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Shore power for reduction of shipping emission in port: A bibliometric analysis

Jinggai Wang [a,b], Huanhuan Li [b,*], Zaili Yang [b], Ying-En Ge [c,*]

[a] College of Transport and Communications, Shanghai Maritime University, Shanghai, China
[b] Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, Liverpool John Moores University, Liverpool, UK
[c] School of Transportation Engineering, Chang'an University, Xi'an, Shaanxi, China

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ABSTRACT

Shore power not only reduces ship emissions and noise in berthing but also has shown practical implications for maritime competitiveness. However, the existing literature and industry reports reveal that a limited number of ships have access to shore power. This highlights the need for research into the constraints faced by the sector and the development of solutions to enhance its adoption. Addressing these issues will enable the port and shipping industries to enjoy the associated benefits. Currently, existing research on shore power remains dispersed, yet it fully addresses such questions and lacks an integrated framework, making it challenging to extract pivotal insights. This paper aims to conduct a state-of-the-art review of shore power by the Web of Science Core Collection and Scopus databases as a pivotal solution to shipping emissions reduction in ports and advancing the maritime sector towards carbon neutrality. This analysis is grounded in a bibliometric analysis of existing literature on this topic, with a focus on the need to devise robust strategies to fully harness the potential of shore power for carbon neutrality. The valuable findings are revealed, including (i) The adoption of shore power by ports is predominantly propelled by regulatory mandates and incentives, inclusive of government subsidies in leading regions such as China, the U.S., and Europe; (ii) Due to the implementation of Emission Control Areas and carbon neutrality regulations, an increasing number of port operators in Europe are turning to shore power to fulfil both the governmental or industrial requirements, especially regarding cruise ships; (iii) The literature on shore power primarily delves into four main research areas: the inherent features of shore power, emission inventory assessments, practical applications of shore power, and energy management strategies; and (iv) Emerging directions in shore power research include cooperative optimisation among stakeholders, integration of new technologies into shore power, a holistic evaluation of the multifaceted advantages of diverse emission reduction strategies, and critical examinations of any unintended consequences stemming from shore power adoption. They offer invaluable insights on enhancing the adaptation and effectiveness of shore power.

1. Introduction

The global ambition is now set on achieving carbon neutrality (Guterres, 2020). As a cornerstone of the worldwide economy, the

* Corresponding authors.
E-mail addresses: H.Li2@ljmu.ac.uk (H. Li), yege@chd.edu.cn (Y.-E. Ge).

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maritime sector is fervently exploring solutions to curtailing ship emissions, including Carbon Dioxide (CO_2), Sulphur Oxides (SOx), Nitrogen Oxides (NOx), Particulate Matter (PM), and Black Carbon (BC) (Xue and Lai, 2023). According to the latest data from Clarksons Research, the shipping industry emitted 1,009 million tons of Greenhouse Gas (GHG) emissions from the well to wake in 2023. An upward trend from 2020 to 2023 is depicted in Fig. 1 (Clarksons Research, 2024). Furthermore, in 2023, shipping accounted for 2.0 % of global anthropogenic GHG emissions, representing a steady percentage trend since 2019 (Clarksons Research, 2024). Without effective interventions and under a business-as-usual scenario, shipping emissions could increase by 90–130 % by 2050 compared to 2008 levels (Lagouvardou et al., 2023).

In recent years, the maritime industry has intensified efforts to adopt environmentally friendly practices aiming at reducing harmful emissions. Through initiatives by the International Maritime Organization (IMO) and governmental agencies, the industry has taken measures to enhance energy efficiency and diminish emissions (Li et al., 2022). These measures include refining ships' hull designs, upgrading propulsion systems, establishing Reduced Speed Zones (RSZs), designating Emission Control Areas (ECAs), implementing Emission Trading Systems (ETSs), exploring alternative fuels (e.g., fuel cells, biofuels, Liquefied Natural Gas (LNG), and other clean gas), setting limits on fuel consumption (Zis and Psaraftis, 2019; Kanrak et al., 2023). Among these, Shore Power (SP), onboard scrubbers, and LNG fuel emerge as the leading solutions to mitigating ships' emissions. The definition of carbon neutrality involves achieving a balance between the amount of carbon emitted and absorbed from the atmosphere in carbon sinks (European Parliament, 2023). Two primary ways to achieve this balance are carbon capture and storage, which involves removing CO_2 from the atmosphere and then storing it, and emission reductions. SP, a system installed in both ships and ports to provide electrical power, which could be achieved from green sources (e.g., wind and solar), to docked ships and allow them to switch off their auxiliary engines, stands out as a desirable choice for achieving carbon neutrality.

SP stands at the intersection of various research areas, including energy, electrical engineering, and maritime transport. Despite being implemented in commercial ports since 1989 as a means to reduce ship-at-berth emissions, its development has undertaken various constraints (Shi and Weng, 2021). Current research primarily focuses on practical implementation and challenges across different countries (Wang et al., 2023b; Bullock et al., 2023b), the inherent features of SP (D'Agostino et al., 2022; Ding and Liu, 2023), its economic cost and environmental benefits (Lathwal et al., 2021; Zhen et al., 2022), emission reduction strategies (Zhen et al., 2023; Wang et al., 2023a), and energy management aspects of SP (Fan et al., 2023; Buonomano et al., 2023). Notwithstanding its potential, the literature on SP remains dispersed and lacks an integrated framework, making it challenging to extract pivotal insights. Therefore, this paper aims to review SP systematically and critically, providing the maritime sector with a holistic perspective of this sustainable solution. It hence makes the following contributions:

(1) An in-depth understanding of the origins, evolution, and trends in the practical development of SP.
(2) A systematic bibliometric analysis of pivotal SP-related publications between 1985 and 2023.
(3) Linking real-world SP applications with academic research to highlight predominant trends in SP research.
(4) Categorising SP research into four parts to visualise its research dynamics and advancements.
(5) Establishing well-reasoned remarks, implications, and an agenda for future studies.

The remainder of this paper is structured as follows: Section 2 explains the research framework used for the SP literature review and analysis. In Section 3, a bibliometrics review is carried out to investigate SP research and present the results. The various topics of SP are discussed to conduct a deep exploration in Section 4. Sections 5 and 6 offer a set of remarks and future research opportunities for SP, respectively. The conclusion is presented in the last section.

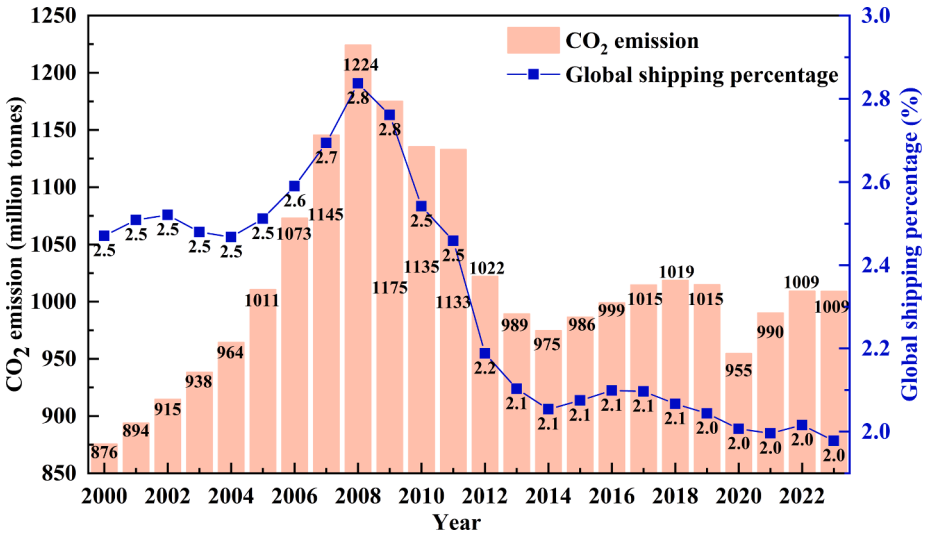


Fig. 1. Overall CO_2 emission from global shipping (2000–2023).

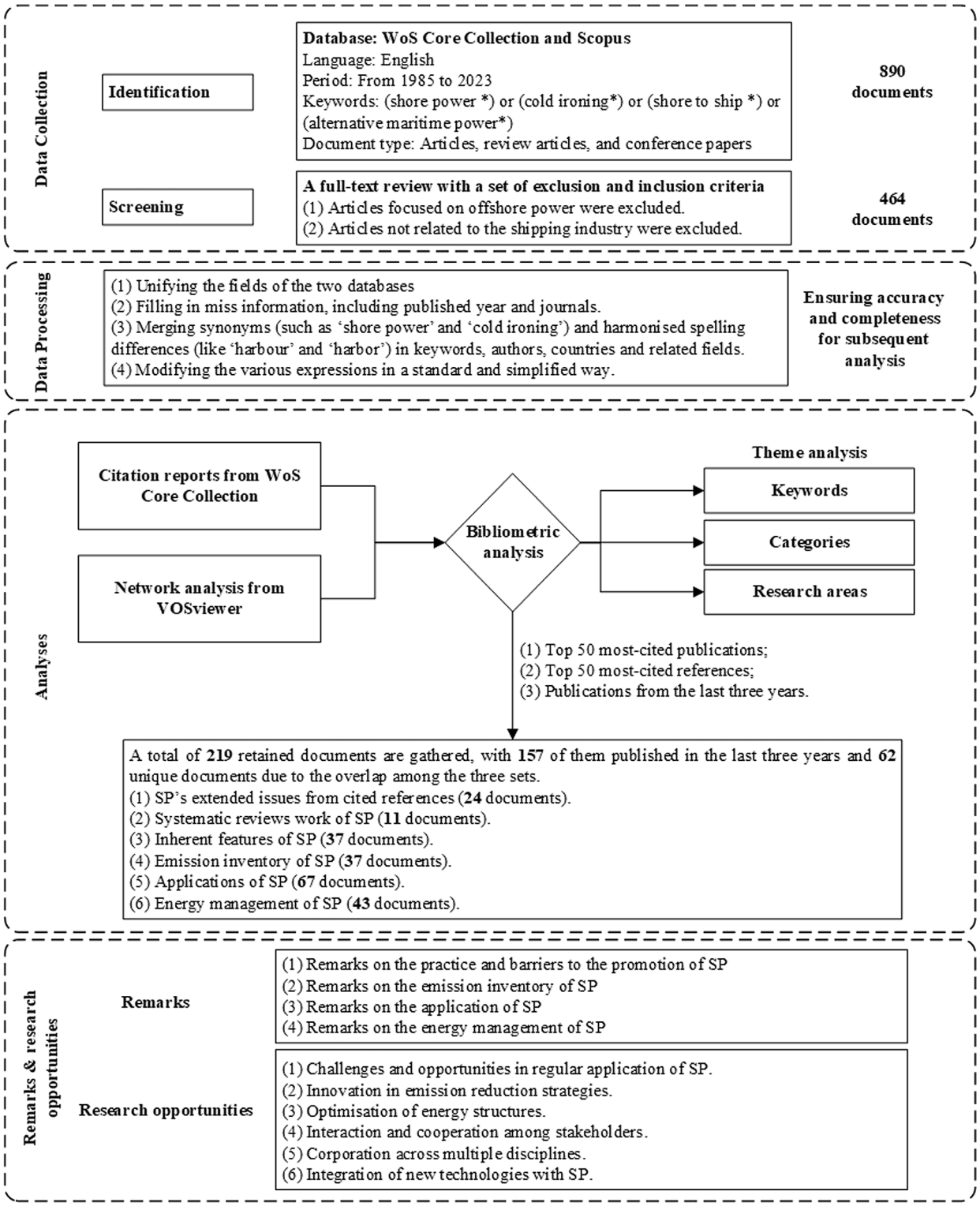


Fig. 2. The research framework.

2. Research framework

SP remains an under-research area within maritime studies. To bridge this knowledge gap, this section introduces a new research framework to support a detailed and systematic review of SP in the existing literature, delving into the progress of SP research.

Bibliometrics emerges at the confluence of mathematics, statistics, and literature, offering a scientific lens to dissect books, articles, and various publications. This method has become a valuable tool for evaluating the development and impact of research across various sectors, including maritime and port operations, by uncovering trends and networks within specific fields. For instance, Dragović et al. (2023) employ bibliometric analysis to assess the characteristics of journal publications related to container terminal operation research. The adoption of bibliometric statistics, especially for analysing data from the Web of Science (WoS) Core Collection and Scopus databases, has seen a significant increase. The VOSviewer software tool is pivotal for constructing and visualising bibliometric networks, which are based on bibliometric data concerning citation, bibliographic coupling, co-citation, and co-authorship. Integrating the descriptive statistics from WoS and Scopus with the visualised network in VOSviewer enables a comprehensive and systematic review.

The systematic review framework is shown in Fig. 2. In the literature retrieval procedures, considering the wide research scope of SP, the direct use of SP as keywords contains a limited number of documents to be found. To overcome this challenge, this paper employs a precise research method within the database. The WoS Core Collection and Scopus are selected as the primary databases due to their detailed and comprehensive literature information. To capture a wide spectrum of the relevant literature, all the topics associated with SP, including "cold ironing*", "alternative maritime power*", and "shore-to-ship*" are selected as the search keywords for comprehension. The search is restricted to articles, review articles, and conference papers from January 1, 1985, to December 31, 2023. Following the removal of duplicate articles between the two sources, this search yields a total of 890 publications related to SP. To ensure the accuracy of the deep analysis, a screening process is conducted through full-text review, resulting in a dataset of 464 publications. Among these, 255 documents are sourced from both the WoS Core Collection and Scopus, while 69 and 140 documents are exclusive to each of them, respectively. This indicates a significant overlap between the two databases alongside distinct differences.

