative requirements to accommodate the rising connection rates of OPS effectively.

Additionally, the adoption of OPS has demonstrated its effectiveness in reducing local carbon emissions and improving the energy efficiency of both port and ship operations. However, when considering the indirect emissions associated with OPS, with an EF value of 581 g/kWh, the emissions from a ship using OPS are only $(707 - 581)/707 \times 100\% = 17.82\%$ lower than those emitted by ships relying on auxiliary engines. Furthermore, studies have shown that there is an energy loss of 10–25% during the connection process to OPS, with an average value of 17.5% [48]. Consequently, when taking into account the indirect emissions of electricity and the energy loss of OPS, the potential for energy efficiency improvement through OPS becomes less apparent. This is also illustrated in Figure 12. A promising solution to this challenge is the adoption of low-carbon electricity sources in ports, such as wind- and solar-generated electricity. By shifting towards these renewable energy sources, ports can significantly reduce their indirect emissions and enhance the overall energy efficiency of OPS. Implementing such measures is crucial for maximizing the environmental benefits and energy efficiency gains of OPS within ports.

5. Conclusions

The pressure to reduce carbon emissions in ports so as to achieve the carbon peak and carbon neutrality goals is substantial. Cold ironing emerges as a prospective approach to effectively reducing the carbon footprint. Through our research, we have conducted a comprehensive evaluation of the potential for energy efficiency improvement through cold ironing, employing Monte Carlo methods and utilizing real data obtained from the port authority to ensure the quality and reliability of our findings.

Our study has proposed two metrics for quantifying the energy efficiency of berthed ships, allowing us to analyze the emissions of ships from the perspective of unit TEU and time. Additionally, we have evaluated the connection status of OPS infrastructure in CPANZP. Our results indicate that there is a considerable amount of OPS infrastructure construction in the port; however, the utilization rate of OPS remains relatively low, with most connections being made by domestic-trade vessels using low-voltage shore power.

Furthermore, our findings highlight the significant potential of providing shore power to berthed vessels in reducing local CO_2 emissions and enhancing the energy efficiency of ships. The rate of energy efficiency improvement in berthed ships is directly proportional to the rate of OPS connection. However, it is important to consider indirect emissions associated with OPS usage as they can significantly diminish the role of OPS in improving energy efficiency. Therefore, the adoption of new energy generation systems in ports becomes crucial to fundamentally reducing CO_2 emissions and further enhancing the energy efficiency of berthed ships.

These research findings contribute to the understanding of the potential benefits and challenges associated with cold ironing implementation in achieving carbon reduction goals within ports. They can assist port authorities and stakeholders in making informed decisions and formulating effective strategies with which to promote the adoption of OPS and enhance energy efficiency in port operations.

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Abbreviations

The following abbreviations are used in this manuscript:

GHG	greenhouse gas
PM	particulate matter
IMO	International Maritime Organization
ECA	emissions control area
CI	cold ironing
OPS	onshore power supply
PA	port authority
EEDI	energy efficiency design index
SEEMP	ship energy efficiency management plan
EEOI	energy efficiency operation index
EEXI	energy efficiency existing ship index
CII	carbon intensity indicator
OGS	ocean-going ships
EF	emission factor
AIS	automatic identification system
CPANZP	Chuanshan Port area of Ningbo Zhoushan Port
TEU	twenty-feet equivalent unit
MCR	maximum continuous rated power

References

1. Wang, K.; Guo, X.; Zhao, J.; Ma, R.; Huang, L.; Tian, F.; Dong, S.; Zhang, P.; Liu, C.; Wang, Z. An integrated collaborative decision-making method for optimizing energy consumption of sail-assisted ships towards low-carbon shipping. *Ocean Eng.* **2022**, *266*, 112810. [CrossRef]
2. Iris, Ç.; Lam, J.S.L. Optimal energy management and operations planning in seaports with smart grid while harnessing renewable energy under uncertainty. *Omega* **2021**, *103*, 102445. [CrossRef]
3. Gutierrez-Romero, J.E.; Esteve-Pérez, J.; Zamora, B. Implementing onshore power supply from renewable energy sources for requirements of ships at berth. *Appl. Energy* **2019**, *255*, 113883. [CrossRef]
4. Huang, L.; Pena, B.; Liu, Y.; Anderlini, E. Machine learning in sustainable ship design and operation: A review. *Ocean Eng.* **2022**, *266*, 112907. [CrossRef]
5. Faber, J.; Hanayama, S.; Zhang, S.; Pereda, P.; Comer, B.; Hauerhof, E.; van der Loeff, W.S.; Smith, T.; Zhang, Y.; Kosaka, H.; et al. *Fourth IMO GHG Study*; Technical Report; International Maritime Organization (IMO): London, UK, 2020.

