WEP Warwick Evans Publishing

International Journal of Global Economics and Management

ISSN: 3005-9690 (Print), ISSN: 3005-8090 (Online) | Volume 6, Number 2, Year 2025
DOI: https://doi.org/10.62051/ijgem.v6n2.07
Journal homepage: https://ijgem.org

A Review of Research on Government Shore Power Subsidy Strategies and Ship Shore Power Usage Strategies

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ABSTRACT

With the rapid development of the global shipping industry, emissions from ships during port berthing have become an increasingly prominent issue. As an effective emission reduction measure, shore power systems have received widespread attention. However, the promotion of shore power systems involves multiple stakeholders, including the government, shipping companies, ports, and power supply companies, each with different interests, leading to limitations in shore power adoption. This paper reviews the background of shore power promotion, the emission reduction effects of port shore power, government shore power subsidy policies, berth allocation optimization, and related research. Based on the analysis of existing literature, this study identifies key challenges in shore power promotion, such as the lack of coordination between government subsidy policies and port berth allocation optimization, as well as the low willingness of shipping companies to use shore power. This research aims to provide a reference for the government in formulating shore power promotion policies while assisting shipping enterprises in optimizing their operational strategies, ultimately fostering the widespread adoption of shore power and the green, low-carbon development of ports.

KEYWORDS

Shore power system; Government subsidies; Berth allocation

1. RESEARCH BACKGROUND

The rapid development of the shipping industry, accounting for over 90% of global trade volume, has positioned ports as critical hubs for maritime and land transport, generating significant economic value while also imposing substantial environmental pressure. Since China's reform and opening-up in 1978, the country's outward-oriented economic growth has driven a leap in the port and shipping industry. In 2023, the total cargo throughput of China's ports reached 16.973 billion tons, with container throughput at 310 million TEUs. Among the world's top ten ports by container throughput, six are in China, highlighting the country's strong maritime industry. Leading enterprises such as Shanghai International Port Group, Ningbo Zhoushan Port, and China Merchants Port have become globally leading port operators.

Despite these remarkable achievements, China's port and shipping industry still faces the challenges of high investment, high emissions, high energy consumption, and low efficiency ("three highs and one low"). In particular, pollution caused by ship emissions at ports has become a critical issue restricting high-quality industry development, necessitating effective governance measures.

China has strongly promoted the construction of shore power facilities to reduce port carbon emissions. By the end of 2019, more than 5,400 shore power facilities had been built nationwide, covering over 7,000 berths [1]. However, in the actual promotion of shore power at Chinese ports, shipping companies have generally shown low enthusiasm for its use, limiting the broad application of shore power. The reasons include:

Differences in objectives between the government and shipping companies regarding shore power usage. While the government prioritizes the environmental benefits of shore power promotion, especially under China's "carbon peaking" and "Yangtze River Protection" strategies, shipping companies are more concerned with the economic benefits of using shore power. These include the costs of onboard shore power reception equipment, shore power prices, and time costs. Moreover, shipowners must retrofit vessels to accommodate shore power facilities, which entails significant expenditures. Surveys of ship shore power reception equipment suppliers indicate that the retrofitting costs for cargo ships range from hundreds of thousands to millions of yuan. By comparing the long-term investment costs of ship modifications for shore power with the daily fuel savings after retrofitting, shipping companies expect a significant cost reduction before they are willing to install shore power reception equipment on ships.

Interdependence between shore power and berths as critical port resources. The allocation of shore power not only affects ship emissions at ports but also impacts berth resource utilization. A pressing challenge is how to efficiently allocate limited government funds to incentivize shipowners to retrofit their vessels for shore power use, thereby achieving port carbon reduction, while also ensuring optimal berth utilization without compromising port operational efficiency.

2. LITERATURE REVIEW ON THE EMISSION REDUCTION EFFECTS OF SHORE POWER AT PORTS

The adoption of shore power by port enterprises is an effective means of reducing ship carbon emissions and has been widely promoted. Scholars worldwide have conducted extensive research on shore power technology. Hall et al. [2] calculated the changes in NOx, SO2, and CO emissions when shore power was implemented in the UK, finding that in most major coastal nations, using shore power from the national grid can significantly reduce CO2 emissions. Hul et al. [3] proposed a method for estimating ship berthing emissions based on actual fuel consumption and fuel quality, highlighting that shore power and restrictions on sulfur content in marine fuels are crucial for port emission reductions. Liu Zhenyu et al. [4] analyzed the economic and social benefits of shore power usage for inland river vessels in China, concluding that shore power adoption significantly improves the quality of life for inland vessel operators and enhances air quality in inland waterways. Kotrikla et al. [5] used a top-down approach to estimate pollutant emissions at Mytilene Port, employing the Homer Energy microgrid simulation software to model renewable energy sources. They proposed using wind turbines and photovoltaic hybrid renewable energy systems connected to the grid to power ships, but did not consider cost-effectiveness, leaving feasibility open to discussion.

