CO_2 Emission Accounting and Energy-saving Potential Analysis for Mobile Sources in Coastal Ports

Chengmeng Li[1], Lu Bai[2], Jun Zhao[2], Tonghe Zhang[2], Qingbiao Wang[2*]

[1] Shenhua & CHEC Dredging Co.,Ltd., Cangzhou 130900, China
[2] Environmental Technology Development of TIWTE (Tianjin) Co., Ltd, Tianjin 300000, China

Abstract. In order to address the key issues of insufficient specificity and poor data adaptability in CO_2 emission accounting for mobile sources at ports, and to support the upgrading of port energy-saving technologies and renewable energy substitution projects, this paper constructs a standardized CO_2 emission accounting system tailored to the coastal port scenario. Through a systematic comparison of five mainstream accounting methods (Direct Measurement Method, Mass Balance Method, Life Cycle Assessment (LCA) Method, Input-Output Method, and Fuel Consumption Method)in terms of their adaptability to port scenarios, we identify the significant advantages of the Fuel Consumption Method in data availability, accounting efficiency,and suitability for energy-saving technology evaluation. This method is established as the core accounting method. Furthermore, the paper defines the physical accounting boundaries and builds a CO_2 emission accounting model that includes activity level data, industry-specific emission factors, and emission reduction technology correction factors. This study using a northern Chinese port area as a case , emission characteristics and energy-saving potential are analyzed. The results indicate that transport ships and port machinery are the primary emission sources, accounting for 89.68% of total emissions. The emissions intensity at the ore terminal is the highest (34.57 t CO_2/kt), 5.20 times that of the container terminal. Self-unloading trucks and front-end loaders account 62.69% of port machinery emissions and are key reduction targets. The Fuel Consumption Method accurately quantifies the emission reduction effects of different energy-saving technologies and renewable energy substitution solutions, providing a standardized accounting tool for ports' low-carbon transformation. This study provides core data support for the selection of energy-saving technologies and optimization of renewable energy substitution ratios at ports.

1. Introduction

Under the dual drivers of the global "dual-carbon" strategy and the construction of world-class smart green ports, ports,as the central hubs of integrated transport systems and key nodes for energy consumption in the fields of carbon emission accounting and low-carbon transformation [1-2]. The Chinese government's "Implementation Plan for Accelerating the Establishment of a Unified and Standardized Carbon Emission Statistical and Accounting System" explicitly proposes the establishment of a unified carbon emission statistical and accounting system covering all industries by 2025, which will provide support for carbon reduction policy formulation, energy-saving technology promotion, and the layout of renewable energy substitution [3]. During port operations, mobile sources (including port machinery, transport vehicles, and shipping vessels)is the main carriers of fossil fuel consumption, account for over 70% of total CO_2 emissions at ports, making them the key breakthrough point for energy-saving retrofits and renewable energy substitutions [4].

Currently, the large-scale deployment of renewable energy technologies: electric port machinery, LNG-powered vessels, and port photovoltaic power systems, as well as energy recovery devices and intelligent scheduling systems, urgently requires accurate carbon emission accounting tools to serve as the basis for effect quantification [5]. Researchers established a comprehensive carbon emission accounting framework for ports covering both fixed and mobile sources, but did not optimize the methodology to account for the strong operational regularity and concentrated energy consumption characteristics of mobile sources[2]. Guo[4] measured the port's carbon foot print from the perspective of energy consumption and identified carbon emission drivers, but failed to form a standardized accounting process directly supporting the implementation of energy-

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*Corresponding author's e-mail: tkswqb@163.com

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saving technologies. Therefore, building a scientific and efficient CO_2 emission accounting system tailored to port mobile sources can not only fill the gap in the application of existing methods in port accessible, but also accounting boundaries have not been effectively aligned with energy consumption statistics and the scope of energy-saving measure implementation. Moreover, there is no linkage mechanism between accounting results and renewable energy substitution ratios or energy-saving technology retrofit effects. Based on this, the objectives of this paper are:1) Select and verify the effectiveness of core accounting methods for port mobile sources; 2) Construct a standardized accounting system including boundary definition,parameter selection, and model construction; and 3) Identify core emission sources and energy-saving potential through an empirical case study, providing data support for renewable energy substitution and energy-saving technology-saving fields, and offer technical references for the global green and low-carbon development of ports.