6. Liu, H.; Meng, Z.H.; Lv, Z.F.; Wang, X.T.; Deng, F.Y.; Liu, Y.; Zhang, Y.N.; Shi, M.S.; Zhang, Q.; He, K.B. Emissions and health impacts from global shipping embodied in US–China bilateral trade. *Nat. Sustain.* **2019**, *2*, 1027–1033. [CrossRef]
7. Cames, M.; Graichen, J.; Siemons, A.; Cook, V. *Emission Reduction Targets for International Aviation and Shipping*; European Parliament: Brussels, Belgium, 2015.
8. Corbett, J.J.; Winebrake, J.J.; Green, E.H.; Kasibhatla, P.; Eyring, V.; Lauer, A. Mortality from ship emissions: A global assessment. *Environ. Sci. Technol.* **2007**, *41*, 8512–8518. [CrossRef]
9. Nguyen, D.H.; Lin, C.; Cheruiyot, N.K.; Hsu, J.Y.; Cho, M.Y.; Hsu, S.H.; Yeh, C.K. Reduction of NOx and SO_2 emissions by shore power adoption. *Aerosol Air Qual. Res.* **2021**, *21*, 210100. [CrossRef]
10. Innes, A.; Monios, J. Identifying the unique challenges of installing cold ironing at small and medium ports—The case of Aberdeen. *Transp. Res. Part D Transp. Environ.* **2018**, *62*, 298–313. [CrossRef]
11. Ministry of Transport of the People's Republic of China. *Implementation Scheme of the Domestic Emission Control Areas for Atmospheric Pollution from Vessels*; Ministry of Transport of the People's Republic of China: Beijing, China, 2018.
12. Ministry of Transport of the People's Republic of China. *Guidance on Building World-Class Ports by the Ministry of Transport, National Development and Reform Commission, Ministry of Finance, Ministry of Natural Resources, Ministry of Ecology and Environment, Ministry of Emergency Management, General Administration of Customs, State Administration for Market Regulation, and China State Railway Group Co., Ltd.*; Ministry of Transport of the People's Republic of China: Beijing, China, 2019.
13. Yun, P.; Xiangda, L.; Wenyuan, W.; Ke, L.; Chuan, L. A simulation-based research on carbon emission mitigation strategies for green container terminals. *Ocean Eng.* **2018**, *163*, 288–298. [CrossRef]
14. Tang, D.; Chen, Z.; Xu, C.; Yuan, Y.; Zhong, X.; Yuan, C. Energy consumption and emissions analysis of large container seaports considering the impact of COVID-19: A case study of Ningbo Zhoushan Port. *Ocean. Coast. Manag.* **2023**, *244*, 106781. [CrossRef]
15. Hoang, A.T.; Foley, A.M.; Nižetić, S.; Huang, Z.; Ong, H.C.; Ölçer, A.I.; Nguyen, X.P.; Pham, V.V. Energy-related approach for reduction of CO2 emissions: A strategic review on the port-to-ship pathway. *J. Clean. Prod.* **2022**, *355*, 131772. [CrossRef]
16. Bakar, N.N.A.; Bazmohammadi, N.; Vasquez, J.C.; Guerrero, J.M. Electrification of onshore power systems in maritime transportation towards decarbonization of ports: A review of the cold ironing technology. *Renew. Sustain. Energy Rev.* **2023**, *178*, 113243. [CrossRef]
17. Tan, Z.; Zeng, X.; Wang, T.; Wang, Y.; Chen, J. Capacity investment of shore power berths for a container port: Environmental incentive and infrastructure subsidy policies. *Ocean Coast. Manag.* **2023**, *239*, 106582. [CrossRef]