Wan et al. [6] developed a multi-agent-based simulation model to analyze the impacts of three emission reduction strategies—shore power systems, low-sulfur marine fuels, and improved crane efficiency—on emission reduction and associated costs at container ports. The results indicated that among single emission reduction strategies, shore power had the greatest reduction effect, and the authors recommended prioritizing shore power systems if government funding is sufficient.

Some scholars have analyzed the limitations and feasibility of shore power. Lin Jieqing et al. [7] used internal rate of return and break-even analysis to assess port shore power investment models, arguing that promoting shore power system retrofitting for ships is currently feasible. Innes et al. [8] noted that for small vessels, installing shore power equipment requires considering issues such as long cables and cable reel storage. Chen et al. [9] summarized and applied the DEMATEL fuzzy model to analyze twelve constraints on China's shore power sales, their interaction mechanisms, and proposed relevant solutions and policy recommendations. Radwan et al. [10] studied Djibouti as a case and concluded that the main obstacles to shore power implementation there are electricity demand, investment costs, and power costs. Yang Yuzhuo et al. [11] reviewed shore power demand, application status, and development trends, discussing technical difficulties and optimizing system configurations for port shore power technology. Dai et al. [12] argued that inadequate shore power infrastructure can cause port congestion and that the carbon emissions resulting from delays when using shore power are higher for large vessels than for smaller ones.

The aforementioned studies focus on the emission reduction effects of shore power and the challenges of its implementation. Additionally, many scholars have explored the decision-making behavior of stakeholders regarding shore power usage. Song et al. [13] analyzed the construction and operating costs of the entire shore power system from an economic perspective, developing a mathematical model to determine the optimal shore power price while examining the relationship between government subsidy rates, shore power utilization time, and stakeholder benefits. Hu Xiaoqing et al. [14] constructed a mathematical model to analyze shore power operating costs and stakeholder cost-benefit dynamics, computing the optimal shore power price to provide a reference for shore power promotion. Yang et al. [15] compared the cost-effectiveness of using shore power facilities versus low-sulfur fuel in port supply chains, constructing three different game models to analyze their impacts on equilibrium outcomes from the perspectives of profit and social welfare.

3. LITERATURE REVIEW ON GOVERNMENT SHORE POWER SUBSIDY POLICIES

According to the International Transport Forum [16], at least €3 billion is spent annually on maritime subsidies across 36 countries. For example, in many major ports, the government acts as the owner or shareholder, playing a key role in port operations and development through investment and subsidies. Additionally, in China, South Korea, and the United States, government subsidies are provided to ships flying the domestic flag or to state-owned shipping companies. Some European countries, including Italy, the United Kingdom, Sweden, and Norway, offer subsidies to shipping companies to reduce congestion and greenhouse gas emissions. Specifically, the European Union (EU) provides financial incentives to encourage the retrofitting of ships with shore power equipment. It also subsidizes ports for installing shore power facilities under programs such as the Marco Polo and Trans-European Transport Network initiatives [17]. Moreover, the UK’s 2019 Maritime Strategy 2050 explicitly stated that the government was considering subsidies and investments for ports and ships to increase shore power usage [18].

Zis et al. [19] pointed out that government regulations are crucial for the adoption of shore power. Wu et al. [20] studied the shore power allocation problem in container shipping networks, aiming to minimize ship berthing emissions under a government subsidy scheme. They proposed a pruning and labeling algorithm, which was validated through numerical experiments and demonstrated that subsidy programs can yield substantial environmental benefits. Li et al. [21] used game theory to determine the optimal government subsidy intensity and reduction point. They applied a system dynamics approach and optimal response functions to analyze the effects of multiple game scenarios on subsidy efficiency, information asymmetry, and decision-making inconsistencies. Yin et al. [22] conducted in-depth interviews to explore the obstacles to implementing ship subsidy policies in China. They developed a cost-benefit model based on subsidy policies to estimate the costs and payback periods of reconstructing port ship subsidy policies.

Han et al. [23] constructed a revenue-sharing model for the maritime-port service supply chain from a system optimization perspective. Their study showed that government subsidy mechanisms directly affect the profits of maritime-port supply chains, providing a reference for balancing emission reduction and cost management in maritime enterprises. Teng et al. [24] analyzed the impact of government subsidies on port carbon emissions reduction by considering both subsidies and carbon taxes, identifying different carbon reduction subsidy rates to inform government decision-making. Xu et al. [25] argued that the government’s initial strategy significantly influences the strategic development of port enterprises and shipping companies. They found that without government incentives, the higher the policy cost of implementing shore power, the greater the social benefits.