Before initiating the analysis, the importance of data processing is underscored. It is imperative to ensure the dataset's accuracy and completeness. This includes such tasks as unifying the fields of the two databases, filling in missing information, merging similar keywords, and standardising and simplifying various expressions. Such data refinement not only enhances the dataset's quality but also helps to mitigate potential errors or inconsistencies in the subsequent analysis, which could occur after data extraction but before processing in VOSviewer. For instance, before analysing keyword co-occurrences, similar terms are consolidated into a thesaurus by merging synonyms and harmonising spelling differences. As a result, the keyword count decreases from 1295 to 916.

In the analyses, citation reports and network analysis from VOSviewer are combined to conduct a bibliometric analysis. For a comprehensive understanding, this paper categorises the analysis of keywords, categories, and research areas into theme analysis, which is crucial for bibliometric analysis. Based on the insights from the bibliometric analysis presented in Section 3 and its relevance to SP, this paper further categorises the retained documents into six subtopics (e.g., (v) Applications of SP and (vi) Energy management of SP in Fig. 2) for in-depth analysis. Finally, the remarks and future research opportunities are summarised at the end.

According to the whole content, the theoretical contributions of this study are summarised as follows:

(1) It introduces a holistic framework that outlines the structure of this review, which can be used as a theoretical model to guide the development of future studies of the same kind.
(2) By integrating academic research with practice applications, this work lays a theoretical foundation for the examination of new technologies, applications, regulations, and policies within other fields.
(3) The techniques used for data collection and processing, which integrate resources such as the WoS Core Collection and Scopus, enhance the accuracy and completeness of preliminary work, thereby contributing to the theoretical novelty and empirical robustness of the study.
(4) This review enriches the academic discussions on SP's role in emission reductions within the maritime industry.

Through these contributions, this study not only deepens the academic discussions regarding the use of SP in the shipping industry but also delivers valuable insights into enhancing the adaptation and effectiveness of SP.

3. Bibliometric analysis of SP-related publications

3.1. Evolution of SP

The conception of SP has evolved significantly over time. Initially, Anderson and Fifer (1948) introduced SP by discussing its technical aspects and suggesting that naval vessels could supply emergency power to cities. A notable example of World War II is the USS Donnel' (DE-56), a United States (U.S.) Navy destroyer escorting with a large turbo-electric generator. After being damaged, it was converted into an electric power barge in 1944, providing power to shore installations in France. This successful experiment paved the way for other ships to use SP, similarly making an early milestone for SP. Today, SP is defined as the provision of shore-side electrical power to seagoing ships or inland waterway vessels at berth, as stated by the European Parliament (Tseng and Pilcher, 2015). This method not only reduces emissions but also moves power generation emissions away from densely populated areas.

Currently, modern SP systems allow ships to switch off their auxiliary diesel generators while docked, relying on electricity from

the shore. The concept of SP isn't entirely new; ships have used SP during construction or repair for a long time. Military vessels have benefited from SP for decades, and by 1989, it gradually spread to commercial ports, driven by both economic and environmental reasons. Nowadays, SP is known by various terms, including 'cold ironing', 'onshore power supply', 'alternative maritime power', 'shore-to-ship power', 'shore-to-ship electrification', 'shore to ship connection', and 'shore-side electricity technology', reflecting its widespread adoption and the diverse benefits.

Fig. 3 illustrates the development of SP in three distinct phases based on popularity from a review of modern SP applications. Prior to 2014, in the first stage termed 'SP development in local ports', individual ports began to implement SP tailored to their specific needs. The period between 2014 and 2020 marks a more extensive 'SP development in region/country' in which various countries and regions started using SP. The U.S., for instance, enforces its at-berth regulations under the California Air Resources Board (CARB) and mandates the use of SP or alternative emission-reduction measures, imposing penalties for non-compliance. China encourages SP through incentives and recommendations. The post-2020 driven by global carbon reduction and carbon neutrality commitments sees regions like Europe, Japan, and Australia laying the groundwork for wider SP adoption with policies and subsidies, anticipating a significant upswing post-2025, referred to as the 'SP development in global'. Concurrently, SP itself evolves from low-voltage systems in commercial ports to advanced high-voltage configurations, eventually incorporating frequency conversion facilities. The transition also encompasses a shift from fixed to mobile installations, and an expansion from official vessels and inland river ships such as tugboats, dredgers, and rescue ships to a broader spectrum including ferries, ro-ro passenger ships, cruise, cargo ships, and ocean-going vessels. It also includes migration from grid-source power to cleaner forms and a trend towards more intelligent SP systems.

Since the inauguration of the first commercial SP in Sweden in 1989, there has been a rising trend of ports and ships embracing this technology to neutralise carbon and other emissions. Over the years, support from organisations such as the IMO, and the European Commission (EC), along with initiatives like the World Port Climate Initiative, as well as leading countries like the U.S. and China, have propelled the shipping industry towards the acceptance of SP (Wang et al., 2023b). According to the description provided by the British Port Association (2021), the installations of SP are global yet distributed unevenly across continents. A higher density of these facilities is observed along the East and West coasts of the U.S., Western Europe, and East Asia. Conversely, the Southern Hemisphere—specifically regions in Africa, South America, and Australia—exhibits a scarcity of installations. This distribution pattern is associated with efforts aimed at reducing emissions and improving air quality in port areas. According to the Green Technology Tracker report by Clarksons Research in May 2024, from a maritime perspective, more than 2,635 vessels in the fleet are equipped with SP connections or scheduled to be equipped. Given the total number of vessels (i.e., 109,527) in the world fleet (100 + GT), the percentage of vessels engaged with SP only counts 2.4 % (Clarksons Research, 2024). Furthermore, the surveys and industry reports show that the application of SP for ships is lower than expected, indicating that only a limited number of vessels connect to SP while berthed (Bullock et al., 2023b; Wang et al., 2023b; British Port Association, 2021). Meanwhile, the integration of ships and shores poses significant engineering, economic, and environmental challenges, and the widespread adoption of SP depends on overcoming these challenges (Bakar et al., 2023).

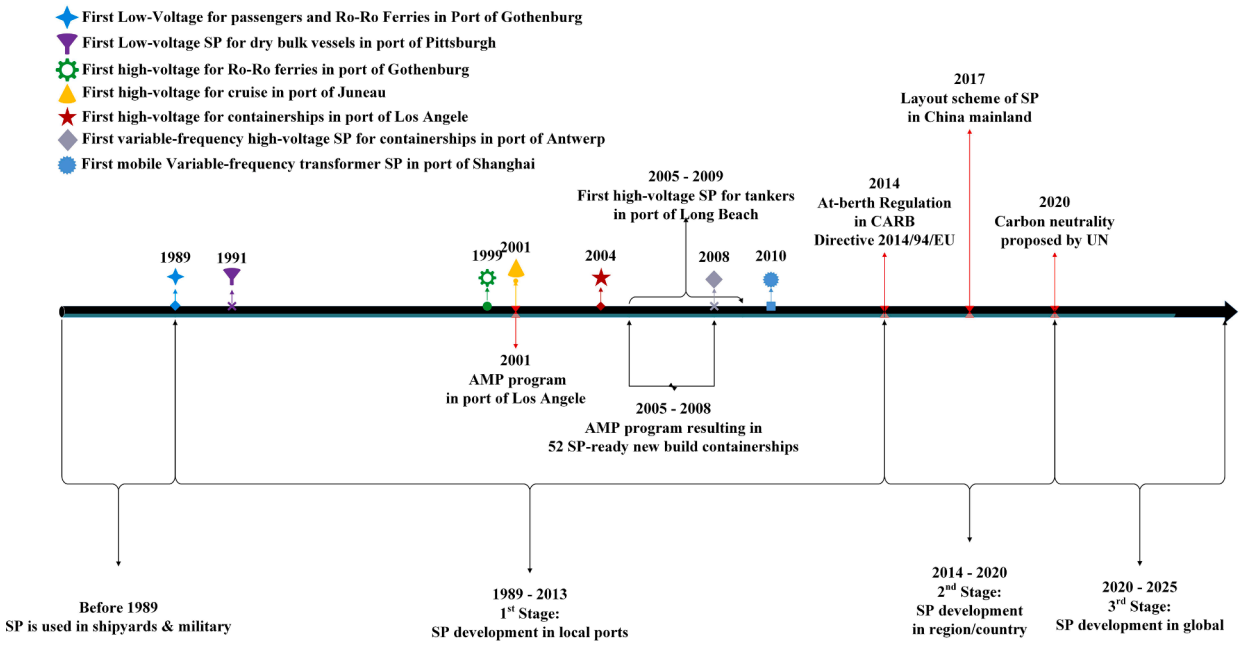


Fig. 3. The chronological representation of key milestones in SP evolution.

3.2. Bibliometric statistics

To comprehensively understand the evolution of SP, this study employs bibliometric statistics, providing a data-driven insight into the progression and impact of SP within the research field. From 1989 to 2023, SP-related literature has evolved through three distinct stages, as illustrated in Fig. 4. The initial stage, before 2014, saw a modest pace with an average of 2.16 documents annually. From 2014 to 2020, there was a significant increase in interest, resulting in an average of over 27 documents per year. In post-2020, an even greater surge in interest is evident, with an annual average of 73 documents. This trend indicates the growing emphasis on SP as a strategy for emissions reduction within the maritime industry since 2014. Interestingly, there is a direct and strong correlation between the trends shown in Fig. 3 and Fig. 4, highlighting 2014 and 2020 as key years in SP development. For example, the first rule concerning SP, the CARB at-berth regulation, was introduced in 2014. This mandate necessitates that at least half of the fleets deactivate their engines and opt to connect to Renewable Energy Sources (RESs), predominantly SP, or employ an alternative emission-reducing technology (CARB, 2014). Concurrently, China began rapidly adopting SP, starting a pilot in 2009 and then expanding, reinforced by various guidelines over the subsequent five years. The European Parliament in 2013 (EC, 2013) and the Marco Polo Programme in 2014 (EC, 2014) also played key roles in accelerating SP development. Hence, the increasing trend in published literature aligns with the practical advancements and implementation of SP solutions. As for citations, the number of citations shows variability but follows an overall upward trend, peaking in specific years. This could indicate that certain key publications or breakthroughs in those years have driven interest and further research. Meanwhile, the peak in citations does not always coincide with the peak in publications, suggesting a time lag between when research is published and when it is cited by other documents.

3.3. Theme analysis

The thematic analysis of SP focuses on key indicators about keywords, categories, and research areas. From the 464 screened publications, 52 categories are generated, covering domains like *Energy Fuels*, *Engineering Electrical Electronics*, *Environmental Sciences*, *Transportation*, and T*ransportation Science & Technology*. The results also touch upon 34 adjacent research areas, including *Engineering*, *E*nergy *& Fuel*, and *Transportation*. The field of *Energy & Fuels* is the earliest contributor to SP and maintains a consistent stream of publications. *Engineering* subsequently takes the lead in contributions, reaching its peak in 2019. The field of *Transportation* started exploring SP in 2004, while *Oceanography* joined in 2009. Even though they are smaller contributors to SP, their involvement has shown steady growth. Surprisingly, the *Computer Science* domain ventured into SP in 2015 and saw a swift surge in its contributions. Overall, SP research is multidisciplinary, initially rooted in the *Energy Fuels* domain, branches out into *Engineering* and *Environmental Sciences & Ecology* fields, and then delves into *Transportation*, and eventually finds its way to *Computer Science*. Table 1 displays the top 10 categories and research areas with the most significant contributions to SP.

As outlined in Table 2, the most prominent keyword is ‘shore power’, which leads with the highest occurrences and total link strength, underscoring its centrality in SP research. The keyword ‘energy management’ boasts the highest average citation, along with ‘energy storage’, suggesting a strong focus on how SP integrates into the broader context of energy systems with ‘ports’ and ‘ships’. Other important keywords include ‘air-pollution’, ‘battery’, ‘emissions’, and ‘optimisation’. Delving deeper reveals a broader keyword range addressing energy management, economic analysis, and ship emissions. As Fig. 5 illustrates, these keywords are grouped into some distinct clusters:

Yellow Cluster: Featuring keywords like ‘droop control’, ‘electrification’, ‘port microgrids’, ‘ship microgrids’, ‘power generation’, and ‘renewable energy resources’, this cluster underscores the technical and infrastructure aspects of SP and characterised a shift towards integrating renewable energy and advanced power system into SP system. This trend indicates a growing concentration on renewable energy in recent years, reflecting a broader industry move towards sustainability and energy efficiency.

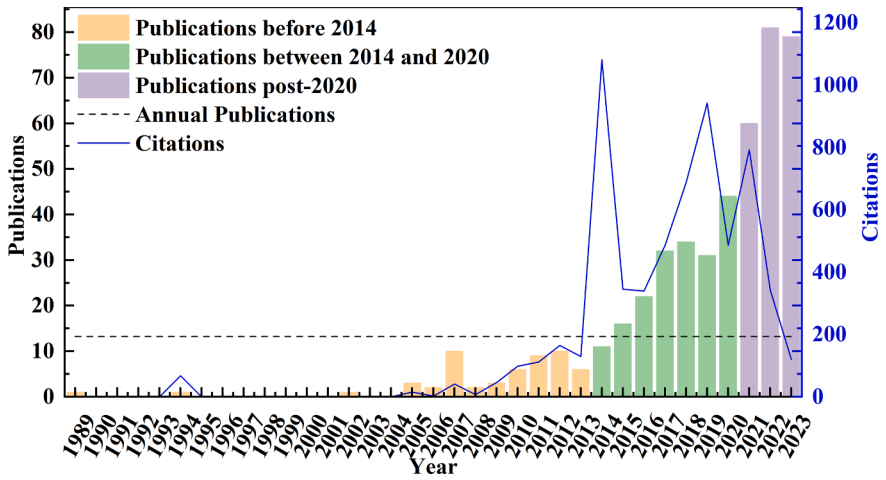


Fig. 4. Time cited and publications over time.

