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Onshore power supply–trends in research studies

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Restrictive regulations introduced by the European Parliament and the United Nations have forced the seaport authorities to reach net zero gas emissions by 2030. An important source of pollution emitted in ports involves exhaust gas emissions from ships powered by ship engines while they are berthed in seaports. One of the ways to reduce the level of pollution and nuisance caused by ship engines is to equip ships with Onshore Power Supply (OPS). Unfortunately, still few ports can boast this type of systems at their quays. There are many publications devoted to the analysis of this phenomenon in the technical and engineering terms, but a significant part also concerns the economic, financial, logistic and organizational aspects. The aim of this research is to identify the directions of development as for research into OPS, to organize the terminology devoted to OPS, and to define scientific disciplines of research in the field of OPS. This research was conducted on the basis of the data mining method using the Scopus, EBSCO and Web of Science databases, applying the multi-stage selection of criteria. The research results may provide an interesting material for scientists to identify the gaps of research regarding OPS.

KEYWORDS

port management, onshore power supply, sustainable development, smart grid, energy efficiency

1 Introduction

The seaport authorities are currently facing a major challenge related to investments supporting the protection of environment and counteracting its pollution. Changes in the Earth's climate resulting from heavy environmental pollution, caused to a large extent by the activities in the maritime economy, have made international institutions and organizations raise the alarm and introduce numerous restrictions regulated by law. Next to the International Maritime Organization (IMO) Convention for the Prevention of Pollution from Ships (MARPOL) (IMO, 1973), It is worth mentioning primarily the most important ones, i.e., The Directive 2000/59/EC on port reception facilities for ship-generated waste and cargo residues with subsequent additions; Annex VI MARPOL Convention regarding limits on emissions of SOx, NOx and particulate matter from exhaust gases emitted from ships (IMO, 2015), and also a document called "Transforming our world: the 2030 Agenda for Sustainable Development" (General Assembly, 2015). In addition, two other documents developed in recent years, i.e.,: 17 Sustainable Development Goals (SDGS) issued in 2015 by the Organization of United Nations, and the European Green Deal (EC, 2019) issued in 2019 by the European Commission should also be mentioned.

The above-mentioned documents specify, *inter alia*, the permissible limits for pollutant emissions in maritime transport and when ships are berthed in ports, and pave the way for zero. In the case of seaports, it primarily refers to creating conditions aimed to reduce the level of pollution emitted by ships in ports (Viana et al., 2014) increase the energy efficiency in port facilities and provide it for the operators of ships at berth as well. Seaports are taking various measures in this regard, and among them there is one solution that is lately gaining in popularity, i.e., Onshore Power Supply (OPS). (Vaishnav et al., 2016; Winkel et al., 2016; Innes and Monios, 2018; Chen et al., 2019; OPS Master Plan, 2021; World Port Sustainability Program, 2021). Recently, the area of research as regards OPS has been very popular, but it should be noted that the source literature provides various definitions for OPS, and they are discussed below in the first part of the study.

The above-mentioned issues and many other related to OPS are currently the subject of numerous studies and analyses of scientists from around the world. Therefore, the aim of this paper is to identify the directions of OPS research development and to define the scientific disciplines of research in the field of OPS. The following research questions were formulated: 1) What are the benefits of investments in OPS? 2) In which scientific disciplines is OPS research currently conducted? 3) What are the current trends and areas of research devoted to OPS?

The content of this paper is typical of such scientific papers; it means that the paper consists of five main sections, including an introduction to the subject related to the issues concerning OPS. The second part of this article presents the review of current achievements in the area of studies regarding OPS. The methodology of the systematic literature review applied in the analysis was described in the third part of this article, and the fourth part was devoted to the presentation of the results. The article ends with a discussion and conclusions expressing the recommendations for further research for the potential groups of interests as well as a list of reference literature.

In the article the method of a multi-stage systematic literature review with the use of data mining was applied. The process of selecting the criteria for analysis and the stages of research process are presented in the chapter devoted to methodology. This article may constitute the subject of interest for seaport authorities and cruise ship owners.

2 Literature review

The International Association of Ports and Harbours (IAPH) World Port Climate Initiative (WPCI) has developed an important document on Onshore Power Supply, which is a key source of information for all entities interested in investing in and using OPS, showing the benefits of replacing onboard-generated power from diesel auxiliary engines with electricity generated onshore (IAPH, 2010). In addition, the international standards for High-Voltage Shore Connection (HSCV) (ISO/IEC/IEEE 80005-1:2012, 2012) have been developed, describing systems for suppling ships with electrical power from shore.

The website provides information on the environmental benefits of OPS and the associated costs. It highlights the existing installations in ports worldwide and the existing suppliers of the OPS technology and overall provides guidance for OPS implementation. The website is primarily targeted to port authorities, terminal operators and shipping companies who are considering the introduction or expansion of OPS technology.

According to the International Maritime Organization (IMO) Shore Power Supply (OPS) "is considered a measure to improve air quality in ports and port cities, to reduce emissions of air pollutants and noise and, to a lesser extent, to reduce carbon dioxide through ships at berth replacing onboard generated power from diesel auxiliary engines with electricity supplied by the shore" (International Maritime Organization IMO, 2012). At this point, however, it should be noted that in the literature there are several terms defining OPS, i.e.,

- Onshore Power Supply (OPS) (Li and Du, 2020),
- Shore-To-Ship Power (SSP) (Innes and Monios, 2018),
- Cold Ironing (CI) (Ballini and Bozzo, 2015),
- Shore Side Electricity (SSE) (Winkel et al., 2016; Stolz et al., 2021),
- High-Voltage Shore Connection (HSCV) (ISO/IEC/IEEE 80005-1:2012, 2012), and
- Alternative Maritime Power (AMP) (Chen et al., 2019).

Bouman et al. (2017) indicated that Shore Side Electricity (SSE) is an effective CO^2 reduction measure for ships. Additionally, (Stolz et al., 2021), proved that "shore side electricity can drastically reduce the emissions from fossil fuel-powered auxiliary engines of ships at berth". They published very interesting research results presenting the "CO^2 emissions from the production of electricity required for SSE and compared to the emissions of ships at berth". (Stolz et al., 2021).