2. Methods

2.1 Selection of accounting method

Currently, mainstream CO_2 emission accounting methods, both domestically and internationally, can be broadly categorized into five types: 1) Direct Measurement Method, which relies on real-time monitoring data; 2) Mass Balance Method, based on carbon flow tracking; 3) Fuel Consumption Method, grounded in quantitative energy use logic; 4) Life Cycle Assessment (LCA) Method, focusing on full-process analysis; and 5) Input-Output Method, leveraging correlations within economic systems.

In the operational stage of ports—comprising handling, transportation, and other repetitive and regular activities—mobile source CO_2 emissions predominantly originate from fossil fuel combustion. The corresponding energy consumption data can be obtained directly from enterprise energy reports, equipment operation logs, and fuel transaction records, providing a robust data foundation for practical implementation of emission accounting.

To determine the most suitable methodology for port scenarios, a comprehensive evaluation was conducted across four key dimensions: data availability, accounting complexity, economic cost, and compatibility with energy-saving technologies (Table 1). The results indicate that the Fuel Consumption Method stands out due to its operational simplicity, low cost, and high accuracy in matching device-level energy consumption data. This method also facilitates direct quantitative evaluation of energy-saving retrofits (e.g., electrification, energy recovery) and renewable energy substitutions (e.g., LNG propulsion, photovoltaic power supply). These advantages are consistent with findings from other comparative studies on port energy consumption accounting methods [6].

Accordingly, this study adopts the Fuel Consumption Method as the core methodology for CO_2 emissions accounting of mobile sources in port operations.

2.2 Definition of Accounting Boundaries

Clearly defining the boundaries of the accounting system is essential to ensure the accuracy and consistency of CO_2 emission statistics. These boundaries should align with the energy consumption control scope of port operators, the implementation limits of energy-saving technologies, and the applicable scope of renewable energy substitution scenarios.

Table 1. Comparison of mainstream CO_2 accounting methods in terms of port scenario suitability.

Accounting Method	Data Availability	Accounting Complexity	Economic Cost	Energy-Tech Compatibility	Scenario Suitability
Direct Measurement	Low	Low	High	Medium	Low
Mass Balance	Medium	High	Medium	Medium	Medium
Life Cycle Assessment	Low	High	High	Medium	Low
Fuel Consumption	High	Low	Low	High	High

In this study, the accounting boundary is explicitly defined as all CO_2 emissions resulting from fossil fuel combustion by mobile sources during the port operation and maintenance phase, specifically including: 1) Port machinery such as rubber-tired gantry cranes, front-end loaders, dump trucks, and yard tractors; 2) Transport vehicles responsible for inbound and outbound cargo movements, such as trucks; 3) Vessels at berth, including container ships, bulk carriers, and oil tankers; 4) Port service vessels such as tugboats, pilot boats, and bunkering ships.

The accounting period is uniformly set to one calendar year to ensure the temporal representativeness and comparability of the data collected.

2.3 Construction of the Emission Accounting Model

Based on the Technical Guidelines for the Compilation of Port Atmospheric Pollutant Emission Inventories (JTS/T 163-1-2021) [7], the 2019 Refinement to the IPCC Guidelines for National Greenhouse Gas Inventories [8], and the Fourth GHG Study [9], and considering the operational characteristics of port mobile sources and applicable energy-saving technologies, a standardized CO_2 emission accounting model is established as follows:

$$E=(EF\times FC\times TCF)\times 10^{-6} \tag{1}$$

Where: E: CO_2 emissions (in tonnes); EF: emission factor (g/kg of fuel),with a preference for sector-specific factors; FC: net fuel consumption (kg), derived from refueling records or calculated using unit energy consumption methods; TCF: technology correction factor, defined as TCF=1−η, where η represents the removal efficiency of emission reduction technologies.

The activity data required to calculate fossil fuel-related CO_2 emissions should comprehensively cover all mobile sources within the defined boundary, including the net consumption of all fossil fuels and their corresponding average lower heating values.

Emission factors are obtained from the following sources: 1) Technical Guidelines for Emission Inventories of Non-Road Mobile Sources(Trial); 2) GHG Accounting and Reporting Guidelines for Land Transport Enterprises (Trial); 3) Technical Guidelines for Port Atmospheric Pollutant Emission Inventories – Part 1:Container Terminals (JTS/T 163-1-2021);- Fourth IMO GHG Study; and 4) IPCC Emission Factor Database and the COPERT IV model.