Table 1
Top 10 categories and research areas.

Ranking	Top 10 categories		Top 10 research areas	
	Category	No.	Research area	No.
1	Engineering, Electrical & Electronic	106	Engineering	181
2	Energy & Fuels	77	Energy & Fuels	77
3	Environmental Sciences	48	Environmental Sciences & Ecology	63
4	Green & Sustainable Science & Technology	44	Transportation	60
5	Transportation	41	Science & Technology − Other Topics	48
6	Transportation Science & Technology	39	Computer Science	23
7	Environmental Studies	33	Business & Economics	19
8	Automation & Control Systems	19	Automation & Control Systems	19
9	Engineering, Industrial	18	Oceanography	13
10	Computer Science, Information Systems	18	Operations Research & Management Science	11

Table 2
Top 10 keywords ranked by occurrences.

Ranking	Keywords	Occurrences	Total link strength	Avg. citation
1	shore power	232	382	11.72
2	ports	42	126	19.02
3	energy management	32	90	33.28
4	ships	32	96	20.03
5	green port	26	63	18.69
6	air-pollution	23	55	16.83
7	battery	23	77	7.91
8	emissions	21	59	15.62
9	optimisation	20	68	7.80
10	energy storage	18	65	18.28

Blue Cluster: Keywords such as ‘alternative fuels’, ‘decarbonisation’, ‘economic analysis’, ‘environmental analysis’, ‘Life Cycle Assessment (LCA)’, GHG’, and ‘maritime transportation’, reveal a focus on environmental and economic consideration within the maritime transportation sector. This emphasis is primarily driven by researchers’ objectives to assess the effectiveness of SP as a strategy for reducing emissions and to evaluate its economic feasibility.

Red Cluster: Centralising on the environmental implications and application of SP, this cluster includes ‘shore power’, ‘air quality’, ‘air-pollutant’, ‘AIS’, ‘incentive policy’, ‘mitigation strategies’, ‘game theory’, and ‘deployment’. It is driven by how the maritime sector compares SP with other ways to lower emissions and make the most of SP for better operations.

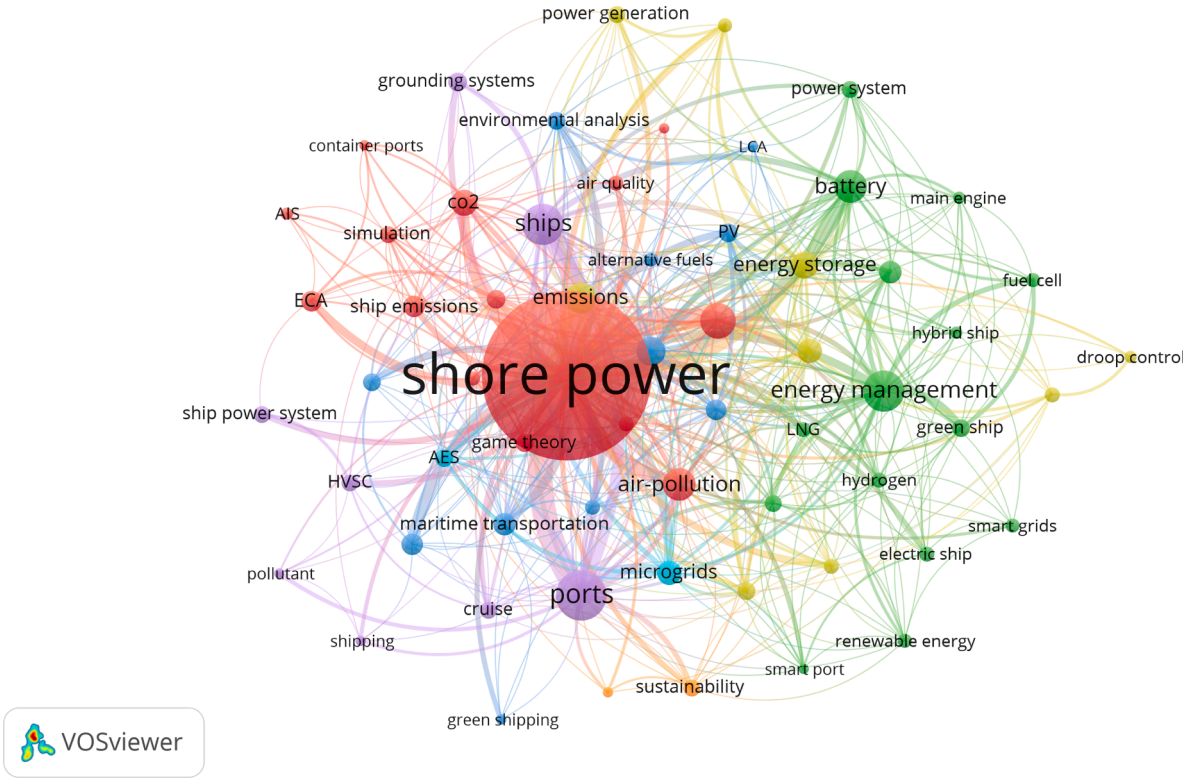
Green Cluster: Focused on SP’s energy management, this cluster is characterised by its emphasis on sustainability and advanced energy solutions. Key terms include ‘energy efficiency’, ‘hybrid power’, ‘renewable energy’, ‘green ships’, and ‘smart grids’. The underlying reason for this trend is the electrical engineering field’s efforts to improve energy efficiency through enhancing energy management strategies. A focus that has been increasingly prominent since 2020.

From 2017 to 2023, there has been a notable transformation in the keyword landscape concerning SP. Initially, the focus was on technical aspects, exemplified by keywords such as ‘grounding systems’ and ‘High-Voltage Shore Connection (HVSC)’. The emphasis gradually shifts towards emission reduction, particularly ‘emissions’ and ‘air quality’. Subsequently, broadened to strategic and operational considerations, like ‘energy management’, ‘policy’, ‘deployment problem’, and ‘optimisation’, eventually points to advanced and innovative technologies and sustainable practices, including ‘hydrogen’ and ‘All-Electric Ships (AES)’. This evolution reflects ongoing technological innovation and an increasing focus on environmental concerns within the maritime industry.

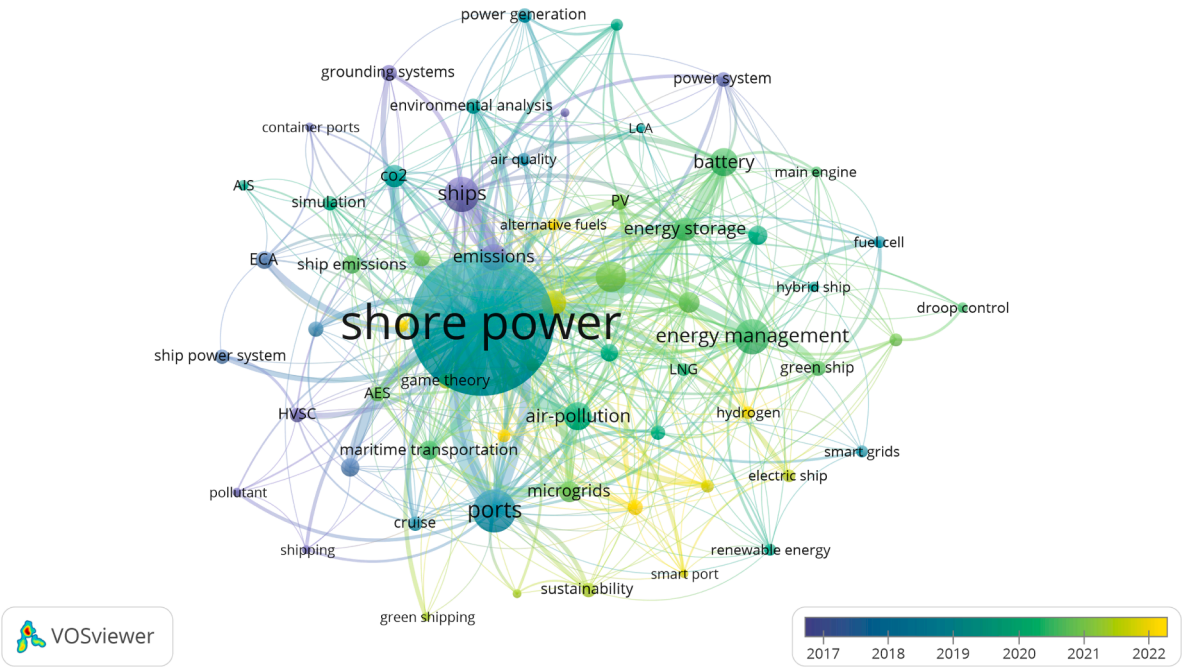
After analysing the literature, including the evolution of SP, bibliometric statistics, and research themes, a comprehensive understanding of the published works has been achieved. The key literature and important references extracted from VOSviewer provide an important basis for subsequent research on SP-related topics.

4. Distributions and analysis of the publications related to SP

To conduct a thorough analysis, the top 50 most-cited documents and references related to SP are selected. Additionally, the top 50 most-cited references, even those not directly addressing SP, are crucial for understanding the methodologies and categories of shipping emissions. This approach ensures coverage of both SP-specific research and foundational references. To make it comprehensive, documents from the last three years are incorporated, as they may contain recent developments and important insights for this examination. In total, 219 retained documents were gathered, with 157 of them published in the last three years. However, since there is some overlap between the two sets of top 50 documents and 157 identified documents, this results in the extraction of 62 unique documents. They have been categorised into six groups for further analysis based on their relevance to SP and specific topics. This categorisation will help to explore various facets of SP research and its related areas effectively. Each of them will be analysed in the ensuing subsections respectively.



(a) Network visualisation with weights of occurrence.



(b) Overlay visualisation with weights of occurrence and scores of average published years.

Fig. 5. Visualisation map of keywords on SP. Note: 1) The larger the label and the frames of the item, the higher the weight of an item; 2) The thicker the line, the stronger the links between items; 3) The closer the two items are to each other, the stronger their relatedness. The same meanings are in other visualisation maps.

(i) SP's extended issues from cited references (24 documents).
(ii) Systematic reviews work of SP (11 documents).
(iii) Inherent features of SP (37 documents).
(iv) Emission inventory of SP (37 documents).
(v) Applications of SP (67 documents).
(vi) Energy management of SP (43 documents).

4.1. SP's extended issues from cited references

This paper identifies seven pieces of literature that do not directly address SP and seventeen publications that either mention SP as one of the emission reduction options or consider SP in their future research. Within this collection, three are review articles, seventeen focus on environment inventory, one centres on application, and three are dedicated to energy management in the maritime industry. These studies span from 1997 to 2023, showing a balanced distribution of publications before and after the year 2020. Specifically, one of the earliest studies on shipping emissions was conducted by Corbett and Fischbeck (1997), who employed a top-down method to calculate the global emission inventory from ships in the context of establishing ECA. Subsequently, the bottom-up method, based on the data from registered vessels and engines in service, is introduced to update the global fleet emissions, making it more accurate and comprehensive (Corbett and Koehler, 2003). The topic of shipping emissions sees significant development, with studies exploring various aspects. Corbett et al. (2007) introduce the concept of mortality affected by emissions, and Corbett et al. (2009) examine the effectiveness and costs of various reduction options. These contributions add depth and breadth to the field of shipping emissions research. Further advancements are made by researchers such as Tichavska and Tovar (2015), who apply the Operational Meteorological Air Quality Model (OML) to estimate air pollutants like NO_X, SO_2, PM, CO, and CO_2 when vessels are in ports. Considering the external cost, Tzannatos (2010) and McArthur and Osland (2013) estimate ship emissions when they are maneuvering and berthing at ports and examine the external costs of pollutants to assess SP's social benefits. In response to stricter regulations on SO_X and NO_X emissions, most companies have switched to fuel oil (e.g., Marine Gas Oil (MGO)), LNG or have implemented AES power systems to meet these stringent requirements in different local regulations (Tichavska et al., 2019).

From a ship perspective, researchers have explored the feasibility and optimisation of AES applications by employing innovative technologies such as online control strategies and Energy Storage Systems (ESSs). Dynamic programming models have been developed to assess the effectiveness of these systems (Kanellos, 2014). Vakili and Ölcer (2023) conduct a comprehensive LCA on the emissions of battery-powered vessels, from the well to the propeller, suggesting the environmental viability of electrification with prerequisites. Ahn et al. (2018) explore a molten carbonate fuel cell and gas turbine system for a hydrogen tanker, while Mutarraf et al. (2022)

Table 3
Distributions of literature not directly concerning or just mentioning SP in topics and methodologies.