Cold-Ironing (CI) is another frequently used term for OPS. For example (Ballini and Bozzo, 2015), wrote that CI is "a fully developed technology that allows vessels at berth to use shore power rather than rely on electricity generated by their Auxiliary Engines (AE)". Moreover (Bakar et al., 2022), defined cold ironing as "an electrification alternative in the maritime sector used to reduce shipborne emissions by switching from fuel to electricity when a ship docks at a port". In this paper, the authors presented the method of forecasting ship berthing duration that can contribute to track of the cold ironing consumption. The forecasting method can be used by other seaports in estimating demand.

These various terms used to describe OPS have been applied as keywords in the data mining process among scientific databases.

Various technological solutions for OPS solutions for ships are currently offered on the market, i.e.,: mobile power generator units, compact modular cabling system, or main transformer station with local stations at the berths, and also shore power box and other. It is worth emphasizing that the costs of OPS installations depend on (Bullock et al., 2023):

- types of OPS unit technology (e.g., centralised unit, outlet points, transformer, frequency converter, groundworks etc.);
- shore network ancillary equipment;
- distance from the power source of OPS devices;
- power draw required for ships and OPS devices;
- cable management system;
- types of vessels moored at the berths in seaports;
- berthing capacity, and
- many other factors.

The average cost of the OPS installation varies between €1 million and €35 million, e.g., a total budget of 36.4 million US dollars was invested in the OPS installation in the Port of Bremen/Bremerhaven (The Port of Bremen, 2023). Moreover, important are also the costs of electricity transportation to the OPS devices, which depend on.

- port location;
- accessibility to the berths from land and sea;
- sources of energy generation;
- power demand;
- vessels types;
- frequency of cruise ships calls.

Low-power ferries and, for example, small cruise ships with the capacity up to 1000 passengers (Pax) require power only < 3 MW (megawatt), but giant cruise ships with the capacity of 10,000 Pax onboard require power from 6 MVA (megawoltamper) to 20 MVA. The average cost of energy transportation can amount from $300,000 to $4 million per berth. (Bullock et al., 2023; The Port of Bremen, 2023) [6969].

It is also crucial to maintain OPS, and the related costs depend on many factors, i.e.,: costs of maintenance of OPS infrastructure, price of electricity, number of ships mooring into berths (calls), and time of mooring ships into berths (hours).

For more than a decade, scientific research has been conducted in various fields of OPS science by scientists representing technical, engineering, geographical, biological, chemical sciences, as well as social sciences in the field of economics and management (Puig et al., 2022). Maritime transport causes huge environmental pollution. As research shows among global atmospheric pollutants, 2 percent of carbon dioxide (CO_2), 10 to 15 percent of nitrogen oxides (NO_x) and 6 percent of sulfur oxides (SO_x) come from ships. Solutions that will reduce the scale of this phenomenon have been sought (Stolz et al., 2021). OPS is just one of such solution that can bring numerous benefits to the region, local communities, as well as ship owners. The use of OPS in ports provides, among others: lower fuel consumption by ships, reduction of pollution emitted by ships, ship engine noise reduction, removal of vibration caused by ship engines, and easier maintenance of water purity.

Moreover, disconnecting the ships from ship engine power supply and connecting them to the onshore generator also involves savings for the shipowners. However, one more issue needs to be raised, namely, the fact that still few vessels are equipped with devices for connecting the ships to onshore power supply. Despite obvious environmental benefits resulting from using OPS in seaports, many port authorities are still reviewing the economic effectiveness of these solutions. Investments in OPS are highly capital-intensive and their return is spread out over time. The first economic reports indicate that the investments in OPS in ports do not always show satisfactory economic efficiency, but they are certainly ecologically responsible and socially justified (Ballini and Bozzo, 2015).

A review of previous achievements in the field of research on energy system models and onshore power supply systems has showed that this area of research is studied by researchers around the world, i.e.,: in China (Chen et al., 2019), United States, (Bouman et al., 2017; Bullock et al., 2023), Norway (McArthur and Osland 2013), Germany (World Port Sustainability Program, 2021), Spain (OPS Master Plan, 2021). and other European seaports (Winkel et al., 2016). For example, the team (Mattsson et al., 2021) studied, among others: the factors for onshore and offshore wind power, and existing and future hydropower as part of research on the Energy System Model. The authors noted that in order to develop an effective energy system model, cross-sectoral cooperation is necessary and research in this area should also be carried out.

In 2016, (Winkel et al., 2016). raised in their research the economic and environmental aspects of the use of OPS, but they used the term Shore Side Electricity (SSE). Innes and Monios (2018) presented analyses regarding the data on energy demand, and presents a few scenarios for small and medium size ports in the field of cold ironing installation. Qi et al. (2020) showed the results of analysis concerning shore power economic challenges from the perspective of different groups of interests including, i.e., ship owners, port authorities, and state.

Interesting research on policy support on both capital funding and tax reform, and also factors affecting shore power economics for ship and port operators presented by the team of Bullock et al. (2023) based on research in port of Aberdeen in Scotland. The authors raised an important issue with OPS, i.e., "high capital costs for ports, high taxes on land-side electricity and the global lack of taxation on ships' fuel oils" (Bullock et al., 2023) and pointed to a gap in research on this issue. This work is particularly worthy of deeper analysis, because it contains both economic aspects and feasibility study, including, *inter alia*, potential shore power demand by ship type and economic viability, and what is crucial environmental and social valuation. Bouman et al. (2017) presented a comprehensive review of CO_2 studies, emissions, reductions, potentials and measures. Many works address the issues of shipping decarbonisation. OPS installations are one of the solutions that is just analyzed by the author.

An important element of research that should also be taken into account is the development of energy facilities in the vicinity of seaports enabling the connection to OPS. Interesting studies on offshore energy hubs were presented by Zhang et al. (2022). The authors presented the model that "can be used to analyse the interaction of an offshore energy system and onshore energy system transition" (Zhang et al., 2022) It should be emphasized that OPS should be powered by renewable energy sources. It is crucial in the decarbonization process.

Current research studies regard the use of new technologies to optimize processes in electrification. The really interesting research in this area has been carried out, among others, by the research team (Wang et al., 2021b) who presented the design principles and techniques used to implement ternary logic gates using memristor-CMOS hybrid chips for use in strategies for optimizing performance indicators, including, e.g., power consumption. A similar line of research was also carried out by Su et al. (2023) presents innovative research presenting ways to monitor the condition of batteries, based on the integration of physical modelling with machine learning techniques. These types of solutions allow for monitoring and evaluation of battery performance and can be used in optimising the performance of batteries and in projects related to the electrification of port devices.