3. Case Empirical Analysis

3.1 Overview of the Accounting Object

A northern China-based representative comprehensive port area was selected as the empirical case for this study. The port area includes a variety of terminal types and mobile source operational scenarios, making it highly representative of the industry. The port area currently has 59 berths, of which 36 are designed for vessels of 10,000 tons or more. The port features five types of terminals: Container Terminals (CT), General Cargo Terminals (BT), Bulk Cargo Terminals (OT), Multipurpose Passenger Terminals (MPPT), and Multipurpose Roll-on/Roll-off Terminals (MPRT). The mobile sources at the port include four categories: Port Machinery (PM), Transport Vehicles (TV), Transport Vessels (CTV), and Port Operation Vessels (POV). Energy consumption is primarily derived from fossil fuels, which aligns with the typical energy consumption characteristics of northern ports.

The accounting period for this study is one calendar year. The activity-level data collection methods are as follows: 1) Port Machinery: Data on power range, emission standards, fuel types, and fuel consumption were collected through equipment logs, nameplates, environmental certification labels, and refueling transaction records at a northern port area. 2) Transport Vehicles: Vehicle type, emission standards, and transport Vessels. Fuel type and consumption data were collected through engine type records and refueling transaction documents. Missing data was supplemented through sampling surveys. To address the missing data, a one-week sampling survey was conducted separately at the Container Terminal and the General Cargo Terminal to gather representative activity data. The collected data was then statistically extrapolated to estimate annual activity levels, taking into account observed patterns such as seasonal variations and operational trends.

3.2 Accounting Results and Analysis

3.2.1 Emission Characteristics Analysis.

The CO_2 emission distribution across different terminal types is shown in Figure 1a. The bulk cargo terminal has the highest annual CO_2 emissions, reaching 35,800 tons, which accounts for 38.92% of the total emissions from all five terminal types. Container and general cargo terminals have similar emissions, with values of 20,700 tons and 19,400 tons, respectively, each accounting for approximately 21.5% of the total. The multipurpose passenger terminal and multipurpose roll-on/roll-off terminal emit relatively low CO_2, together contributing less than 8%. This distribution is directly related to terminal operational intensity, cargo types, and equipment energy consumption levels. The bulk cargo terminal, characterized by high handling intensity, long durations of port machinery and transport vessel operation, results in highly concentrated CO_2 emissions.

From the perspective of emission sources (Figure 1b), transport vessels and port machinery are the dominant emission sources, accounting for a total of 81,534 tons, or 89.68% of the total emissions. Among these, transport vessels contribute the highest emissions (40,566.19 tons), representing 44.84% of the total emissions. These vessels primarily consume heavy fuel oil (92.3% of total fuel consumption) and are a key area for renewable energy substitution. Port machinery emissions (36,967.81 tons), representing40.84%, are primarily from diesel consumption. Port operation vessels emit 7,991.52 tons (8.83%), while transport vehicles contribute the least, accounting for only 1.08%, due to the port's reliance on rail transport for cargo movement. The distribution characteristics of these key emission sources provide a clear direction for energy-saving technological retrofitting and renewable energy substitution.

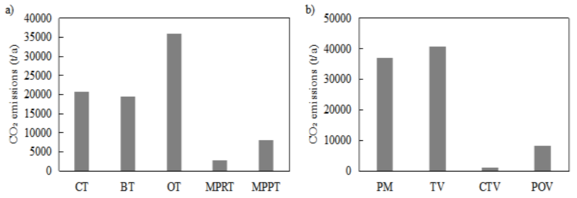

Figure 1. CO_2 emissions distribution in a) different terminal types and b) different emission sources (Including Container Terminals (CT), General Cargo Terminals (BT), Bulk Cargo Terminals (OT), Multipurpose Passenger Terminals (MPPT),Multipurpose Roll-on/Roll-off Terminals(MPRT), Port Machinery (PM), Transport Vehicles (TV), Transport Vessels (CTV), and Port Operation Vessels (POV)).

3.2.2 Identification of Key Emission Equipment.

The port machinery was further subdivided into 11 equipment types for a detailed accounting. The results (Figure 2) revealed significant disparities in emissions between different equipment, with the highest emission variation reaching427.4 times. Among the equipment, the dump trucks (12,096.05 tons) and front-end loaders (11,081.08 tons) are the primary emission sources, accounting 62.69% of the total emissions from port machinery. These two types of equipment are central to bulk cargo handling, characterized by high operational loads and concentrated fuel consumption, making them prime targets for energy-saving retrofits. Excavators (4,488.00 tons), used mainly for site leveling and short-distance cargo transport, contribute 12.14% of emissions, with significant potential for clean energy substitution. The accurate identification of key emission equipment provides essential data for optimizing energy-saving technology allocation, enhancing the specificity and economic feasibility of emission reduction measures.