References	Emission inventory				Methodology	Energy management		
	Inventory	Inventory and cost	Inventory and health	Inventory and map		Ship	Port	Optimisation
Corbett and Fischbeck (1997)	√				Fuel-based			
Tichavska et al. (2019)	√				STEAM & regulation			
Shi and Weng (2021)	√				Bottom-up & Covid-19			
Vakili and Ölcer (2023)	√				LCA			
Corbett et al. (2009)	√	√			Bottom-up & profit-maximising			
Tzannatos (2010)	√	√			Bottom-up & external cost			
McArthur and Osland (2013)	√	√			Bottom-up & monetary			
Song (2014)	√	√			Bottom-up & social cost			
Corbett et al. (2007)	√		√		ICOADS-based & ATC Models			
Tichavska and Tovar (2015)	√			√	STEAM & spatial and temporal distribution			
Toz et al. (2021)	√			√	Bottom-up & spatial and temporal distribution			
Spengler and Tovar (2022)	√	√			Bottom-up & external cost			
Shi and Weng (2021)	√	√			Performance analyses	√		
Kanellos (2014)	√	√			Dynamic programming	√		√
Mutarraf et al. (2022)					Simulation	√		√

STEAM: Ship Traffic Emission Assessment Model.
ATC Models: Atmospheric Transportation and Chemistry Models.

examine the impact of ESS on shipboard microgrids, underlining ESS's role in energy management. Contributions from Lam and Notteboom (2014) on green port management tools further enrich the understanding of sustainable maritime practices.

Regarding references mentioning SP, researchers have demonstrated a keen interest in studying ship emissions while berthed in different regions, such as Las Palmas Port (Tichavska and Tovar, 2015), EU (Tichavska et al., 2019), Incheon (Toz et al., 2021), and Shanghai port waters (Shi and Weng, 2021). These studies have investigated ship emissions within various regulatory frameworks and environmental contexts. Researchers view SP not only as a promising means of reducing emissions from shipping but also as a potential energy source for future vessels. The wide range of topics where SP is suggested or mentioned highlights the multifaceted nature of this technology, warranting further attention and exploration in future research.

Based on the information presented above and the categorisation of these documents by their topics and methodologies (see Table 3), it becomes evident that James J. Corbett's pioneering work has significantly contributed to the understanding of shipping emissions, particularly those occurring at berth. Within the field, two fundamental methods for calculating emissions have emerged: the fuel-based top-down approach and the activity-based bottom-up one. Combining approaches such as LCA and OML, while considering spatial and temporal distribution patterns, can yield a more comprehensive and realistic analysis of shipping emissions. Cost-benefit analyses have been essential for assessing the economic implications of ship emissions, with the precise definition and measurement of costs and benefits serving as crucial parameters. Moreover, optimisation techniques and simulation models have gained prominence in analysing shipping emissions, adding a scientific foundation to this field. While the documents in this domain may not be directly related to SP, they are vital references for understanding the history and evolution of shipping emissions research. These documents collectively serve as a rich resource to inspire and guide researchers in conducting valuable studies in this field.

4.2. Systematic review works of SP

There are 11 reviews related to SP, which can be categorised into three main areas. The first category views SP as a multifaceted green technology within the maritime industry. It is recognised as a measure to reduce emissions, an integral part of seaport energy efficiency, and a crucial element of port microgrids. For instance, reviews by Sadiq et al. (2021) and Lin et al. (2022) summarise the characteristics of SP, its role in emission reduction, research problems, and research trends, and emphasise its practical application, especially in the context of green ports. The reviews suggest that future research directions may focus on environmental analysis, operation optimisation, policy assessments, and health implications. Papers like those by Bouman et al. (2017), Gossling et al. (2021), Iris and Lam (2019), and Alamoush et al. (2020) enrich the discussion on SP by comparing it with other reduction measures and examining its energy efficiency, application, challenges, and policies context at global, national, regional, and port-levels. Abu Bakar et al. (2021) consider SP as one element of seaport microgrids to review its load forecasting and potential future research challenges, which reflects the industry's growing confidence in SP's potential.

In the second category, SP is examined independently, focusing on its barriers, drivers, and technological issues. Williamsson et al. (2022) categorise these factors into four key categories and identify three areas of concern based on an analysis of 82 documents, while Bakar et al. (2023) highlight the technological limitations, such as high cost and installation challenges on ports and ships. They also discuss the potential synergy between SP and seaport microgrids for achieving decarbonisation goals. Furthermore, the third category, exemplified by Ding et al. (2022), will have little connection with emissions measures. This paper combines three key components of SP with two types of fault diagnosis technology, providing insights into the application of fault diagnosis within the SP framework.

In light of the foregoing, while the existing reviews on SP provide valuable insights, they often present a limited scope and are one-sided, offering a piecemeal of the comprehensive SP work in the literature. Despite SP's potential as a promising technique for mitigating shipping and port emissions, reviews to date have been partial and incomplete. Given this context, this paper introduces an innovation by providing a thorough review of SP, intending to fill the existing gaps in the literature.

4.3. Inherent features of SP

The transition of logistics and transportation towards electrification, coupled with their evolution into smart and sustainable infrastructures, represents a favourable trend. The adoption of SP, a system requiring megawatt-level power, brings about considerable challenges for various sectors, including port operators, shipbuilding, ship operators, electrical equipment suppliers, and power suppliers. These challenges span technological, economic, environmental, and health aspects. Consequently, research on the inherent features of SP often involves the analysis of its components, requirements, and standards, as well as existing connection systems. For example, Sulligoi et al. (2015) retrospectively examine the components of SP that contain shore equipment, onboard devices, shore-to-ship interface, applications, specific features, and experiences of SP in the Italian Navy during the early 1950 s, offering insights into existing connection systems. The evolution of standardisation issues and technical advancements related to SP has occurred in the years 2002, 2006, 2012, 2016, 2019, and 2022, including organisations like the Institute of Electrical and Electronics Engineers (IEEE), International Organization for Standardization and International Electrotechnical Commission, which is described in Hoven (2023), Peterson et al. (2009), and Paul et al. (2024). It also addresses challenges and barriers, with a focus on safety, stability, and risk assessment. For instance, Khersonsky et al. (2007) identify three key challenges facing SP: power sources, power delivery, and ship modifications in the early application of SP. In recent years, attention has shifted to address specific issues such as arcing during non-load conditions in SP transformer taps (Paul and Yan, 2021), the application of improved sliding mode control strategy (Su et al., 2021), and the system behaviour of grounding resistance selection and short-circuit current evaluation (D'Agostino et al., 2022) to improve its safety and stability issues. Risk assessments have also been expanded to embrace infrastructure, grid architecture, spare capacity, and the integration of renewable energy (Ding and Liu, 2023). Additionally, the impact of SP on both seaport and shipboard

power systems is a crucial area of study, which includes improving power quality, facilitating power sharing among various energy types within seaport microgrids and shipboard microgrids, and integrating these systems into smart grids. According to the electrical characteristics of SP, Sciberras et al. (2015) assess the impact of centralised SP typology on the existing seaport power to ensure the normal operation of the other electrical equipment. Similarly, Rahman et al. (2021) propose the use of an active filter in SP system to reduce the total harmonic distortion and thereby enhance power quality.

The installation of SP is increasingly considered a vital component for future port and shipboard power systems. From the perspective of shipboard power systems, SP is viewed as an additional power supply, particularly beneficial for electrical and hybrid-electric ferries in RESs, energy storage, and battery issues (Bosich et al., 2023). Xiao et al. (2019) investigate the coordinated control of shipboard microgrids, focusing on modes such as pure electric, extended range, and SP integration. Oo et al. (2022) present a mixed-integer non-linear programming approach to optimise the power system of fixed-route ferries, aiming to enhance fuel efficiency. Considering the forced outage rate of ship electric generators and SP, Tsekouras and Kanellos (2016) analyse the reliability of ship power systems. Additionally, Kumar and Panda (2023) and Aditya et al. (2023) investigate the challenges of charging electric vessels using SP, especially considering the megawatt-level energy demand of these vessels. Regarding ports, the introduction of SP has attracted increasing researchers to investigate power energy management, power sharing, and the integration of ESS integration with port microgrids to improve port energy efficiency (Parise et al., 2016; Mutarraf et al., 2021; Kermani et al., 2022). Moreover, the development and implementation of control strategy and pre-synchronisation controls between SP in ports and shipboard power girds are gaining importance (Zhu et al., 2022).

In terms of academic contributions, the *IEEE Transactions on Industry Applications* and the *IEEE Transactions on Transportation Electrification* are prominent in SP's inherent features research, with a focus on electrical engineering. This highlights the ongoing challenges associated with electrical safety, stability, reliability, integration of RESs, and microgrid technologies. In contrast, the shipping industry places significant focus on standards, regulations, applications, challenges, and initiatives aimed at mitigating carbon emissions.

Overall, the evolution of SP is multifaceted, involving technological, safety, and efficiency considerations in both port and shipboard contexts, with significant contributions from electrical engineering and a growing focus on environmental sustainability in the shipping industry.

4.4. Emission inventory of SP

In terms of the documents related to emission inventory, there are 37 publications to be examined. Among these, 20 are exclusively dedicated to SP as their primary objective, while the remaining 17 documents incorporate SP as one of several alternatives in their analysis. This dual perspective provides a holistic view of the role of SP in emission inventory assessments and highlights its significance in the broader context of emissions reduction strategies.

In papers that exclusively focus on SP, the central theme revolves around emission inventory, environmental feasibility, and related external costs, approached from various angles, such as ships, one port, and multi-ports in different countries. From the port perspective, Adamo et al. (2014) combine gross register tonnage, power tonnage ratio, Load Factor (LF), hoteling time, and Emission Factor (EF) to roughly estimate ship emissions in the port area. Kose and Sekban (2022) estimate the share of hoteling emissions in a port's total air emissions from vessels to highlight the importance of SP with the classic bottom-up method. Meanwhile, Schiavoni et al. (2022) assess port noise emission to emphasise SP's role in noise reduction. He et al. (2023) consider the impacts of COVID-19 on port operations and vessel emissions in the Port of Long Beach, concluding that SP is an effective strategy for reducing emissions. This is particularly true during specific times, such as the COVID-19 pandemic and periods of ship congestion. Dai et al. (2020) consider the effect of SP-related delays on emission reduction efforts, finding that delays have a more significant impact on CO_2 for larger vessels and longer distances than smaller vessels on shorter routes. To enhance SP's effectiveness in reducing emissions, Gutierrez-Romero

Table 4
References related to mitigation strategies.

References	SP	Slow steaming or RSZs	Alternative fuels				Others
			LSFO/ MGO	PV	Battery	LNG	
Kao et al. (2022)	√	√					
Lee et al. (2021)	√	√					Local ECAs; emission platform
Zhao et al. (2023)	√	√				√	Ammonia; hydrogen
Lopez-Aparicio et al. (2017)	√	√				√	
Styhre et al. (2017)	√	√				√ and methanol	Reducing turnaround time at berth
Winnes et al. (2015)	√	√				√, methanol, and bio methanol	Ship design; operation
Chang and Wang (2012)	√	√	√				
Zis et al. (2015)	√	√	√			√	ECA
Wu and Huang (2023)	√		√				
Wan et al. (2021)	√		√				Increasing quay crane efficiency
Colarossi et al. (2022)	√			√			Local grid; cogeneration; PV

et al. (2019) adopt RESs, such as wind and photovoltaic (PV), to supply power for SP and estimate their sufficiency. Additionally, Nguyen et al. (2021) combine the bottom-up method and the AERMOD model to estimate SP's impact on air emission reduction and to simulate the dispersion. Within the context of emission inventory, some studies assess SP's social benefits by analysing the external costs or monetary values associated with pollutants. For example, Ballini and Bozzo (2015) take population into account and employ the External Valuation of Air Pollution Model (EVAPM), factoring external health costs per kilogram of emissions. Lathwal et al. (2021) extend this analysis by assessing the impact of pollution reduction through SP on premature deaths. Similarly, Winkel et al. (2016) monetise the health effects of pollutants using the new energy externalities development for sustainability. Consequently, the cost-benefit analysis becomes an essential extended topic of SP emissions, with parameters like Net Present Value (NPV), Payback Period (PBP), and Internal Rate of Return (IRR) further investigated for SP projects. For example, Vaishnav et al. (2016) formulate a mixed-integer linear problem and utilise the Gurobi solver to optimise the two costs and benefits. In multiple-port studies, the sources of SP are examined to determine the suitable energy sources for its application. For instance, Hall (2010) conducts a comparative analysis, evaluating the impact of SP on CO_2 emissions across 20 major maritime countries/regions with diverse sources of electricity generation. Kotrikla et al. (2017) employ Homer Energy microgrid simulation software to calculate CO_2 and PM_{10} emissions, simulating PV and wind as potential sources of SP for 40 calls. Additionally, from the vessels' perspective, Osses et al. (2022) explore the feasibility of bi-directional SP for a tanker vessel, contributing diverse perspectives on SP's role in emission reduction and environmental sustainability.

As one of the mitigation strategies, SP is frequently compared or combined with other alternatives in 16 different research papers. In Table 4, this paper summarises and analyses these comparisons, with slow-steaming, alternative fuels, such as Low Sulphur Fuel Oil (LSFO) and LNG, being the two most common mitigation options contrasted or integrated with SP. Lee et al. (2021) carry out a study comparing slow-steaming near ports within a 12-nautical-mile zone with SP during hoteling activities. Their findings indicate that SP outperforms slow-steaming in terms of reducing CO_2, NO_X, and BC emissions. In essence, SP proves to be a more effective strategy compared to slow-steaming in this context. Another interesting comparison involves SP and alternative fuels. Martinez-Lopez et al. (2021a) evaluate the effectiveness of SP and LNG in three shore-sea shipping routes and find that LNG is more effective than SP in these specific shipping scenarios. Wu and Huang (2023) calculate the external benefits and costs of switching from 1.5 % sulphur content fuel oil to LSFO with 0.5 % or less sulphur content and compare these with SP. The study concludes that the benefit-to-cost ratio of SP lies between that switching from 1.5 % to 0.5 % sulphur content and using even lower sulphur fuel. Such comparisons provide valuable insights into the relative advantages and limitations of different emission reduction strategies, shedding light on the role of SP within the larger landscape of sustainable shipping solutions.