Another interesting field of research concern the safety assurance was carried out by Siu et al. (2022) who presented the use of a multi-agent command authentication system as a solution to increase security and economic reliability in power systems, with particular emphasis on the possibility of emerging cyberattacks.

The important area of research studies in the field of OPS relates process of integration of energy systems with various power sources. An interesting study in this area was carried out by the team of researchers V. Saxena et. al. (2021) (Saxena et al., 2012) who proposed the MPC Based Algorithm and its validation method for a multifunctional grid-integrated photovoltaic system. The results demonstrate the effectiveness of the model-based predictive control (MPC) algorithm for ensuring energy quality and reliability in the integration of renewables into the power grid. Similar studies relating to the management of the integration of renewable energy sources and the operation of microgrids were carried out by the team of N. Kumar et. al. (Kumar et al., 2018). The paper proposes an intelligent control strategy with the use of artificial intelligence to effectively synchronize the microgrid with the main power grid, taking into account the situation of partial shading. Thanks to the proposed solutions, it is possible to ensure energy efficiency and thus reduce economic and environmental costs. On the other hand, research supporting practical solutions for the control and limitations of control techniques for complex systems in various network structures and dynamic conditions was presented by G. Chen (2023) (Chen, 2022)**.** To sum up, it can be seen that onshore power supply is the subject of numerous scientific studies of various nature and range, both geographical and thematic and it seems reasonable to try further in-depth analysis.

3 Methodology of the systematic literature review

The research was a type of qualitative research. In the article, the method of a multi-stage systematic literature review with the use of data mining was applied. The independent variable is Onshore Power Supply (OPS). The literature analysis process consisted of six stages. To achieve the intended objective of the analysis, i.e., to identify the development of OPS research and to organize the terminology devoted to OPS, in the first stage, key phrases and key words related to onshore power supply were defined. In the second stage, three databases were selected to conduct the search, i.e., Science Direct, EBSCO and Web of Science. In the third stage of analysis, selection criteria that narrowed the search to specific areas were defined. The first criterion involved defining the period of search time, which was limited to a decade, i.e., from 2014 to 2023. In addition, the type of publications to be analysed were specified; only research papers and review papers available in the Open Access option were included. Using publications with limited access to conduct the extensive data analysis, as is the case here, is too expensive and often exceeds the researchers' budgets.

In the next stage of analysis (the fourth), the search was narrowed down to the phrases listed in No_x table in the titles of publications, keywords and abstracts from these publications. As a result, a list of publications for detailed analysis was defined. In the fifth stage, further criteria narrowing the search area were indicated and the collected database was grouped into four subject areas, i.e.,: 1) Engineering analysis (technology, technical, etc.) 2) Socio-economic analysis (financial, fiscal, business, management, etc.), 3) Environmental analysis (protection, pollution, emissions, etc.), 4) Legal analysis (legal standards, law regulations, etc.) (Scheme 1).

The full texts of selected publications were verified, selected and put through detailed substantive analysis, and the results thereof are presented in the next part of this study.

To analyse the data mining of the databases results, the critical and comparative analysis was applied, as well as inductive and deductive reasoning.

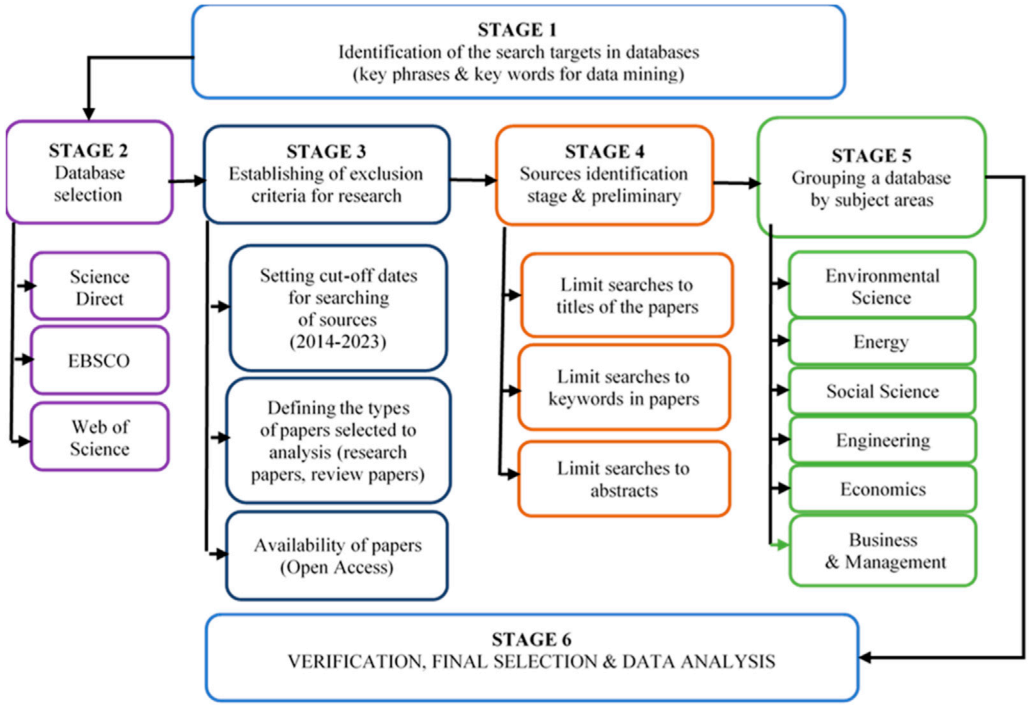
4 Discussion

A systematic review of databases showed that between 2014 and 2023, assuming the previously described selection criteria, a total of 74,111 scientific publications related to OPS were registered. The EBSCO database included a total of n = 70,424 scientific publications placed in review papers and research papers, which referred directly or indirectly to the issue of OPS, which accounted for as much as 94.98% of all publications in the examined scientific databases. Meanwhile, ScienceDirect database registered a total of 3431 publications (i.e., 4.63% of all publications) during the period under analysis. Unfortunately, in the Web of Science database there are few scientific publications related to OPS, i.e., 279, which accounts only for 0.39% of the total number (Figure 1).