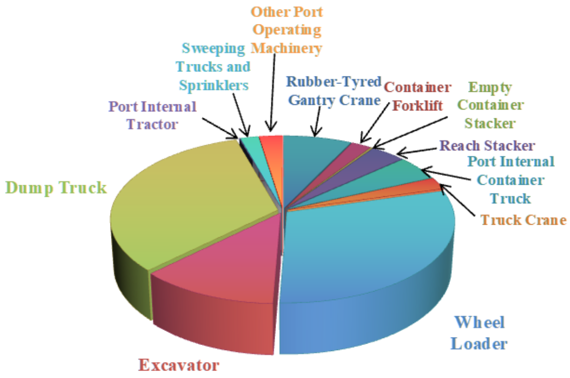

Figure 2. CO_2 emission distribution of port machinery.

3.2.3 Emission Intensity and Energy-Saving Potential Assessment.

Emission intensity (CO_2 emissions per unit throughput) is a key indicator for evaluating the port's low-carbon operational level and identifying potential energy-saving areas. Table2 presents the emission intensity for different terminal types. The Container Terminal has the lowest emission intensity (6.647 t CO_2/kt), benefiting from high levels of equipment automation and electrification and excellent cargo handling efficiency. The General Cargo Terminal has an emission intensity of 18.526 t CO_2/kt, while the Bulk Cargo Terminal has the highest emission intensity (34.565 t CO_2/kt), 5.2 times that of the container terminal. This terminal also presents the most significant energy-saving potential and is a critical target for the port's low-carbon transformation.

Table 2. CO_2 emission intensity for major terminal types.

Terminal Type	Annual Throughput (kt)	Emission Intensity (t CO_2/kt)
Container Terminal	31088.8	6.647
General Cargo Terminal	10465.0	18.526
Bulk Cargo Terminal	10356.6	34.565

Based on the energy consumption structure and technological status of core emission sources, the primary energy-saving potential lies in the following areas:

Transport Vessels: Heavy fuel oil accounts for 92.3% of fuel consumption, and renewable energy applications are not yet widespread. The energy-saving potential lies in desulfurization device upgrades (with removal efficiencies of 30%~40%) and LNG propulsion substitution (with a reduction rate of approximately 25%~30%). Studies have already verified the effectiveness of LNG as a transitional fuel for port vessels [10]. If 50% of transport vessels were to switch to LNG propulsion, annual CO_2 emissions could be reduced by 5,070 tons.

Port Machinery: Dump trucks and front-end loaders consume 100% diesel fuel and are characterized by high operational intensity. Electrification (with an emission reduction rate of nearly 100%) and hybrid power technology application are the core energy-saving directions. After the electrification retrofit of existing equipment, annual CO_2 emissions could be reduced by 14,146 tons.This result is consistent with Xu's [11] emission reduction evaluation of electric port machinery.

Despite the significant emission reduction potential of LNG propulsion and electrification, their implementation faces challenges. For LNG-powered vessels, high initial investments, lack of infrastructure, and crew training are key obstacles. Electrification, while reducing local emissions, requires extensive grid upgrades and charging infrastructure, with carbon benefits dependent on the regional electricity mix. To achieve port decarbonization, both approaches should be adopted strategically, considering local conditions, phased investments, and coordinated policies. Targeted deployment, such as LNG in regions with developed bunkering infrastructure and electrification in areas with green power, can maximize benefits while addressing feasibility challenges.

4. Conclusions

The fuel consumption method demonstrates significant advantages in data availability, calculation efficiency, and adaptability to energy-saving technologies. This method aligns well with the operational characteristics of port mobile sources and provides accurate support for the quantitative evaluation of energy-saving technology transformations and renewable energy substitutions. It is the preferred method for calculating CO_2 emissions from port mobile sources, offering technical support for precise carbon emissions accounting.

Transport vessels (44.84%) and port machinery (40.84%) are the primary sources of CO_2 emissions from mobile sources at coastal ports.The ore terminal is identified as a high-emission intensity area (34.565 t CO_2/kt). Self-dumping trucks and single-bucket loaders are key equipment in port machinery for emission reduction (accounting for a total of 62.69%). These elements should be prioritized in port decarbonization efforts, they providing a scientific basis for optimizing the allocation of resources aimed at emission reductions.

The energy-saving potential of port mobile sources is primarily concentrated in the substitution of LNG-powered transport vessels and the electrification of port machinery. Through scientific selection and large-scale implementation, significant emission reductions can be achieved, providing a clear path for the substitution of renewable energy and the upgrading of energy-saving technologies at ports.

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