Regarding combined mitigation strategies, research has shown that using SP and slow-steaming together can significantly reduce emissions (Lopez-Aparicio et al., 2017). When combining these strategies with ECAs, Lee et al. (2021) estimate substantial reductions

Table 5
Summary of studies related to emission inventory of SP.

References	Case study	Operation mode	Method	Pollutant	Power source
Hall (2010)	Three cruise ships	Berthing	N/A	CO_2, SO_2, NO_X, CO	Multiple national grids
Adamo et al. (2014)	Port of Taranto, Italy	Berthing	EO	CO_2, NO_X, PM_{10}	Italian electrical system
Ballini and Bozzo (2015)	Cruise port of Copenhagen	Berthing	EO, cost-benefits	CO_2, SOx, NO_X, PM	Nord energy mix
Vaishnav et al. (2016)	U.S. ports	Berthing	EO, cost-benefits	CO_2, SO_2, NO_X, $PM_{2.5}$	Grid electricity
Winkel et al. (2016)	European ports	Berthing, Maneuvering, Moving	Top-down & EO, environmental, and economic benefits	GHG, SO_2, NO_X, $PM_{2.5}$	Grids
Kotrikla et al. (2017)	Port of Mytilene, Greece	Berthing, Maneuvering	EO, renewable energy	CO_2, $PM_{2.5}$	Solar PV, wind
Gutierrez-Romero et al. (2019)	Port of Cartagena, Spain	Berthing	EO (Monte Carlo procedure)	CO_2, SO_2, NO_X, CO PM VOC	Solar PV, wind
Zis (2019)	Ships (Ro-Ro, cruise, container) and port	Berthing	FC, economics	CO_2, SOx, NO_X, BC	Multiple national grids
Lathwal et al. (2021)	12 major ports in India	Berthing	EO, environment, and health benefits	CO_2, SO_2, NO_X, $PM_{2.5}$	State grids
Martinez-Lopez et al. (2021b)	Three maritime routes	Berthing, Maneuvering,	N/A, Capital cost, IRR	CO_2, SO_2, NO_X, $PM_{2.5}$, PM_{10}	Electricity grids
Nguyen et al. (2021)	Port of Kaohsiung	Berthing	EO, ARMED	SO_2, NO_X, $PM_{2.5}$, PM_{10}	N/A
Lee et al. (2021)	Port of Incheon	Berthing, Maneuvering, Cruising, Anchor	EO, FC	CO_2, SO_2, NO_X, PM, CO, VOC, NH_3	N/A
Colarossi et al. (2022)	Port of Ancona	Berthing	FC	CO_2	Local grids, cogeneration, PV
He et al. (2023)	Port of Long Beach	Berthing, Maneuvering, Cruising, Anchor	EO	CO_2, SO_X, NO_X, CO, $PM_{2.5}$, PM_{10}	N/A
Stolz et al. (2021)	714 major ports in EEA and UK	Berthing	EO	CO_2, SO_2, NO_X, PM_{10}, CO, CH_4, NMVOV, N_2O	National grids

in various pollutants, including a reduction of 29 % in CO, 30 % in NO_X, 93 % in SO_X, 64 % in PM, 28 % in VOC, 30 % in NH_3, and 30 % in CO_2 emissions. Colarossi et al. (2022) compare the emission effectiveness of traditional SP, SP integrated with a congenator, and SP combined with PV. The study finds that the two integrated approaches are much more effective than the traditional SP. It highlights the potential synergies achievable by combining SP and other strategies, particularly within ECAs and renewable energies. This underscores the need for a holistic approach to emission reduction, one that considers the entire voyage of a vessel and adopts a LCA of energy sources, rather than a partial approach.

As aforementioned, two main methods, the top-down (fuel-based) and the bottom-up (activity-based) method, have been widely used in the field, with variations and combinations depending on the specific research objectives.

The top-down method relies on fuel consumption data, typically obtained from reports or marine bunker fuel sales records. It is employed to estimate the electricity demand of ships berthing at ports. In some cases, it is integrated with the bottom-up method for comprehensive analysis, as demonstrated by Winkel et al. (2016). Notably, emissions calculated using the top-down approach often yield higher values compared to those from the bottom-up method, as concluded by Lopez-Aparicio et al. (2017).

The bottom-up method involves estimating the energy demand of vessels based on their movements and activities during berthing. It utilises data from AIS and ship register information to identify vessel operation modes and parameters. There are two main variations of the bottom-up method: one is the total Energy Output (EO), calculating the energy demand by multiplying engine power, LF, and operation time; the other estimates energy demand as the total Fuel Consumption (FC) of engines, computed by multiplying Specific Fuel Consumption (SFOC), LF, and operation time. In a comparative analysis conducted by Lee et al. (2021), it is observed that, except for CO emissions, the majority of pollutants calculated using the EO method tend to yield higher values than those calculated using the FC method.

In recent research, efforts have been made to enhance estimation accuracy. Stolz et al. (2021) incorporate emission reports from Monitoring, Reporting, and Verification (MRV) into the bottom-up database to mine relationships among main engine, AE, auxiliary boiler, and ship register information. Yeh et al. (2022) analyse the factors influencing ship energy consumption using multiple linear regression, considering factors like the number of refrigerated containers loaded, tailwind, headwind, and sea temperature.

As shown in Table 5, the EO method is predominantly used for calculating emissions inventory in SP research. CO_2, SO_2, and NO_X are the three most contributed pollutants considered in these studies. Case studies often involve ports with diverse vessel types, particularly in European ports, with a focus on the operational mode of hoteling-at-berth. Hence, this subsection reviews the literature related to SP's emission inventory and associated issues. The result reveals that most publications related to SP's emission inventory and other mitigation strategies were published between 2014 and 2019. This timeframe aligns with the heightened implementation of SP during the SP development in the region/country stage. More recent publications are shifting focus to finer aspects of ship emissions and the advancement of SP, moving away from broader port emissions, voyages emissions, and traditional SP approaches.

4.5. *Applications of SP*

The applications of SP encompass various aspects, including barriers, feasibility, potential, strategies, behavioural choices, and other application-related challenges. A review of the literature reveals that 67 publications primarily delve into the applications of SP. Among these, 49 target SP-specific concerns exclusively, while the others employ SP merely as an illustrative tool for their research.

Identifying obstacles to the effective propagation of SP reveals inconsistencies arising from diverse research methods, geographic areas, and respondent backgrounds. Surveys stand as the primary research technique in this domain. Wang et al. (2023b) construct a structural equation model to discern the interrelationships between diverse variables in the Chinese shipping industry. Kim et al. (2023) conduct a survey in South Korea's liner shipping industry to identify the barriers of SP using a Fuzzy Analytic Hierarchy Process approach. These studies both conclude that technical barriers significantly deter shipowners from retrofitting vessels with SP. Selen (2023) summarises the application and challenges of SP in Europe based on industry surveys. Bullock et al. (2023b) employ the Technological Innovation Systems and the Multiple-Streams Approach to explore SP issues in the United Kingdom (U.K.), considering socio-technical and political aspects. Tseng and Pilcher (2015) engage in in-depth interviews to investigate SP's drivers, timelines, and obstacles, as well as its potential to reduce emissions and save on environmental costs. Furthermore, Daniel et al. (2021) conduct a Strengths, Weakness, Opportunities, and Threats analysis of SP, assess its ecological efficiency in terms of the Energy Efficiency Design Index, Energy Efficiency Existing Ship Index, and Carbon Intensity Index, and highlight SP's pivotal role in the decarbonisation of future shipping. In summary, while SP appears to address technical concerns sufficiently for large-scale implementation, there is still a need for further refinement in standardisation. From an economic perspective, factors like costs, benefits, and state subsidies currently do not present strong incentives, posing a substantial challenge to SP's wider acceptance.

Numerous researchers have embarked on cost-benefit analyses using metrics like PBP, NPV, and IRR to evaluate whether adopting SP is economically viable. However, there is a notable disparity in the evaluations of the costs and benefits, both in terms of their quantities and classifications. For instance, the investment costs for SP systems' installation at ports range from USD 1.04 million to USD 3.45 million per set in various port conditions (Dai et al., 2019). Conversely, the cost of retrofitting ships spans from USD 2,040 to USD 8.13 million, depending on the vessel's size and specifications (Piccoli et al., 2021). Such cost analyses typically cover categories such as installation, operations, and maintenance, catering to both the viewpoints of port operators and shipowners. Moreover, researchers have delved into specific cost elements, including tax rates applicable to CO_2, SO_2, and NO_X, transformation costs, charges tied to procuring electricity from the grid, and contributions to environmental externalities under the EU ETS (Dai et al., 2019; Kim, 2022). On the flip side, benefits primarily revolve around energy conservation, health improvements, and environmental advantages. Certain studies also explore alternative revenue avenues, such as revenue from trading CO_2 emission allowances, earnings from selling electricity to shipowners, as well as incentives and subsidies. Interestingly, the time needed to connect or disconnect vessels from SP

sources—a critical factor in balancing benefits and costs, exhibits a broad spectrum, from instantaneity to 2 h across different studies (Zhen et al., 2022; Dai et al., 2019). Surprisingly, this element has largely been overlooked in many studies. Recognising the population density in port cities and their vulnerability to pollution, Spengler and Tovar (2021) leverage the BeTa approach—an approach gauging pollution's impact on health, buildings, and other factors—to assess pollution-related externalities.

The SP Deployment Problem (SPDP) is a complex challenge in SP applications research, involving a multitude of stakeholders operating under various incentive and subsidy policies. Recently, there has been a surge in research focusing on SPDP, especially over the last three years. To improve the review process, this paper summarises research on SPDP under diverse incentive policies and scenarios, as illustrated in Table 6. These studies, taking into account the economic and environmental impacts of different incentives and subsidies, primarily focus on the collaborative strategies among governments, ports, and shipping companies to optimise SPDP. These optimisations have employed a variety of modelling techniques, including mixed-integer bilevel programming, integer programming, stochastic optimisation, and nonlinear programming models, to solve the complexities of the problem. This paper highlights key findings from related references, indicating that subsidies for construction and operation, berth priority incentives, the price of fuel and electricity, SP pricing, efficiency in load/unloading, and as well as other factors (such as visit frequency, voyages routes, and energy sources), significantly influence SPDP. These factors affect economic feasibility and environmental outcomes, which are fundamental considerations in the decision-making process regarding SP adoption. Government subsidies and berth priority are identified as significant drivers for increasing adoption rates, while competitive pricing can stimulate usage, thereby aiding in emission reduction efforts. However, subsidy strategies ought to balance short-term and long-term financial and environmental benefits. While SP contributes to emission reduction, the PBP is lengthy. Optimal solutions promise considerable reductions in emissions and operational costs but may require substantial initial investments. Hence, an initial emphasis on subsidies for SP construction, followed by a transition to operational funding for continued use, is suggested. Berth priority incentives could be implemented when subsidies are low, with an increase in subsidies as SP adoption expands. Comprehensive financial strategies, including subsidies, may shorten the PBP for SP investments, potentially aiding future applications and research. There is a consensus that SP can yield substantial environmental benefits. Nevertheless, the adoption and effective utilisation of SP relies heavily on well-designed subsidy policies that

Table 6
Summary of research on SPDP under different incentive and subsidy policies.

References	Research focus	Method	Research object	Key finding
Wang et al. (2021)	Investigate collaborative decision-making on SP adoption between regulators and ports.	Mixed-integer bilevel programming model; column and constraint generation method	Port; government	The model is feasible for finding cost-effective SP deployment strategies.
Peng et al. (2019)	Determine SP allocation strategies to balance costs and reduce ship carbon emissions.	Integer programming and simulation	Container terminal with five berths	Electricity prices significantly influence optimal SP power capacity and allocation.
Zhen et al. (2020)	Analyse the choice between SP and scrubbers for fleet deployment costs.	Nonlinear mixed integer programming; three-phase heuristic	Shipping route; only scrubbers; only SP; both scrubbers and SP; without scrubbers or SP	SP adoption is less sensitive to fuel price changes compared to scrubbers.
Yin et al. (2022)	Integrate SP with vessels' oil inventory plans to showcase its benefits and impact.	Linear programming	Port; shipping company; government; grid company	SP is cost-effective when surpassing oil prices; subsidies are not the sole incentive.
Zhen et al. (2022)	Examine the impact of subsidy and berthing-priority policies on SP utilisation.	Nonlinear programming; sequential heuristic algorithm; critical-shaking neighbourhood search	ships and berths in port	Berth priority is effective especially when government subsidies are limited.
Tan et al. (2021)	Decide on SP use within inland river shipping networks.	Network-based modelling and simulation	Inland river container shipping networks	Efficiency improvements may reduce SP use by lowering operational fuel costs.
Wang et al. (2022)	Weight the port's financial benefits against environmental regulations.	Stochastic optimisation and tailored solution	Ports; shipping companies	Competitive SP pricing and subsidies motivate its use.
Yu et al. (2019)	Design ship modifications for SP; optimising environmental gains.	Improved multi-objective genetic algorithm	A set of retrofit strategies for container ships	Prioritisation for retrofitting is given to frequently visiting ships; PBP: 46 years.
Peng et al. (2021)	Decide on SP provision per berth and analyse environmental tax impacts.	Cooperative optimisation and multi-objective Particle Swarm Optimisation (PSO)	Bulk terminal; shipping companies	Optimal solutions significantly reduce emissions and costs; if cutting all emissions, the cost will increase by 183.7 %.
Daniel et al. (2023)	Determine the optimal size for multi-source SP to cut costs and emissions.	Multi-objective optimisation	Bulk carriers	A low-voltage SP system with a battery can remove emissions and is cost-effective; If half of the initial investment is covered by subsidies, the PBP drops to 6 years.
Wu and Wang (2020)	Design subsidy strategies to encourage SP use and maximise financial port benefits.	NP-hard problem; a tailored labeling algorithm	Container ports; shipping lines; government	The method is feasible for adjusting subsidies to benefit the government and ports.

account for both immediate and long-term economic impacts on ports and shipping companies. Importantly, SPDP extends beyond route optimisation, it encompasses berth allocation across a network of ports, berths, vessels, and routes. This complex matrix aims to streamline operations and enhance environmental benefits, making it a vital challenge.