A review of the ScienceDirect, EBSCO and Web of Science scientific databases also indicated that the majority of publications related to OPS, i.e., 63.47% is devoted to issues under the heading of "STSP" and 32.38% of "OPS". This is valuable information for scientists who will take up the subject of OPS in their future scientific work. The search limited in the literature queries only to the common (as it might seem) terms, i.e.: "OPS" (Onshore Power System) and neglecting "STSP" (Shore To-Ship Power) could significantly distort the scope of analysis. Other terms related to OPS, i.e., CI, SSE, or HVSC are less commonly used in the scientific literature (Figure 2).

By comparing the resources of the three scientific databases above-mentioned, in the area of publications devoted to OPS with the use of criteria described above, we also come to the conclusion that the largest number of publications devoted to "Shore To-Ship Power" and "Onshore Power Supply" was registered in the EBSCO database (94.98%). Similarly, in the ScienceDirect database, the largest number of publications were devoted to "Onshore Power Supply" and "Shore To-Ship Power". Whereas scientists rather rarely use other terms, i.e.: "Cold ironing", or "Alternative Maritime Transport" (Figure 3).

As a result of the analysis, a total of 74,135 publications were filtered from all three examined databases where references to OPS were found (3rd Stage). Then, in 4th Stage, in accordance with the planned model of systematic literature review, the search was narrowed only to publications referring directly to specific phrases in the titles of these publications and abstracts and keywords. This resulted in a reduction in the number of publications to 302. The next step in the 5th Stage was to group the publications into individual subject areas. In the last stage of the analysis (6th Stage) the publications were verified and selected. After



SCHEME 1
Database mining and analysis process. Source: own elaboration.

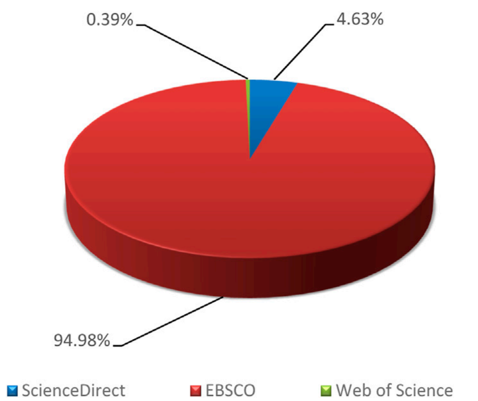


FIGURE 1
Percentage structure of the examined scientific databases by publications devoted to Onshore Power System. Source: own study.

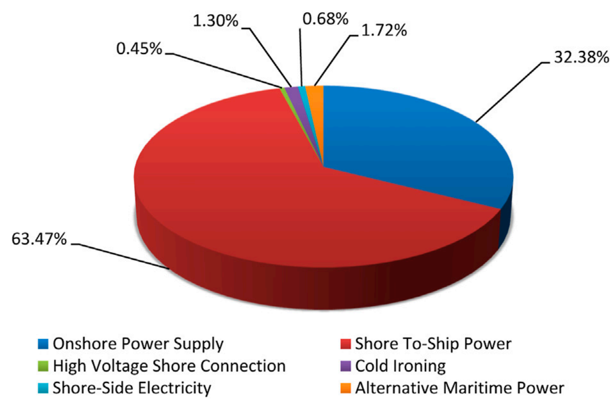


FIGURE 2
Percentage structure of Onshore Power System publications in the scientific databases analysed. Source: own study.

this stage, only 63 publications were qualified for deeper analysis, which accounted for 20.9% of those selected for analysis, which met the criteria of the 3rd stage (Table 1).

An important element in the considerations, and also the superior objective of the analysis, involves the issue of subject areas of research conducted in the area of OPS (Figure 4). As it was previously mentioned, OPS is the subject of interest to researchers from various fields and disciplines of knowledge. Some areas are excessively analysed in terms of research, while other, not much. Obviously, one can argue that perhaps these are the needs on the market, but one can also argue, quite the opposite, that perhaps these are topics convenient for researchers because they are consistent with their research interests, and not necessarily important for stakeholders.

A review of the scientific achievements to date related to the issue of OPS has shown that this issue is very topical and subject to analysis within different areas of knowledge, which can basically be divided into four main research areas, i.e.,: 1) environmental analysis (protection, pollution, emissions, etc.) 2) engineering analysis (technology, technical, etc.), 3) socio-economic analysis (financial, fiscal, business, management, etc.), and 4) legal analysis (legal standards, law regulations, etc.) (table 2).

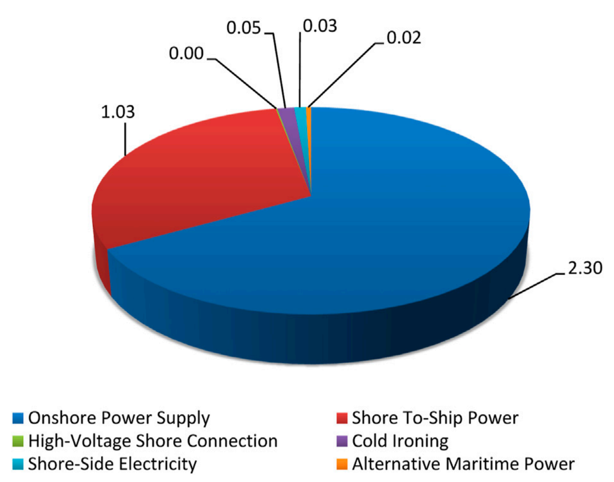


FIGURE 3
Number of publications related to Onshore Power System in the scientific databases analysed (in thousand). Source: own study.

The main reason for investing in OPS refers to the environmental benefits that reduce noise, vibrations and emissions of pollution from ships when they are berthed. Hence, in databases there are numerous publications on this subject presenting environmental benefits of using OPS technology (Kizielewicz and Skrzeszewska, 2021; Sciberras et al., 2015; Saxena et al., 2012; Kumar et al., 2018; He et al., 2020; Wang et al., 2021b; Reusser and Pérez, 2021; Chen, 2022; Siu et al., 2022; Su et al., 2023) in particular in the area of CO_2 reduction potential of OPS (Stolz et al., 2021). The research carried out by Reusser and Pérez (2021) (Wang et al., 2021b) is a good example showing "the reduction in the specific fuel consumption of the auxiliary engines, thus reducing emissions in 20% for CO_2, 34% for NO_x and 30% for SO_x" thanks to applying CI power configuration.