18. Chen, J.; Zheng, T.; Garg, A.; Xu, L.; Li, S.; Fei, Y. Alternative maritime power application as a green port strategy: Barriers in China. *J. Clean. Prod.* **2019**, *213*, 825–837. [CrossRef]
19. Wang, Y.; Guo, S.; Dai, L.; Zhang, Z.; Hu, H. Shore side electricity subsidy policy efficiency optimization: From the game theory perspective. *Ocean Coast. Manag.* **2022**, *228*, 106324. [CrossRef]
20. Martínez-Moya, J.; Vazquez-Paja, B.; Maldonado, J.A.G. Energy efficiency and CO_2 emissions of port container terminal equipment: Evidence from the Port of Valencia. *Energy Policy* **2019**, *131*, 312–319. [CrossRef]
21. Buhaug, Ø.; Corbett, J.; Endresen, Ø.; Eyring, V.; Faber, J.; Hanayama, S.; Lee, D.S.; Lee, D.; Lindstad, H.; Markowska, A.Z.; et al. *Second IMO GHG Study*; Technical Report; International Maritime Organization (IMO): London, UK, 2009.
22. Wang, K.; Xue, Y.; Xu, H.; Huang, L.; Ma, R.; Zhang, P.; Jiang, X.; Yuan, Y.; Negenborn, R.R.; Sun, P. Joint energy consumption optimization method for wing-diesel engine-powered hybrid ships towards a more energy-efficient shipping. *Energy* **2022**, *245*, 123155. [CrossRef]
23. Wang, K.; Li, J.; Huang, L.; Ma, R.; Jiang, X.; Yuan, Y.; Mwero, N.A.; Negenborn, R.R.; Sun, P.; Yan, X. A novel method for joint optimization of the sailing route and speed considering multiple environmental factors for more energy efficient shipping. *Ocean Eng.* **2020**, *216*, 107591. [CrossRef]
24. Wang, K.; Wang, J.; Huang, L.; Yuan, Y.; Wu, G.; Xing, H.; Wang, Z.; Wang, Z.; Jiang, X. A comprehensive review on the prediction of ship energy consumption and pollution gas emissions. *Ocean Eng.* **2022**, *266*, 112826. [CrossRef]
25. Duan, M.; Wang, Y.; Fan, A.; Yang, J.; Fan, X. Comprehensive analysis and evaluation of ship energy efficiency practices. *Ocean Coast. Manag.* **2023**, *231*, 106397. [CrossRef]
26. Czermański, E.; Oniszczuk-Jastrząbek, A.; Spangenberg, E.F.; Kozłowski, Ł.; Adamowicz, M.; Jankiewicz, J.; Cirella, G.T. Implementation of the Energy Efficiency Existing Ship Index: An important but costly step towards ocean protection. *Mar. Policy* **2022**, *145*, 105259.
27. Bojić, F.; Gudelj, A.; Bošnjak, R. Port-related shipping gas emissions-A systematic review of research. *Appl. Sci.* **2022**, *12*, 3603. [CrossRef]
28. Lee, H.; Pham, H.T.; Chen, M.; Choo, S. Bottom-up approach ship emission inventory in Port of Incheon based on VTS data. *J. Adv. Transp.* **2021**, *2021*, 5568777. [CrossRef]
29. Cammin, P.; Yu, J.; Heilig, L.; Voß, S. Monitoring of air emissions in maritime ports. *Transp. Res. Part D Transp. Environ.* **2020**, *87*, 102479. [CrossRef]
30. Chen, D.; Wang, X.; Nelson, P.; Li, Y.; Zhao, N.; Zhao, Y.; Lang, J.; Zhou, Y.; Guo, X. Ship emission inventory and its impact on the PM2. 5 air pollution in Qingdao Port, North China. *Atmos. Environ.* **2017**, *166*, 351–361. [CrossRef]
31. Gan, L.; Che, W.; Zhou, M.; Zhou, C.; Zheng, Y.; Zhang, L.; Rangel-Buitrago, N.; Song, L. Ship exhaust emission estimation and analysis using Automatic Identification System data: The west area of Shenzhen port, China, as a case study. *Ocean Coast. Manag.* **2022**, *226*, 106245. [CrossRef]