Beyond SPDP, there is an expanding body of research focused on green technologies selection and the impact of carbon prices, incentives, subsidies, and regulations on the shipping industry. The sector includes three key players: 1) governmental bodies/authorities, seeking to minimise emissions through financial and regulatory means; 2) ports, balancing economic benefits with environmental concerns; and 3) shipping companies, striving to maximise economic profits by adopting the green technologies that can meet the regulations by the governmental bodies. The governmental bodies provide a framework mandating and/or encouraging the adoption of green technologies by ports and shipping companies. Ports and shipping companies then align their operations to be both economically sustainable and eco-friendly. Their relationship is mutually beneficial, with ports providing services and shipping companies paying fees. They form a unity to realise an integrated supply chain where each party's decisions impact the others. This dynamic has led to an interest in game theory to analyse their interactions, focusing on various strategic choices.

Captured in Table 7, the research examines decision-making processes regarding the adoption of SP, specifically how economic incentives, environmental concerns, and policy interventions influence stakeholders' strategic choices. Game theory and the derivative methods, including the port/shipping-leader Stackelberg game, Nash game, Noncooperative game, and Evolutionary game, evaluate strategic interactions among the relevant stakeholders under different strategies. Key findings show that carbon price and environmental concerns significantly affect the preference for SP and LSFO; Subsidies and low-carbon preferences of stakeholders can boost SP's application; information sharing and collaboration may not necessarily decrease overall carbon emissions; subsidies tied to emission reduction achievements are more effective than general SP subsidies; government-owned ports are more likely to invest in and lower SP prices, leading to increased utilisation and emissions reductions; setting the right fees and balancing policy costs with social benefits are essential for the wider adoption of SP. Thus, interactions among stakeholders form a complex process, with research aiming to replicate reality closely and offer insights into SP promotion effectively, guiding its development in the right direction.

From a unique perspective, Bjerkan and Seter (2021) integrate the multiple streams approach with real-time events involving SP in Oslo, highlighting the profound influence of policy and politics on the transitions associated with SP. Abu Bakar et al. (2022) select input parameters, including arrival time, ship type, size, mode, and index capacity, to predict berth durations and find that artificial neural networks outperform other forecasting methods. In the realm of innovation, some researchers are pushing the boundaries of SP technology. For example, Qiu et al. (2022) consider SP as the only power source for AES to analyse the relationship among SP pricing, load demand, voyage schedules, and carbon emissions. Li et al. (2023) merge the firefly algorithm with the semi-supervised learning method to forecast SP loading at Zhanjiang Port. Furthermore, Bullock et al. (2023a) explore the interplay of the SP's related stakeholders and conduct a technical and economic assessment.

For the rest of the reference using SP as an example, the majority of the literature still regards it as an innovative concept. Arduino et al. (2013) explore barriers, success determinants, and conditions vital for seaport innovations, including the evolution of SP from a concept to a tangible reality. Acciaro et al. (2014) develop a quantitative technique to measure the overall success of such innovations. Konstantinos et al. (2022) employ a multi-criteria decision framework to evaluate the measures for CO_2 emission reduction, noting that SP and LNG, despite being expensive, offer significant emission reduction potential. Considering SP as one of the key indicators, Puig et al. (2022) evaluate the environmental performance of European ports.

Table 7
Summary of research on stakeholders' interactions using game theory under different strategy choices.

References	Research focus	Method	Research object	Key finding
Liu et al. (2023a)	Impact of carbon tax policies on the adoption of green technologies.	Stackelberg game	Port, liner company; no green technology, SP, LSFO	Knowledge sharing minimises unnecessary emissions without significantly altering the total carbon footprint.
Wang et al. (2023a)	The strategy of a shipping company with/without subsidies and their effect.	Stackelberg game and Nash game	Port, shipping company, government; SP and LSFO; with/without subsidy	Subsidies encourage SP use at moderate carbon prices.
Jiao and Wang (2021)	Equilibrium outcomes of carbon pricing on SP vs LSFO selection.	Noncooperative game model	One port and two carriers; SP and LSFO	Collaborating carriers maximise total profits and consumer surplus in the transport chain.
Xing et al. (2022)	Subsidy framework to encourage SP usage.	Two-stage Stackelberg game	Port, shipping company, government; SP	A two-sided subsidy is more cost-effective for the government.
Song et al. (2022)	Government's intervention in SP adoption and subsidy efficiency for at-berth emission reduction.	Nash game	One port, two shipping companies; SP	Government intervention prevents a prisoner's dilemma and makes SP more attractive.
Peng et al. (2023) and Zhen et al. (2023)	Influence of government subsidies on SP with two main strategies.	Stackelberg game	Port, government; subsidy for construction and subsidy for the price	Both subsidy strategies boost SP usage; price subsidising is more cost-effective under certain conditions; and focuses on emissions reduction for allocation.
Sheng et al. (2023)	Stakeholder strategies influencing SP promotion.	Evolutionary game theory, system dynamics simulation	Port, shipping company, government	An optimal fee range for SP usage encourages adoption.
Xu et al. (2021)	Influence of SP on stakeholders' evolutionarily stable strategies.	Evolutionarily stable strategies	Port, liner companies, government	High policy costs and social benefits drive a quicker shift to a non-incentive government strategy.

Reviewing the literature centres on SP applications reveals a predominant focus on its practicality, potential benefits, SPDP, stakeholders' interactions, and innovation, primarily through technological, environmental, and economic prisms. The momentum of SP adoption depends on various determinants, such as costs, benefits, discount rates, environmental impacts, pollutant types, and financial forecast durations, leading to diverse outcomes. While technological advancements may curtail expenses, the range of capital costs remains broad. Contrasting with discussions in Section 4.4, there seems to be a notable gap in the precision of emission calculations within this sphere. This also extends to the parameters used in SPDP and strategic choices. Future research should concentrate on refining these parameters associated with SP for comprehensive evaluations and facilitating clearer comparisons between different SP applications. In terms of stakeholder interactions, the incentives for SP, particularly regarding its role in emission reduction, as well as the subsidies associated with its construction and operation, should be explored in unison. Future studies could provide a more integrated analysis by considering how these incentives interact and what effects they have on the overall adoption and success of SP. This holistic approach would account for the complex interplay between economic incentives and environmental outcomes, potentially revealing insights into how SP can be more effectively implemented and managed within the maritime industry.

4.6. Energy management of SP

The emergence of SP has intricately linked the energy interactions between ports and berthed ships, encompassing both the port side and shipboard side. Within the port's energy system, SP services as a consumer of energy, whereas in the shipboard energy systems, it acts as a provider. Consequently, the energy management of SP in the maritime industry is intertwined with two distinct types of energy management: Port Energy Management (PEM) and Shipboard Energy Management (SEM). To streamline the review process, this paper consolidates research on SP concerning PEM, as showcased in Table 8. SP is incorporated as a component of port grids, smart grids, port microgrids, and Hybrid Energy Systems (HES). It is analysed in conjunction with various suppliers (such as hybrid energy power plants, RESs, ESS, PV, wind, fuel cells, electrolysers, hydrogen tanks, girds, and batteries) and other consumers in the ports (including reefer areas, cranes, and vehicles). These analyses encompass power balance, economic factors, environmental impacts, strategic approaches, and cost-benefit considerations. The focus of these studies is mainly on the optimisation of operations

Table 8
Summary of research on SP related to PEM.

References	Research focus	Method	Research object	Key finding
Iris and Lam (2021)	Optimise operations and energy management for smart-grid seaports, focusing on crane assignments and berth duration to improve energy efficiency and reduce costs.	Mixed integer linear programming	Smart grid, RES, ESS	Significant cost savings are achieved with smart grid integration; renewable energy usage leads to more cost reductions.
Fan et al. (2023)	Develop an incentive-based framework for port microgrids and ships, using SP power flexibility for demand response.	Cooperative coordination model, asymmetric Nash bargaining	SP, energy management strategy with peak awareness, incentive scheme	Reducing peak power demand and charges results in cost savings for the port's electricity bill.
Zhang et al. (2022)	Optimise port operations and energy systems, including SP and port microgrids.	Day-ahead scheduling algorithm; a two-stage model	SP, port microgrid	Enhanced energy independence and efficiency compared to traditional berth allocation strategies.
Sifakis et al. (2022)	Conduct a techno-economic analysis of hybrid renewable power plants with hydrogen storage compared to traditional SP.	Techno-economic analysis, simulation, optimisation	Hybrid renewable energy power plant; a hydrogen ESS; SP; wind; PV	Hybrid systems fully meet the port's energy needs and offer economic benefits.
Vichos et al. (2022)	Transform a traditional port into a sustainable one by eradicating carbon emissions, assessing energy profiles, GHG calculations, and integrating technologies to boost reliability.	Simulation, Optimisation, HOMER PRO software	SP, RES (PV, wind), hydrogen systems (electrolyser, fuel cell, hydrogen tank)	With the implementation of SP, the average cost of energy could be reduced by up to 51.8 %; The port can operate independently for a full day.
Sifakis et al. (2022)	Survey SP developments to address GHG from docked ships and propose a renewable energy-based SP system.	Simulation	SP with RES (wind, PV)	75 % of ship power is from wind, and 25 % is from PV; the renewable energy SP is stable with no significant frequency fluctuations.
Buonomano et al. (2023)	Optimise the energy and economic impact of ports to the maximisation of system self-consumption and self-sufficiency as well as the minimum simple PBP.	Dynamic simulation, a multi-objective optimisation	Biogas with methane, PV, OECS, Combined Cooling, Heating, and Power (CCHP), BESS, EMS (SP, berth thermal and electricity demand)	High rates of renewable energy exploitation are achieved, significantly increasing port self-sufficiency.
Mao et al. (2022)	Optimise seaport energy systems with flexible berth allocation to minimise costs.	Mixed integer linear programming, GUROBI	PV, wind, grid, CCHP, RES, ESS; berth allocation; reefer area and SP	Dynamic pricing allows for efficient power scheduling, reducing costs by optimising the use of various energy sources.
Kanellos et al. (2019)	Propose a multi-agent system for power management to enhance port power demand flexibility and system efficiency.	Multi-agent systems, simulation	Refrigerated containers, SP, electric vehicles	It ensures a reduction in operational costs, effectively meeting design goals and constraints.

and energy management, power scheduling for system self-sufficiency, and integration of renewable energy. A range of methodologies, including mix-integer linear programming, nonlinear optimisation, day-ahead scheduling, dynamic and techno-economic simulations, genetic algorithms (GA), PSO, and multi-agent systems, are employed to realise optimal performance and enhance energy efficiency. From the key findings, it can be concluded that the introduction of SP significantly impacts the port grid due to megawatt-level power demands, especially intensifying the uncertainty in power demand. Moreover, port smart grids that integrate PV, wind, battery, ESS, and hydrogen storage can enhance the quality of the port grid. PEM concepts and related strategies have been witnessed to optimise energy efficiency, reduce cost, and lower port emissions by refining power schedules, allocating berths, recycling heat and electricity, and selling renewable energy back to the grid. The characteristics of PEM research related to SP underscore a pronounced commitment to sustainability, efficiency, and innovation.

In the field of SEM, the ship-based multi-energy microgrid is distinct from port microgrids. It is essentially a mobile microgrid that includes a diverse array of energy components, such as diesel generators, grid connections, ESS, batteries, SP, fuel cells, PV, and wind turbines. Together, these elements collectively fulfil the power requirements for both cruising and berthing operations. While at sea, the ship operates as an isolated microgrid, independent from any shore-based electrical grids. At port, upon connecting to SP or the local grid, it seamlessly transitions into a grid-connected microgrid or effectively serves as an extension of the grid (Al-Falahi et al., 2018). Consequently, the integration of SP introduces complexities across various facets of maritime operations, particularly for AES, Emission-Free Ships (EFS), and electric ferries. These challenges demand an adept power management system that navigates complexities in emission reduction, operational cost, energy management, and power scheduling. Leveraging insights from the studies summarised in Table 9, this paper identifies critical focus areas within SEM associated with SP. For emission reduction and energy efficiency, these researches collectively underscore a unified effort to integrate HES with RES, aiming for substantial reductions in emissions and enhancing energy efficiency within maritime vessels.

Regarding optimisation and scheduling, it becomes vital to synchronise AES schedules, thereby minimising power demand, emissions, and overall expenses with the consideration of various factors, including flexible voyage planning, the implementation of SP, and its fluctuation price. In terms of advanced power management, the researchers spotlight sophisticated strategies for power

Table 9
Summary of research on SP related to SEM.