These results confirm the expediency of using CI and should constitute an important argument convincing to use these solutions. However, in the area of engineering research, there are numerous scientific works on the development of OPS infrastructure and various technologies in this respect used in seaports, including small and medium ones. Colarossi and Principi (2020) proposed the methodology of evaluation "the energy demand of ships at berth and producing electricity through a highly efficient cogeneration plant". They also studied the annual trend in electrical energy required by ships at berth and tried to estimate the capital, operational and maintenance costs. They presented the system which consists of a cogeneration plant that produces simultaneously heat to cover utilities in port area and power for ships at berth while (Colarossi and Principi, 2020). Numerous works also refer to the issue of connecting OPS to energy sources, including renewable sources. Interesting research on the use of wave energy extraction and wave energy converters was conducted by Cheng et al. (2022a) (Port Technology International, 2021; Cheng et al., 2022a). They described solutions combing floating breakwaters with wave energy converters and integrating them into a very large floating structure and developed mathematical models confirmed by experimental studies. It would be worth considering the use of offshore wave energy converters in OPS. There is still a gap in this area of research, and only a few experimental works have been done in this area. This could also be an interesting direction for future research.

Bearing in mind different energy supply needs of ships, due to their type and gross tonnage, research is also conducted on the electrical characteristics of OPS (Yang and Chai, 2016; Atallah et al., 2017; Gutierrez-Romero et al., 2019; Badakhshan et al., 2022; Farrukh et al., 2022). Bearing in mind different energy supply needs of ships, due to their type and gross tonnage, research is also conducted on the electrical characteristics of OPS (Bakar et al., 2022; Sciberras et al., 2015) and transient overvoltage protection of OPS System (Haddadian and Haddadian, 2011), and energy efficiency assessment of OPS (Karimi et al., 2022). A serious problem raised in scientific works also refers to the cost of energy transportation to OPS from power sources (Jung and Schindler, 2021), and also energy optimization of OPS systems. (Galkin and Tarnapowicz, 2022; Qiong and Xiao, 2015). Martínez-Lopez et al. (2021) noted that the environmental and economic benefits are only seen when OPS is powered by renewable sources.

The dominant group of works related to OPS also comprises studies in the area of socio-economic analysis, including mainly financial and management analysis of investments in OPS and benefits to local communities from OPS systems. Such analyses are a key element in the investment decision-making process of port authorities. Investments in OPS are highly capital-intensive, as already mentioned above, and many factors determine the success of this type of investment. Martínez-Lopez et al. (2021) presented "a calculation method to estimate a environmental charge in ports to incentivize cold Ironing use", which takes into account "a pollutant differentiation system by considering kinds of vessel, technical features, port localization and hinterlands populations". The team led by Najihah (2023) studied the "synergy of the cold ironing and microgrid system on ships" and also presented the "cold ironing cost analysis strategies from ports' and ships' points of view" (Najihah et al., 2023). It is one of the few scientific studies of this type containing both technological and economic aspects of CI. Many scientific papers refer to assessing the economic efficiency of investments in OPS including, *inter alia*, pricing strategy and sale mechanism of OPS (Stolz et al., 2021; Su et al., 2023) and cost-effective optimization analysis of OPS (Hulme, 2006).

The need for financial support for OPS from public funds (Wang et al., 2021a) is also raised, because of the environmental benefits for the region and local communities (Ballini and Bozzo, 2015). Moreover, a valuable source of information for stakeholders includes studies devoted to building strategy for OPS System (Yu et al., 2017) and control strategy for OPS (Ji et al., 2018) presenting also barriers and drivers to the implementation of OPS (Williamsson et al., 2022). Finally, there are also works related to energy management in seaports (Acciaro et al., 2014) including the management of OPS systems and optimization of daily use of OPS (Yu et al., 2022).

However, we can feel certain insufficiency when it comes to scientific studies in the area of managing shipboard energy (Sciberras et al., 2015), and the state of preparing ships to be equipped with devices adapted to connect to OPS system and to

TABLE 1 List of keywords that constitute grounds for searching the scientific databases.

Key phrases	N research papers and review papers in scientific databases available in open access form the period between 2014 and 2023							
1st stage	2nd Stage	3rd stage	4th stage	5th stage				6th stage
				EnA*	EgA*	SEA*	LA*	
Onshore AND Power AND Supply	Science Direct	n = 2295	n = 27	n = 9	n = 15	n = 1	n = 2	12
Shore AND "To-Ship" AND Power		n = 1034	n = 13	n = 3	n = 8	n = 2	n = 0	
"High-Voltage" AND "Shore Connection"		n = 4	n = 1	n = 0	n = 1	n = 0	n = 0	
"Cold Ironing"		n = 49	n = 12	n = 1	n = 10	n = 1	n = 0	
"Shore-Side" AND Electricity"		n = 34	n = 6	n = 0	n = 5	n = 1	n = 0	
Alternative AND "Maritime Power"		n = 15	n = 1	n = 0	n = 1	n = 0	n = 0	
TOTAL ScienceDirect		3432	60	13/12	40/68	5/15	2/3.4	
Onshore AND Power AND Supply	EBSCO	n = 21 511	n = 14	n = 2	n = 8	n = 2	n = 4	35
Shore AND "To-Ship" AND Power		n = 45 977	n = 45	n = 8	n = 30	n = 7	n = 0	
"High-Voltage" AND "Shore Connection"		n = 327	n = 26	n = 4	n = 18	n = 4	n = 0	
"Cold Ironing"		n = 910	n = 82	n = 14	n = 56	n = 12	n = 0	
"Shore-Side AND Electricity"		n = 420	n = 6	n = 1	n = 4	n = 1	n = 0	
Alternative AND "Maritime Power"		n = 1246	n = 3	n = 1	n = 2	n = 0	n = 0	
TOTAL EBSCO		70 424	176	30	118	24	4	
Onshore AND Power AND Supply	Web of Science	n = 194	n = 39	n = 7	n = 26	n = 6	n = 0	15
Shore AND "To-Ship" AND Power		n = 24	n = 18	n = 4	n = 12	n = 2	n = 0	
"High-Voltage" AND "Shore Connection"		n = 5	n = 0	n = 0	n = 0	n = 0	n = 0	
"Cold Ironing"		n = 1	n = 0	n = 0	n = 0	n = 0	n = 1	
"Shore-Side" AND Electricity"		n = 52	n = 6	n = 2	n = 4	n = 0	n = 0	
Alternative AND "Maritime Power"		n = 13	n = 2	n = 0	n = 2	n = 0	n = 0	
TOTAL Web of Science		279	65	13	44	8	0	
TOTAL Scientific bases		74 135	302	56	202	37	7	63
Percentage share in selected publications			100%	18,5%	66,9%	12,3%	2,3%	20,9%

EgA, Engineering analysis; EnA, Environmental analysis; SEA, Socio-economic analysis; LA, Legal analysis and documents.

ensure ship-to-grid integration (Vlachokostas et al., 2019). Few papers present the results of research on equipping the ships, by segments (cruise ships, ferry vessels, cargo, etc.) with devices enabling the connection to OPS, and future electricity and hydrogen demands for shipping (Ortiz-Imedio et al., 2021; Bakar et al., 2022). This is the area that should become the subject of future research. There is also a shortage of reliable economic analyses for shipowners regarding the benefits of using OPS.