Lin Guihua et al. [26] incorporated berth allocation considerations and established a mixed-integer nonlinear programming model aimed at maximizing liner shipping companies' benefits, ultimately providing recommendations regarding fuel prices and government subsidies. Tan et al. [27] used a network model to examine the differential effects of ship behaviors under pollution control and electricity subsidy policies across different ports. Wang et al. [28] constructed a stochastic optimization model to study the optimal subsidy design for government-operated ports, aiming to balance environmental benefits and subsidy costs. Lu et al. [29] analyzed the impact of government subsidies on port shore power construction and ship shore power usage. They developed a multi-period bi-objective shore power allocation optimization model, minimizing operational costs and CO2 emissions. They quantitatively described various subsidy strategies, including unit subsidy rates and subsidy thresholds, and applied the epsilon-constraint method to convert and model the bi-objective optimization problem.

Liang et al. [30] proposed a hybrid incentive strategy, demonstrating that the proposed mixed economic approach offers both environmental and economic advantages. Tao Xuezong et al. [31] constructed an economic analysis of ship shore power usage, arguing that without subsidies, the cost of using shore power is always higher than auxiliary engine power generation. Under such conditions, shore power lacks economic feasibility, and ships are unlikely to use shore power unless the government provides subsidies. The literature on government subsidies primarily falls into three categories: government benefits, subsidy rates, and barriers to subsidy implementation. However, relatively few studies have integrated government subsidies with berth allocation optimization.

4. LITERATURE REVIEW ON BERTH ALLOCATION

I When a ship enters a port, determining its berthing time and location is known as the berth allocation problem (BAP). This problem has long been established as NP-hard [32], involving numerous constraints and decision variables, making it highly complex and difficult to solve optimally. Most studies approach it from a spatial perspective, and the following sections categorize the literature into discrete berth allocation problems and continuous berth allocation problems.

4.1. Research on Discrete Berth Allocation Problems

Imai [33] studied discrete berth allocation problems under both static and dynamic ship arrivals, establishing a mixed-integer programming model to address dynamic discrete berth allocation. Experimental results demonstrated that a relatively optimal solution can be obtained within a short computation time. Cai Yun and Zhang Yanwei [34] developed a simulation optimization model aimed at minimizing the total time ships spend in port. They used a genetic algorithm to generate and evaluate berth allocation plans, incorporating simulation models to ensure berth constraints and crane scheduling strategies. The final optimization output included ship berthing times, locations, and the number of cranes assigned.

Golias et al. [35] and Imai et al. [36] suggested further exploring the relationship between departure time and optimization objectives in the dynamic discrete berth allocation problem (SDBAP). Wang Hongxiang and Yan Wei [37] formulated a mathematical model for dynamic berth allocation strategies based on heuristic algorithms, taking into account limited quay length. Using a container terminal in Shanghai as an example, they simulated and optimized their strategy, confirming its feasibility and practicality in improving container terminal productivity. Ouyang Lingping et al. [38] aimed to minimize ship in-port time, proving that the ant colony algorithm is effective and practical for solving this problem.

Zhang Minyuan [39] optimized berth scheduling with the objective of minimizing the total time spent in port for all vessels. She established a mathematical model incorporating soft time window berthing strategies, penalizing delays. Using a combination of the ant colony algorithm and MATLAB simulation, the study confirmed the model and algorithm's effectiveness. Yang Chunxia et al. [40] developed a multi-objective optimization model considering average ship in-port time, terminal production costs, and safety quality. They solved it using an improved strength Pareto evolutionary algorithm, demonstrating its effectiveness. Prencipe et al. [41] introduced an innovative model to solve the dynamic discrete berth allocation problem, using a new mathematical formulation represented as a mixed-integer program. They applied a heuristic algorithm based on swarm optimization to solve large-scale cases, outperforming CPLEX in performance. Xiang and Liu [42] considered a tactical berth allocation problem with uncertain operation times. Yu et al. [43] proposed a robust discrete berth allocation method with low-carbon objectives, accounting for uncertainties in ship arrival times and handling times.

4.2. Research on Continuous Berth Allocation Problems

Wang [44] transformed the dynamic continuous berth allocation problem into a multi-stage decision process, proposing a random beam search algorithm. Using numerical experiments based on data from the Port of Singapore, they demonstrated the algorithm's effectiveness. Lee et al. [45] applied a heuristic neighborhood search algorithm, treating the terminal as a continuous space to analyze berth allocation models. Zhen and Chang [46] developed a bi-objective optimization model aimed at minimizing costs and maximizing scheduling robustness, introducing a heuristic algorithm to solve large-scale problems.