32. Huang, L.; Wen, Y.; Geng, X.; Zhou, C.; Xiao, C.; Zhang, F. Estimation and spatio-temporal analysis of ship exhaust emission in a port area. *Ocean Eng.* **2017**, *140*, 401–411. [CrossRef]
33. Chen, D.; Zhao, Y.; Nelson, P.; Li, Y.; Wang, X.; Zhou, Y.; Lang, J.; Guo, X. Estimating ship emissions based on AIS data for port of Tianjin, China. *Atmos. Environ.* **2016**, *145*, 10–18. [CrossRef]
34. Liu, H.; Fu, M.; Jin, X.; Shang, Y.; Shindell, D.; Faluvegi, G.; Shindell, C.; He, K. Health and climate impacts of ocean-going vessels in East Asia. *Nat. Clim. Chang.* **2016**, *6*, 1037–1041. [CrossRef]
35. Dai, L.; Hu, H.; Wang, Z. Is Shore Side Electricity greener? An environmental analysis and policy implications. *Energy Policy* **2020**, *137*, 111144. [CrossRef]
36. Zis, T.P. Prospects of cold ironing as an emissions reduction option. *Transp. Res. Part A Policy Pract.* **2019**, *119*, 82–95. [CrossRef]
37. Canepa, M.; Ballini, F.; Dalaklis, D.; Frugone, G.; Sciutto, D. Cold Ironing: Socio-Economic Analysis in the Port of Genoa. *Logistics* **2023**, *7*, 28. [CrossRef]
38. Herrero, A.; Ortega Piris, A.; Diaz-Ruiz-Navamuel, E.; Gutierrez, M.A.; Lopez-Diaz, A.I. Influence of the Implantation of the Onshore Power Supply (OPS) System in Spanish Medium-Sized Ports on the Reduction in CO_2 Emissions: The Case of the Port of Santander (Spain). *J. Mar. Sci. Eng.* **2022**, *10*, 1446. [CrossRef]
39. Xu, L.; Di, Z.; Chen, J.; Shi, J.; Yang, C. Evolutionary game analysis on behavior strategies of multiple stakeholders in maritime shore power system. *Ocean Coast. Manag.* **2021**, *202*, 105508. [CrossRef]
40. Chen, J.; Xiong, W.; Xu, L.; Di, Z. Evolutionary game analysis on supply side of the implement shore-to-ship electricity. *Ocean Coast. Manag.* **2021**, *215*, 105926. [CrossRef]
41. Chen, J.; Fei, Y.; Wan, Z. The relationship between the development of global maritime fleets and GHG emission from shipping. *J. Environ. Manag.* **2019**, *242*, 31–39. [CrossRef]
42. Zis, T.; North, R.J.; Angeloudis, P.; Ochieng, W.Y.; Harrison Bell, M.G. Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports. *Marit. Econ. Logist.* **2014**, *16*, 371–398. [CrossRef]
43. Iris, Ç.; Lam, J.S.L. A review of energy efficiency in ports: Operational strategies, technologies and energy management systems. *Renew. Sustain. Energy Rev.* **2019**, *112*, 170–182. [CrossRef]
44. Tran, T.A. A research on the energy efficiency operational indicator EEOI calculation tool on M/V NSU JUSTICE of VINIC transportation company, Vietnam. *J. Ocean Eng. Sci.* **2017**, *2*, 55–60. [CrossRef]
45. Nguyen, P.N.; Woo, S.H.; Kim, H. Ship emissions in hotelling phase and loading/unloading in Southeast Asia ports. *Transp. Res. Part D Transp. Environ.* **2022**, *105*, 103223. [CrossRef]
46. Starcrest Consulting Group, LLC. *San Pedro Bay Ports Emissions Inventory Methodology Report*; Technical Report; The Port of Los Angeles and The Port of Long Beach: Los Angeles, CA, USA, 2022.
47. Zhang, S. Reflections on Optimizing and Adjusting Carbon Emission Factors in the Context of the Dual Carbon Initiative. *China Power Enterp. Manag.* **2022**, *22*, 62–65.
48. IMO. *Train the Trainer (TTT) Course on Energy Efficient Ship Operation*; Technical Report; International Maritime Organization (IMO): London, UK, 2016.