We should also mention the legal and regulatory issues related to OPS systems, issued by the IMO (IMO, 1973) or IAPH (IAPH, 2010) and ISO (ISO/IEC/IEEE 80005-1:2012, 2012) regarding the technical aspects of OPS. These documents provide practical information about OPS, which constitute the subject of analyses and scientific discussions (IAPH, 2010; Yu et al., 2017; Tarnapowicz and German-Galkin, 2018).

Summing up the analysis of databases on previous research on OPS, it should be emphasized that the main streams of research concern the following areas.

- Environmental research area–the use of renewable energy sources to power the operational activities of seaports, including supplying ships with shore energy (OPS). The aim is to reduce greenhouse gas emissions and reduce the emission of harmful substances into the environment.
- Engineering research area–the use of modern technologies in the construction of OPS infrastructure, including in particular in relation to transformers, converters, energy storage devices in order to increase energy efficiency.
- The area of computer science research–the use of new technologies in the management of energy distribution in

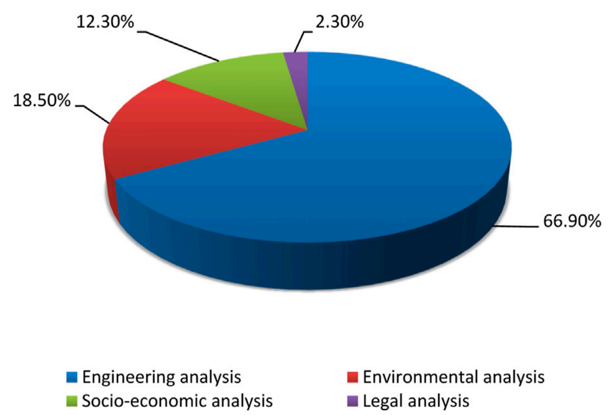


FIGURE 4
Subject areas of research publications in databases. Source: own study.

port areas in order to optimize its consumption, increase energy efficiency and estimate energy demand in the future.

- The area of economic research–using knowledge in the field of management and economics to prepare economic analyses of the efficiency of investments in OPS in relation to individual case studies.

It should be emphasized that the research conducted so far has focused mainly on the analysis of individual cases of engineering, organizational, technical or architectural solutions in the field of OPS. Stakeholders interested in investing in OPS and their development are looking for comprehensive analyses containing legal, economic, environmental and social analyses, showing a map of the benefits and costs resulting from investments in OPS. This type of interdisciplinary research would be more applicable and could have a greater popularizing value.

4.1 Conclusion and policy implications

In conclusion, it must be emphasized that despite numerous scientific studies dedicated to the economic analysis of investments in OPS, there is still a noticeable gap in studies directly dedicated to the management of investments in OPS and the social aspects of OPS. Considering that OPS are relatively new investments in seaports and new technological solutions for OPS continue to enter the market, port authorities are looking for the most effective solution models in this regard.

Frequently, port authorities also commission dedicated studies on the cost-effectiveness of investments and new solutions in OPS. However, these are industry-related studies rather than scientific papers and present a case study rather than a broader spectrum of solutions related to the solidity of investments in OPS.

At present, there are various technological solutions in the field of OPS, which are described above. The port authorities would be very interested not only in a comparative analysis of all these systems, in terms of energy efficiency, technological solutions and their development (engineering analysis), but also in the environmental benefits of specific OPS solutions (environmental analysis), and, most importantly, in assessing the economic viability of these investments (economic analysis). An important area of research on OPS is also the way of the OPS management, and development in seaports (business and management analysis).

One of the limitations of the analysis presented above involves the subjective criteria adopted by the author of this article. Limiting the analysis only to a decade, just only to research papers and review papers published between 2014 and 2023 and available as open access may affect the analysis results. Nevertheless, the conclusions that can be drawn present the general trends in research and areas of interest for scientists as regards the issue of OPS.

The analysis conducted in the study enables to indicate the areas of knowledge and research working currently on research related to OPS, which represented the main objective of this research. The analysis also proved that scientists use different abbreviations (e.g.,: OPS, SSP, CI, SSE, HSCV and AMP) and concepts to think and research the same phenomena. This can make analysis and search difficult and provides an important clue for researchers, It seems that the terminology in this area should be sorted out.

The review of the previous studies allowed to indicate the main directions for further scientific research to be conducted in this area of OPS, i.e.,.

- management of OPS systems and their integration with onshore energy systems,
- integration of offshore wave energy converters with onshore energy systems;
- budgeting policy of the investments in OPS co-financed by public funds;
- demonstrate the policy for economic efficiency of OPS for stakeholders (port authorities and ship owners);
- popularization of various technical and technological solutions related to OPS;
- social and environmental policy for OPS development;
- ships' equipment with a device enabling the connection to OPS;
- verification of the demand for OPS among shipowners;
- economic efficiency of OPS from the perspective of shipowners;
- identification of risks associated with investments in OPS.

Summing up, the future research should also address areas that are still insufficiently researched and described and represent gaps in research. The future research fields should concern.

- Comparative analyses of various engineering and technical solutions in the field of OPS, showing which of the solutions should be used under specific environmental conditions and financial capabilities of stakeholders.
- Economic analyses using an indicator analysis of the economic efficiency of individual OPS solutions together with a prospective analysis of the economic effects of these solutions in various variants for the region. Such analyses would be of great application value and could be an interesting source of information for entities managing port areas, including port authorities, local governments and private owners of the port lands.

TABLE 2 Research areas and topics in the field of onshore power supply.