References	Research focus	Method	Research object	Key finding
Rafiei et al. (2021)	Analyse an all-electric HES with the consideration of load profiles and paths.	Improved sine cosine algorithm	HES with fuel cell, batteries, and SP	HES demonstrates high performance and feasibility for marine applications.
Barone et al. (2021)	Power management for AES, considering load requirements and battery.	Deep deterministic policy gradient	AES with fuel cell, battery, SP, and Recuperative Organic Rankine Cycle (RORC), load	Enhanced fuel cell performance and cost-effective operation have been achieved.
Zhao et al. (2022)	Optimise ESS sizing and power management for AES, considering variable SP electricity prices to reduce the cost, GHG, and navigation time.	Multi-objective mixed-integer optimisation	AES with ESS and SP	The proposed method increases efficiency and underscores the need for navigation route planning.
Hein (2022)	Coordinated scheduling for AES to minimise fuel use, emissions, ESS wear, and auxiliary costs.	NSGA-II/III	AES with ESS and PV	Efficient convergence in scheduling for AES results in significant operational improvements.
Pan et al. (2022)	Coordinated navigation and power generation scheduling for AES, balancing investment and operational costs with GHG.	Bilevel tri-objective differential evolution algorithm	AES with diesel, BESS, fuel cell, PV, and SP	It helps to reduce operational costs and emissions; Increases in SP prices affect costs but do not significantly impact emissions.
Tang et al. (2018)	Optimal power flow dispatch for a maritime HES to utilise solar energy effectively and reduce electricity costs.	Swarm-intelligence-based optimal power flow dispatching strategy	HES, PV, battery, SP, and diesel	Significant cost savings and robust system performance are achieved.
Tao et al. (2022)	Flexible voyage scheduling for AES to meet transportation demands while easing power grid load during charging.	Simulation	AES with ESS, renewable integration, and SP	It will reduce energy costs for AES and improve grid voltage stability, with benefits even during emergencies.
Wen et al. (2021)	Coordinate power generation and voyage scheduling for AES, considering SP price fluctuations.	Two-stage scheduling model; forecasting method	AES in a navigation route with the consideration of SP price	High energy utilisation efficiency is achieved, along with a significant impact of SP on AES operations.
Barone et al. (2021)	Assess ships' thermal load and energy demand with advanced simulation techniques in energy analysis, economic analysis, and environmental analysis.	Dynamic simulation	SP, waste heat recoveries	Significant savings in primary energy and emissions are achieved, accompanied by a quick PBP.
Kanellos et al. (2017)	Optimal SEM to balance generation/storage and travel time.	Fuzzy-based optimisation	Electric propulsion, energy storage, and SP	It minimises operational costs and GHG emissions.
Banaei et al. (2021)	Manage energy of EF-Ships with hybrid FC/ESS/SP, taking into account ageing factors and environmental conditions.	Non-linear model; stochastic model predictive control method	EF-Ships with fuel cell, ESS, and SP	The model ensures ageing considerations of FCs and ESS while optimising operation costs.

regulation in EFS, considering load demands and battery storage capacities in detail. Additionally, there is an emphasis on refining power flow dispatch within maritime hybrid systems that unitise a mix of PV, batteries, diesel, and SP. This approach seeks to maximise the use of solar energy and reduce electricity costs. Moreover, energy management of EFS with hybrid systems incorporates considerations for ageing factors and environmental conditions to ensure durability and sustainability. The challenges identified in these researches are tackled through a series of optimal methodologies, such as improved since cosine algorithm and multi-objective mixed-integer techniques. They are employed to handle nonlinear issues and discover balanced solutions across multiple objectives in SEM. Algorithms for non-dominated sorting, like Non-Dominated Sorting Genetic Algorithm II and III (NSGA-II/III), are applied for the coordinated scheduling of AES to minimise fuel consumption, emission, ESS wear, and SP cost. Swarm-intelligence-based strategies are harnessed for the optimal dispatch of power flow in SEM. Dynamic simulation emerges as a crucial instrument for decoding and forecasting shipboard energy system's behaviour under various operating conditions. Moreover, a two-stage joint scheduling model, integrated with deep learning-based forecasting, utilises artificial intelligence to boost the accuracy of predictions and the efficiency of scheduling. The key findings reveal that SEM serves as an effective mechanism for managing shipboard grids, enhancing system performance, operational efficiency, cost reduction, regulatory compliance, and bolstering the sustainability of SEM.

In summation, when integrated with SP, both ships and ports can seamlessly function as microgrids. Although current research on SEM and PEM has largely charted independent trajectories, there is a promising landscape for mutual enrichment, driving energy efficiency, cost curtailment, and emission mitigation. As SP assimilates an array of energy sources, spanning from bioenergy to wind, integration becomes paramount. Future inquiries should prioritise uncertainties, reliability, and the stability of the energy management system. The stochastic and dynamic attributes of different ship configurations can induce grid fluctuations that require careful consideration. It is imperative to underscore that this overview offers a condensed glimpse, given our limited specialisation, and earnestly calls for more in-depth exploration in this domain.

5. Remarks

Based on the detailed analysis provided in Sections 3 and 4, it becomes evident that SP plays a crucial role in the ongoing electrification of the maritime industry. However, its exploration within academic research remains relatively novel and segmented into specific domains. The application of SP has experienced rapid growth in the past five years, accompanied by a corresponding increase in scholarly scrutiny. This section will synthesise the key findings to draw insightful remarks and discussions.

5.1. Remarks on the practice and barriers to the promotion of SP

Reflecting on the evolution of SP and a review of practices and barriers to its application, this paper remarks that most SP-ready ports are primarily located in China, the U.S., and Europe, largely owing to favourable regulations and incentives. In the U.S., especially in California, strict emissions rules at berths have simulated the adoption of SP. China's swift adoption of SP since 2010 is a testament to its strong governmental backing, even if it is a late entrant in this domain. This growth trend is segmented into distinct phases: starting in 2010, followed by 2016, and then a subsequent phase from 2020 onwards. Europe ports, driven by incentives like reduced port fees, port electricity accessibility, green awards, and government support, have been among the early adopters of SP. Notably, ports in the Netherlands, including Rotterdam and Amsterdam, have digitised SP details, simplifying the process for ships to ascertain SP availability. Conversely, the U.K. has approached SP with caution due to concerns over port ownership, high electrical costs, and a lack of substantial foundation and incentive policies, resulting in a limited number of U.K. ports adopting SP. Thus, the development of SP remains unbalanced globally. From the perspective of shipowners, survey results indicate that most shipowners do not consider it to be a sufficiently mature technology for widespread adoption at this time (Wang et al., 2023b; Kim et al., 2023). Additionally, there are missed opportunities for generating revenue by vessels in the U.K. and other countries with high electricity prices (British Port Association, 2021; Department for Transport, 2023). The results also highlight that operation and management, laws and regulations, emission reduction, finance, and development play significant roles in fostering a positive attitude among shipowners towards the promotion of SP (Yin et al., 2020; Chen et al., 2019). To improve their receptiveness, shipowners favour strategies such as cost reduction, technological advancements, berthing priority, and stronger policy implementation or enforcement. Furthermore, it is recommended that larger container vessels, especially those on international and regional routes, along with cruise ships and ferries, should be prioritised for SP usage.

Despite the increase in SP installations, it is crucial to point out that actual usage lags due to disparate information among stakeholders. Recent research suggests that the obstacles to promoting SP have changed, with technical concerns being resolved and scepticism being diminished. Notably, countries in the same stage of SP development face similar challenges. Modern SP integrations, including smart grids, microgrids, ORC systems, RESs, ESSs, batteries, PV, and wind, aim to boost SP's energy efficiency and sustainability. Nevertheless, the substantial power demands for SP remain a significant challenge, posing an increased risk for SP-related power systems, especially with the growing utilisation of SP. With the development of SP globally, another challenge arises from the inconsistent regulations across different geographical locations, which create uncertainty among port operators about their competitive standing. For instance, if SP becomes mandatory in one location, ships might prefer proximate ports, inadvertently increasing shipping distances and corresponding emissions. Nevertheless, there is an observable momentum towards greater standardisation of SP, along with a growing emphasis on global integration and digitalisation in SP infrastructure allocation and connectivity. Concurrently, the rapid development of emerging technologies supports this movement, facilitating SP's wider acceptance. The persistent absence of significant economic benefits remains a formidable barrier to the widespread adoption of SP. Striking an optimal equilibrium between incentives and penalties emerges as a pivotal exploration domain. Consequently, fostering interaction and

cooperation among key stakeholders in SP's ecosystem, especially between port operators and shipping enterprises, has become even more paramount than in previous years.

5.2. Remarks on the emission inventory of SP

Drawing on insights from Subsection 4.4, this paper finds that methods employed in SP research for estimating emission reductions closely resemble those used for ship emissions. Given these methods, this paper outlines the advantages, disadvantages, and applicability of different emission methods as follows:

The top-down approach category includes fuel-based and trade-based methods. (1) Fuel-based methods. This method category depends on the strong correlation between fuel consumption and emissions. It integrates marine fuel sales data with various ship characteristics, including vessel type, voyage areas, and the distribution of engine type and navigating status, to allocate total emissions without needing detailed navigation data. Widely used in the late 1990 s and early 2000 s (Lee et al., 2020), it is accepted in the EU, the U.S., and some developing countries such as China and Turkey. However, its accuracy heavily depends on precise fuel sales data and errors in this data can cause significant misleading conclusions, making it suitable mainly for macro-level estimations and providing rough figures. (2) Trade-based methods. This method group calculates ship emissions based on port cargo throughput (Liu et al., 2018). For instance, it uses a fitting function between ship emissions and passenger, cargo, and container throughput in Hong Kong to estimate emissions for Shenzhen Port (Li and He, 2011). It is more suitable for estimating ship-in-port emissions but is less accurate and not widely applicable for overall ship emissions. Currently, only few studies opt for the top-down method to estimate ship emissions.

Conversely, the bottom-up methods focus more on specific ship activities and leverage detailed data on ship characteristics, technical information, and ship movements to estimate emissions. The introduction of the automatic identification system in the 1990 s has greatly advanced its development, improving the accuracy and spatiotemporal resolution of emission calculations. Liu et al. (2018) divide them into statistical and dynamic methods. The statistical methods use static ship data statistics to calculate emissions, while the dynamic ones rely on real-time data to monitor ship movements and conditions, applying precise emission factors. Peng et al. (2020) improve the bottom-up method accuracy by integrating a sample method to mitigate the impacts of missing data. The approach provides a more reliable and detailed analysis of ship activities and emissions by overcoming data reliable issues, although it requires more extensive efforts due to its detailed and comprehensive nature.

Nowadays, bottom-up methods are widely used to create emissions inventories for SP. An emerging trend is obvious, reflecting the fact that with the aid of machine learning and data mining, emissions monitoring from ships and ports, along with detailed insights into ship characteristics and SP applications, will enhance the accuracy of ship-related emissions estimation. Surprisingly, there are limited references in the literature that support the thorough comparison of these methods. Such a comprehensive comparison is crucial to ascertain the consistency of their outcomes, as significant discrepancies among these methods may necessitate re-evaluating the most effective strategy. Adding to the complexity, the diversity in vessel specifications—spanning design, type, age, maintenance, and weather—introduces uncertainties in emission estimations (Chang and Wang, 2012; Stolz et al., 2021). Furthermore, the considered factors themselves, as well as the lagging emission factors, exhibit significant disparities. To address these multifaceted challenges, it is necessary to propose more nuanced methods that adequately accommodate these uncertainties and variations. Specifically, the data collection related to SP applications will provide more substantial support for research into emissions from ships at berth, thereby improving the accuracy of emission estimation methods.

While emissions estimation efforts usually prioritise reducing pollutants such as CO_2 and SO_X, the critical contribution of SP in diminishing NO_X and noise emissions has not received enough attention. As more stringent NO_X emission rules come into play, and with the limitations of alternatives like scrubbers, SP's benefits in this area become increasingly salient. Given that SP serves as a vital link towards green and sustainable development for ports and vessels, the adoption of various RESs can significantly reduce emissions during ship docking periods, further highlighting the advantages of SP promotion. Thus, it is essential to distinguish between various emission mitigation options in different scenarios and to scrutinise them meticulously. In economic terms, external costs—often termed spillovers or third-party costs—are those expenses borne by entities not directly participating in an economic transaction. Traditional evaluations of external costs from air pollution predominantly factor in health repercussions, such as premature deaths and diseases. However, upcoming research endeavours should adopt a more expansive perspective, encompassing additional costs related to infrastructure usage, traffic jams, accidents, noise pollution, and climate change.

With the shipping industry moving towards more rigorous regulations and a growing emphasis on green shipping, it is increasingly challenging to rely on a singular emission reduction option. Thus, the need to contrast diverse emission reduction strategies and to discern the collective impacts of an assortment of such measures is becoming increasingly critical to maximising environmental benefits.

5.3. Remarks on the application of SP

Drawing from the analysis in Subsection 4.5, an increasing number of publications focus on investigating the barriers, factors, economic analyses, SPDP, and the selection of green technologies. Indeed, the use of surveys and questionnaires has provided valuable insights into the limited adoption of SP across different countries. However, it is essential to gather responses from a broader range of respondents to mitigate potential preference bias. Regarding economic analysis, the prevailing method employed by researchers is the classic cost-benefit analysis, augmented by considerations such as the time value of money and sensitivity analysis. These analyses can vary significantly depending on several factors, including the study's scope (e.g., a single port or a cluster of ports, individual vessel or

clusters of vessels, a single or multiple routes, government involvement, or national grid integration), costs incorporated (ranging from construction costs, operational expenses, maintenance costs, and additional costs to environmental taxes, ETS costs, penalties), and types of benefits envisaged (environmental benefits, incentives, health impacts). Additionally, the service lifetime of SP can fluctuate between 5 and 30 years. It is crucial to ensure consistent impact factors and parameters for comparative scenarios, as deviations can considerably sway outcomes.