Yang Jie [47] optimized container ship berth scheduling by minimizing overall operational costs, establishing a nonlinear mixed-integer programming model. They applied an improved genetic algorithm based on an extension correlation function, verifying the model and algorithm's effectiveness through numerical experiments. Hao Yangyang et al. [48] focused on berth allocation and crane deployment under stochastic conditions, incorporating penalty factors for overdue berthing and berth preference impacts. They developed a continuous berth and quay crane allocation model, using a neighborhood search rearrangement method to improve transportation efficiency.

Şahin [49] proposed a dynamic berth allocation model based on a differential evolution algorithm, optimizing berth layout in continuous terminals. Their fitness function incorporated penalty functions to minimize costs, and their algorithm outperformed others in finding optimal solutions. Hou [50] integrated shore power applications into berth allocation modeling, considering emissions from container ships using continuous shore power. They developed a mixed-integer nonlinear programming model to minimize total penalty costs, fuel costs, and emissions, solving it using a heuristic algorithm.

Zheng Hongxing et al. [51, 52] considered the effects of tides and the dynamic scheduling of quay crane operations, integrating berth allocation and quay crane scheduling optimization for both discrete and continuous berth scenarios. They formulated a mixed-integer programming model with the objective of minimizing ship operational costs at the port and designed a genetic algorithm embedded with heuristic rules to solve the model.

Cahyono et al. [53] analyzed berth and quay crane allocation under continuous berth conditions, developing a coupled model based on berth-quay crane interaction. They also proposed a genetic algorithm that incorporates berth-quay crane internal loops and an optimal external loop to find solutions. Martin [54] studied a multi-port continuous berth allocation problem based on speed optimization, integrating ship scheduling and multi-port berth allocation into a collaborative framework. They introduced a graph-based formulation and a branch-and-price method to solve the problem.

Zhen et al. [55] focused on port berth planning under uncertainty, proposing a multi-stage stochastic integer programming model. They also developed a novel decomposition algorithm to solve the model and conducted experiments using real berthing data from Xiamen Port. Their findings demonstrated the algorithm's effectiveness, offering valuable insights for port operators aiming to improve container terminal efficiency under uncertain conditions.

The above literature review highlights research progress on berth allocation. Most studies approach the problem by categorizing it into discrete and continuous berth allocation models. Common modeling methods include mixed-integer programming, mixed-integer nonlinear programming, and mixed-integer second-order cone programming. Typical algorithms used to solve these models include local branching, particle swarm optimization, genetic algorithms, and other heuristic approaches, as well as exact solution algorithms [56]. These studies have proven effective in improving berth utilization efficiency and reducing operational costs. However, existing research mostly focuses on either berth allocation optimization or shore power application, lacking systematic integration of government subsidy strategies, ship operation costs, and carbon emission reduction objectives.

5. SUMMARY OF LITERATURE REVIEW

A comprehensive review of the existing literature reveals significant progress in research on port shore power promotion, government subsidies, berth allocation, and bi-level programming models. However, certain gaps and limitations remain. The key findings and critiques of previous studies are summarized as follows:

(1) Regarding the emission reduction effects of shore power, research primarily focuses on the significant impact of shore power on ship carbon emissions, as well as the technical and economic feasibility challenges of its implementation. However, most studies evaluate single-strategy approaches and rarely consider the collaborative effects and integrated optimization among multiple stakeholders in shore power promotion.

(2) Regarding government subsidy policies, scholars have explored the intensity and mechanisms of subsidies and their impact on emission reduction benefits, while also identifying barriers to policy implementation. However, relatively few studies have systematically integrated government subsidies with berth allocation and shore power infrastructure optimization, limiting comprehensive analysis of policy and technological synergy.

(3) Regarding berth allocation research, studies have developed mature mathematical models and heuristic algorithms for both discrete and continuous berth allocation problems. However, most research remains limited to single-objective optimization and does not incorporate the combined effects of shore power usage, government subsidies, and carbon reduction targets.

(4) Regarding the integration of government subsidies and berth allocation within a bi-level programming model, existing studies largely focus on either subsidy design or berth allocation optimization but rarely consider their combined impact. There is a lack of research systematically integrating government decision-making, port operation strategies, and emission reduction policies into a unified framework.

Overall, while substantial progress has been made in the field, there remains a need for further research to develop a more comprehensive and integrated approach that aligns government incentives with port operations, berth scheduling, and environmental sustainability goals.

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