Research areas	Research topics
Engineering analysis (technology, technical, etc.)	Technologies of OPS
	Optimal deployment of OPS
	Electrical characteristics of OPS
	Transient Overvoltage Protection of OPS System
	Energy Optimization of OPS systems
	Energy efficiency assessment of OPS
	Ship-to-grid integration
	Distance to power grids
	Fault diagnosis for onshore grid-connected converter in wind energy conversion systems
	Uninterruptable Shore-side Power Supply of OPS
	Implementing OPS from renewable energy sources
	Application Systems to Supply Onshore Grid Power to Offshore O&G Installations
	Potential of local solar generation for providing OPS
	Integrating Offshore Wind Farms with Unmanned Hydrogen and Battery Ships
	Installing cold ironing at small and medium ports
Socio-economic analysis (financial, fiscal, business, management, etc.)	Cooperative optimization of OPS
	Barriers and Drivers to the Implementation of OPS
	Strategy for OPS System
	Control Strategy for OPS
	Energy management in seaports
	Government subsidize for OPS
	Electricity subsidy efficiency of OPS
	Economic Benefits of OPS
	Cost-effective optimization analysis of OPS
	Optimization of daily use of OPS
	Sale Mechanism of Onshore Power Supply
	Pricing Strategy of Cold Ironing
	Improving OPS project economics
	Techno-economic analysis of OPS
	Socio-economic benefit of cold-ironing technology
	Managing Shipboard Energy
	Ship berthing forecasting for cold ironing
	Future electricity and hydrogen demands for shipping
Environmental analysis (protection, pollution, emissions, etc.)	Environmental Benefits of Using low-Sulphur Oil and OPS Technology
	Evaluation of the emission impact of OPS
	Environmental emission Impact of OPS
	CO2 reduction potential of OPS
	Environmental charges to boost Cold Ironing

(Continued on following page)

TABLE 2 (*Continued*) Research areas and topics in the field of onshore power supply.

Research areas	Research topics
	Reducing shipboard emissions
	Environmental Ben46efits of OPS
Legal analysis (legal standards, law regulations, etc.)	Regulation strategy for OPS
	Standardization in the Design of OPS

Source: own elaboration on the base of: (IMO, 2015; Innes and Monios, 2018; IAPH, 2010; Winkel et al., 2016; Stolz et al., 2021; Bakar et al., 2022; Bullock et al., 2023; Hulme, 2006; AAPA, 2007; Haddadian and Haddadian, 2011; Acciaro et al., 2014; Qiong and Xiao, 2015; Sciberras et al., 2015; Yang and Chai, 2016; Atallah et al., 2017; Yu et al., 2017; Chengdi et al., 2018; He et al., 2018; Ji et al., 2018; Tarnapowicz and German-Galkin, 2018; Gutierrez-Romero et al., 2019; Kumar et al., 2019; Sun et al., 2019; Vlachokostas et al., 2019; Zis, 2019; Colarossi and Principi, 2020; He et al., 2020; Wang et al., 2020; Wang et al., 2021a; Jung and Schindler, 2021; Kizielewicz and Skrzeszewska, 2021; Martínez-Lopez et al., 2021; Ortiz-Imedio et al., 2021; Peng et al., 2021; Spengler and Tovar, 2021; Badakhshan et al., 2022; Farrukh et al., 2022; Galkin and Tarnapowicz, 2022; Karimi et al., 2022; Qiu et al., 2022; Williamson et al., 2022; Yu et al., 2022; Najihah et al., 2023; Tarnapowicz and German-Galkin, 2018; Port Technology International, 2021; Reusser and Pérez, 2021; Cheng et al., 2022a; Cheng et al., 2022b; Kizielewicz, 2023).

- Environmental analyses showing the benefits of using various OPS solutions and, on the other hand, the benefits and costs associated with not using these solutions in ports for the region and the environment.
- Engineering analyses showing in a comprehensive way the various possibilities of supplying OPS with energy obtained from renewable energy sources. Especially in coastal areas, there are opportunities to use water energy, wind energy and solar energy. Although such studies are already carried out on a random basis, they are individual case studies and not comprehensive and variant analyses. In Europe, investments in the area of offshore wind farms are currently intensifying. The costs of preparing and maintaining the OPS supply infrastructure are significant factors withholding the development of OPS. It is crucial to demonstrate the benefits of using renewable energy sources to power OPS in order to persuade decision-makers to invest in OPS.
- A holistic and interdisciplinary approach showing the state and prospects for the development of OPS in port areas and opportunities for regions thanks to investments in OPS, as well as the risks for the region in the event of a departure from investments in this area.
- Presentation of the state of technical readiness of the fleet of vessels in individual segments (cruies ships, ferry vessels, cargo ships, etc.) for the use of OPS, together with an analysis of plans for the installation of devices enabling connection to shore power supply. Currently, analyses in this area are fragmentary, and the lack of information in this area does not support investors' decisions and causes great concern.
- Develop examples of good practice in relation to the development of international standards and guidelines for the design, installation and operation of onshore energy infrastructure.
- Social analyses showing what is the attitude of stakeholders in relation to both OPS and renewable energy sources. When talking about stakeholders, we must not forget about the inhabitants of port cities, who are not always enthusiastic about, for example, the construction of wind farms and are not aware of the benefits of investments in this area.

So far, the analysis of research results shows that seaport authorities are open to create the policy of investments development supporting the environment management, facilitating the environmental improvement and reducing the amount of pollutants emitted to the environment (Kizielewicz, 2023), but they need support in the form of scientific analyses on the best technological solutions, models, and sources of financing for the investments in OPS. The challenges faced by seaports, especially in Europe, resulting from climate change and restrictive EU and UN regulations, mean that port authorities will have no choice but to invest in this area.

In future research, a set of other phrases can be reviewed, and other publications can be selected for analysis. A significant limitation certainly involves including in the scope of research the publications with limited access which require paid access thereto. This type of analysis could be very expensive and difficult to implement, but perhaps it would provide a different picture of the ongoing scientific research in the area of OPS.

Author contributions

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Conflict of interest

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References

AAPA (2007). "Use of shore-side power for ocean-going vessels," in *White paper, American Association of Port Authorities* (Tetra Tech, Inc), 1035.

Acciaro, M., Ghiara, H., and Cusano, M. I. (2014). Energy management in seaports: a new role for port authorities. *Energy Policy* 71, 4–12. doi:10.1016/j.enpol.2014.04.013

Atallah, A., Kerin, U., and Audring, D. (2017). *Examining the operational and environmental benefits of using high-voltage AC transmission systems to supply onshore grid power to offshore O&G installations*.