Viewed from a supply chain perspective, it is crucial to enhance the interactions among stakeholders related to SP. For instance, joint investments or cross-shareholding arrangements among these stakeholders in SP may mitigate financial challenges and significantly enhance the application of SP. Furthermore, the financial and operational models of SP should be considered in subsequent analyses to strike a balance between the costs and benefits for all participants and encourage stakeholders to jointly reduce emissions. It is also important to recognise that the effects and outcomes of SP could also be influenced by various external factors, such as shifts in the energy source structure and berth priority incentives. Given the industry's current climate, there is a need to refine the consideration of scientific issues. Shipping operations are highly responsive to policy changes, including the increasingly stringent ECAs, the incentive fund, and the guidance for carbon peaking and carbon neutrality. The growing integration among stakeholders promotes collaboration and provides fertile ground for SP development. Hence, it is essential to stay attuned to the dynamic regulatory environment and the increasing interconnectivity among industry players. Besides, the potential applications of progressive concepts from disparate sectors, such as the 'sharing concept' and 'smart transport', to augment SP remains a fertile area for inquiry.

In terms of deploying SP, the predominant method entails either single or multiple-objective optimisation algorithms. These algorithms are designed to optimise SP deployment in fleet management, route schedules, and berth allocation. The goal is to minimise costs while maximising the emission reduction. This strategic application ensures that SP implementation is both economically viable and environmentally beneficial. Furthermore, the integration of SP with berth allocation and quay crane assignment introduces new dimensions for analysis, facilitating the exploration of trade-offs. However, it is crucial to address the inherent uncertainties influencing SP operations, such as the stochastic nature of ship arrivals, the unpredictability of berth availability for SP utilisation, the impact of weather conditions, and the effects of increased SP demand on the power system. To ensure the effectiveness of optimisation models, the defined parameters and influential factors should align with the practical challenges and real-world scenarios. Striving for sustainable development, it is advantageous to incorporate economic, environmental, and social responsibility considerations into multi-objective optimisation models. Such a holistic decision-making approach not only promotes a balanced and responsible approach to SP implementation but also aligns with broader sustainability goals.

5.4. Remarks on the energy management of SP

As summarised in Subsection 4.6, there has been a notable increase in publications related to the energy management of SP in recent years. This trend aligns with the maritime industry's move towards electrification, digitalisation, and the integration of RESs, making a critical shift in how energy is managed and utilised within marine environments. With advancements in AES, intelligent grids, and microgrids, the role of SP as a vital interface for energy transfer between ports and vessels is expected to attract increasing attention in the coming years.

Currently, research on PEM associated with SP primarily examines the impacts of SP on port energy systems, the balance of power supply and demand, and strategies for power scheduling to improve power management. Investigations into the energy interactions among different sources remain relatively rare. Conversely, studies on SEM predominately explore the utilisation of SP in the charging processes of all-electric ferries and cruise ships, integrating SP with existing energy sources to refine power balance, management, and allocation of power flow, as well as voyage paths. These studies take into account the complexities of voyage conditions, port environments, and operational expenses, aiming to achieve efficient energy management in the shipboard energy systems. However, the diversity of energy types and strategies introduces challenges and uncertainties in modelling, indicating the need for individual examination of each study.

The importance of stability and reliability in both PEM and SEM cannot be overstated and requires simultaneous attention. The adoption of SP not only facilitates a connection between the port electricity system and shipboard electricity systems but also highlights a gap in current research—the oversight of challenges in integrated systems. Besides, new emerging technologies, such as Carbon Capture and Storage (CCS), the application of nuclear energy in shipping, and the latest-generation communication technology, alongside innovations like LNG, hydrogen, fuel cell-based barges, and mobile generators, could offer remedies to the prevailing challenges hindering SP's widespread adoption. Moreover, uncertainty is a pressing problem that cannot be ignored so that the resulting solution is feasible and competent.

Additionally, the resilience of SP during unforeseen events, including extreme weather, port congestion, or prolonged vessel stays due to incidents like the COVID-19 outbreak, should be a focal point of future research. With the context of supply chains, it is imperative to understand that port and shipping operations are interdependent, especially when plugging into SP. Therefore, it is crucial to comprehensively consider these interconnected factors when optimising either energy or operational management.

6. Future research opportunities for SP

As detailed analyses mentioned, these insights are invaluable for a wide range of SP stakeholders, including shipping companies and port authorities, consultants, researchers, and policymakers. Furthermore, SP research should embrace the following specific facets in its future research agenda.

(1) Challenges and opportunities in regular application of SP.

Given the remarks on the practice and barriers to the promotion and application of SP, this paper observes that SP has grown from being used in shipyards and for a military purpose to being widely adopted in commercial ports. The expansion includes its application from passenger to cargo ports and extension from sea to inland ports, covering local to global scales. As SP becomes more common, the focus shifts from the challenges of promoting its use to those related to its daily operation, management, and the impact of policies and regulations. This change opens new paths for industry experts, governments, and researchers to prepare for SP's widespread use by understanding and addressing its challenges at various stages.

Future research content should explore these challenges more deeply, such as meeting the high power demands at ports, improving power quality to minimise SP risks, and evaluating the impact of SP policies on operations. For example, prioritising berthing policies for SP-equipped ships can affect port efficiency and emissions, leading to longer wait times for non-SP ships, increased port congestion, and different emissions outcomes depending on policy presence.

For SP operators, analysing SP data offers insights into energy use while ships are docked, including fuel use, connection times, and the impact of weather on emissions. This information is crucial for accurately estimating emissions, improving energy efficiency, and optimising port operations like power use, berth assignments, and voyage planning.

Emission estimation is a key area of SP research. Monitoring power use during SP connections opens new ways to estimate emissions from docked ships, potentially offering more accurate assessments compared to traditional methods. Future studies should focus on improving these estimation techniques using SP data. This approach could lead to better strategies for reducing maritime environmental impacts, optimising energy consumption, and supporting the maritime industry's sustainability goals.

(2) Innovation in emission reduction strategies.

Based on an analysis of emission reduction strategies associated with SP, this paper summarises that SP serves as a strategic toolkit for the transitions from shutting down auxiliary engines to adopting SP in reducing ship emissions at ports, SP's implementation unlocks a wealth of opportunities for introducing groundbreaking energy and technological innovations in the maritime sector. The array of strategies for emission reduction is becoming increasingly diverse, broadening the scope of SP research. Consequently, future studies could explore the mission reduction potential of SP when utilising it as a part of hybrid energy sources, as well as the effects of other innovative emission reduction strategies on SP's effectiveness. Meanwhile, when evaluating SP in comparison to alternative methods, it is essential to account for the unique attributes of each emission reduction technique. This not only improves the accuracy of the comparison but also ensures that the overarching impact on emission reduction is thoroughly evaluated. Furthermore, future research efforts should take a broader view of external costs, incorporating additional costs related to infrastructure usage, traffic jams, accidents, noise pollution, and climate change.

(3) Optimisation of energy structures.

Derived from the analysis of PEM, it is evident that further modifications to energy structure can dramatically decrease ship emissions during their port stays. Future research will predominantly address the optimisation and management of energy structures for both ports and ships, aiming to determine the most effective distribution of energy sources that align with port throughput. Thus, it is imperative to emphasise the introduction and utilisation of clean energy sources in the maritime sector, along with exploring the impact of different energy structures on emission reduction. This effort aims to fully optimise both the economic and emission-reducing potential of these energy structures. Concurrently, as decarbonisation initiatives gain prominence, it is essential to investigate the potential synergy between SP and carbon trading, as well as the implementation of CCS technology

(4) Interaction and cooperation among stakeholders.

The dynamics of interactions and cooperation among stakeholders present a complex domain deserving thorough investigation from multiple perspectives, which can be effectively conducted through an analysis of SPDP and stakeholders' interaction. This includes examining how different policy states affect stakeholders' preferences, devising a pricing strategy for SP that balances economic costs, and environmental benefits, and equitably distributing environmental responsibilities to ensure a more rational alignment of interests among all parties in the regular operation of SP with littler or without support from incentives and regulations. It also involves enhancing stakeholder communication, fostering cooperative intentions, raising corporate environment awareness, and encouraging social responsibility, thereby supporting the development of SP across industries. Such mechanisms will enable SP user to more scientifically adjust their route scheduling and energy management in response to different policies, achieving a multi-objective optimisation. As indicated in Subsection 4.5, initial efforts have been made in this direction, and this paper underscores the need for extensive research in this area.

(5) Corporation across multiple disciplines.

Inspired by the bibliometric analysis in Section 3, more and more studies are multidisciplinary, and this trend has become more obvious in the past years. This paper therefore forecasts an increase in multidisciplinary studies concentrating on SP in the forthcoming years. This could include considerations such as the stability of the power supply to minimise power fluctuations, mitigate energy wastage, and prevent potential damage to the power system. Furthermore, the interaction between national grids and port microgrids could be explored to enhance energy efficiency. Concurrently, it is essential to take into account the characteristics of ship arrivals, the operational modes specific to different types of ports, and the constraints of power grid supply when designing, controlling, and simulating SP systems. Leveraging machine learning and natural language models can facilitate comprehensive analysis (Du et al., 2022; Liu et al., 2023b). Additionally, advancements in digitisation and improvements in berth allocation and power scheduling in PEM and SEM can benefit from in-depth SP analyses.

(6) Integration of new technologies with SP.

With the advancement of new technologies in the maritime field, the integration of new technologies, including renewable energy sources (such as hydrogen tanks, fuel cells, wind, and PV), advanced energy storage systems (like batteries, fuel cells, and other storage systems), all-electric ships, Automatic Identification System (AIS) for berthing data, CCS, microgrids, smart grids, electric vessel

charging infrastructure, advanced control and automation systems (e.g., automatic mooring), alongside Artificial Intelligence (AI), machine learning, and the Internet of Things (IoT) sensors, significantly influences SP. In particular, deploying advanced energy storage technologies enables the storage of surplus energy generated during off-peak hours, ensuring continuous power availability. The integration of electric vessel charging stations with SP supports the electrification of maritime transport, allowing vessels to recharge while docked. IoT sensors could offer real-time monitoring of energy consumption, equipment performance, and environmental conditions, allowing for proactive maintenance and optimisation of SP. Sophisticated control and automation systems enhance SP operation efficiency and reliability, reducing operational costs.

Furthermore, AI and machine learning algorithms can analyse data to forecast energy demand, and tailor SP ulitisation based on both historical and real-time information. In essence, these new technologies render SP more sustainable, efficient, and reliable, aiding the transition towards cleaner maritime operations (Laribi and Guy, 2023). Besides, the adoption of new technologies within SP generates extensive data, enabling researchers to address macro-scale problems through mathematical methods. Thus, this paper asserts with confidence that the implementation of SP will foster a broader range of research into emission reduction and energy management across various domains.

Nevertheless, it is essential to be aware of the potential negative impacts of SP. A case in point is the duration needed to connect and disconnect from SP, which might contribute to port congestion and impede its overall efficiency. With the continuous application of SP, ever-increasing attention has been paid to the problems in the applications, and the methods have become increasingly complex. The relationships between SP and maritime competitiveness are significant. For instance, in the view of shipping carriers, the installation of SP will upgrade the Environmental Ship Index (ESI), enhancing their commitment to green shipping practices (British Port Association, 2021). From the perspective of port operators, the utilisation of SP is a key indicator in measuring the green grade of ports, which in turn boosts its competitiveness (MOT of the PRC, 2020). Hence, SP plays a vital role in advancing green maritime initiatives. Despite being important indicators of maritime competitiveness, the concepts of green shipping and green ports are frequently undervalued in daily operations (Aksoy and Durmusoglu, 2020). To achieve sustainable development in the long term, it is essential for the shipping industry to treat green shipping as a competitive advantage rather than an economic burden.

7. Conclusion

To drive emission reduction initiatives within the maritime industry, it is crucial to focus on promising strategies and instruments. Taking SP as the core theme, this paper provides a critical review grounded on representative references from WoS Core Collection and Scopus databases and employs a bibliometric analysis through a five-pronged process. Firstly, the application and development of SP in the real world are examined to understand its evolution. Next, the literature retrieval procedures and screening methods are then undertaken, serving as the foundation of this research. A thorough bibliometric analysis follows, integrating citation reports from WoS Core Collection and network analysis using VOSviewer. This phase encompasses theme analysis in keywords, categories, and research areas. Fourthly, 219 key publications are identified and categorised into various research areas for further analysis, drawing on insights from the bibliometric data. Finally, the four potential remarks and future research opportunities for SP for both practical and academic areas are summarised, suggesting specific areas where SP research could expand. Overall, this analysis and review present an exhaustive description of SP's cutting-edge applications, current research trends, methods, research domains, and future trajectories. The findings highlight SP's growing significance across various fields, while also pointing to potential areas for innovation and collaboration.

The maritime industry has encountered challenges since the global economic downturn, with companies prioritising survival over emission reduction. This presents a significant hurdle for the promotion of SP. Given the United Nations' mandate for emission reductions to facilitate sustainable development and public concern over environmental degradation, the IMO and regional and national transportation authorities worldwide have implemented various regulatory measures, incentive schemes, and penalties. While this paper offers a thorough overview of SP, it has revealed certain limitations due to constraints in available information/data, knowledge, and cognition. Nonetheless, it addresses the fundamental research topics related to SP and provides valuable insights for future research. The insights gained from this review will also inform future research endeavours, which will focus on evaluating emission estimation methods for ships at berths utilising SP-related data. Additionally, future research could investigate the effects of SP on port operation efficiency and ship emissions, particularly concerning different SP-related incentives and regulations.

CRediT authorship contribution statement

Jinggai Wang: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Huanhuan Li:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Formal analysis, Resources. **Zaili Yang:** Writing – review & editing, Supervision, Funding acquisition, Project administration, Writing – original draft. **Ying-En Ge:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization, Project administration, Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zaili Yang reports financial support was provided by European Research Council.

Data availability

Data will be made available on request.

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