Badakhshan, S., Senemmar, S., Li, H., and Zhang, J. (2022). "Integrating offshore wind farms with unmanned hydrogen and battery ships," in IEEE Kansas Power and Energy Conference, Manhattan, Manhattan, KS, USA, April 25 and 26, 2022, 1–6. doi:10.1109/KPEC54747.2022.9814722

Bakar, N. N. A., Bazmohammadi, N., Çimen, H., Uyanik, T., Vasquez, J. C., and Guerrero, J. M. (2022). Data-driven ship berthing forecasting for cold ironing in maritime transportation. *Appl. Energy* 326, 1–12. 119947. doi:10.1016/j.apenergy.2022.119947

Ballini, F., and Bozzo, R. (2015). Air pollution from ships in ports: the socio-economic benefit of cold-ironing technology. *Res. Transp. Bus. Manag.* 17, 92–98. doi:10.1016/j.rtbm.2015.10.007

Bouman, E. A., Lindstad, E., Rialland, A. I., and Strømman, A. H. (2017). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – a review. *Transp. Res. Part D* 52, 408–421. doi:10.1016/j.trd.2017.03.022

Bullock, S., Higgins, E., Crossan, J., and Larkin, A. (2023). *Marine policy 152 (2023) improving shore power project economics at the port of aberdeen*. Amsterdam, Netherlands: Elsevier, 2–9.

Chen, C. J., Zheng, T., Garg, A., Xu, L., Li, S., and Fei, Y. (2019). Alternative Maritime Power application as a green port strategy: barriers in China. *Barriers J. Clean. Prod.* 213, 825–837. doi:10.1016/j.jclepro.2018.12.177

Chen, G. (2022). Pinning control of complex dynamical networks. *IEEE Trans. Consumer Electron.* 68 (4), 336–343. doi:10.1109/TCE.2022.3200488

Cheng, Y., Chen, Xi, Dai, S. S., Ji, C. Y., Collu, M., Li, M., et al. (2022a). Wave Energy extraction and hydroelastic response reduction of modular floating breakwaters as array wave energy converters integrated into a very large floating structure. *Appl. Energy* 306 (117953), 1–32. doi:10.1016/j.coastaleng.2022.104188

Cheng, Y., Fu, L., Dai, S. S., Collu, M., Ji, C. Y., Yuan, Z. M., et al. (2022b). Experimental and numerical investigation of WEC-type floating breakwaters: a single-pontoon oscillating buoy and a dual-pontoon oscillating water column. *Coast. Eng.* 17, 1–16. doi:10.1016/j.coastaleng.2022.104188

Chengdi, D., Yan, D., Zhongyi, L., Liu, S., and Jia, S. (2018). "Study on the power supply and sale mechanism of onshore power supply under the background of electric power system reform," in 2018 China International Conference on Electricity Distribution. IEEE, Tianjin, China, 17-19 September 2018.

Colarossi, D., and Principi, P. (2020). Technical analysis and economic evaluation of a complex shore-to-ship power supply system. *Appl. Therm. Eng.* 181, 1–11. doi:10.1016/j.applthermaleng.2020.115988

EC (2019). *Communication from the commission, the European green deal, COM(2019) 640 final*, 1–24.

Farrukh, F., Dunks, C., and Marie, M. (2022). "Assessment of the potential of local solar generation for providing ship shore power in the Norwegian harbour Port of Borg," in Conference: 18th International Conference on the European Energy Market, Ljubljana, Slovenia, 13-15 September 2022, 1–6. doi:10.1109/EEM54602.2022.9921031

Galkin, S., and Tarnapowicz, D. (2022). Energy optimization of the 'shore to ship' system-A universal power system for ships at berth in a port. *Sensors* 20 (14), 1–20. doi:10.3390/s20143815

General Assembly (2015). *UN, transforming our world: the 2030, Agenda for sustainable development, A/RES/70/1*, 5–38.

Gutierrez-Romero, J. E., Jose, E., Esteve-Perez, J., and Zamora, B. (2019). Implementing Onshore Power Supply from renewable energy sources for requirements of ships at berth. *Appl. Energy* 255, 113883. doi:10.1016/j.apenergy.2019.113883

Haddadian, P. D., and Haddadian, V. (2011). Transient overvoltage protection of shore-to-ship power supply system. *IEEE Trans. Industry Appl.* 47 (3), 1193–1200. doi:10.1109/tia.2011.2125772

He, J., Li, X., Xu, H., Zhu, J., Dai, P., and Chu, H. (2018). "Review and discussion on standards for shore-to-ship power supply system," in International conference on material engineering and application (ICMEA 2017). Vol. 146, Wuhan, China, December 15th-17th, 2017, 22–26.

He, W., Chen, R., Li, T., Hu, B., Tian, Y., and Meng, W. (2020). Comparative study on environmental benefits of using low-sulphur oil and shore power technology for ship berthing. *E3S Web Conf.* 145, 02010–02015. doi:10.1051/e3sconf/202014502010

Hulme, C. T. (2006). Using cost effectiveness analysis; a beginners guide. *Evid. Based Libr. Inf. Pract.* 1 (4), 17–29. doi:10.18438/B81S34

IAPH (2010). *Onshore power supply*. Available at: https://sustainableworldports.org/project/iaph-onshore-power-supply.

IMO (1973). *Final act of the international conference on maritime pollution, date of access: 23/04/2022*. Available at: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/ConferencesMeetings/Documents/MARPOL%201973 (accessed on April 17, 2022).

IMO (2015). Guidelines for exhaust gas cleaning systems, marine environment protection committee. *IMO Publ. Documents Resolut. MEPC* 259 (68), 1–23.

Innes, A., and Monios, J. (2018). Identifying the unique challenges of installing cold ironing at small and medium ports – the case of aberdeen. *Transp. Res. Part D Transp. Environ.* 62, 298–313. doi:10.1016/j.trd.2018.02.004

International Maritime Organization IMO (2012). *On-shore power supply, MEPC.1/Circ.794 9 october 2012*. Available at: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Circ.794.pdf.

ISO/IEC/IEEE 80005-1:2012 (2012). *Utility connections in port — Part 1: high voltage shore connection (HVSC) systems — general requirements*. Available at: https://www.iso.org/standard/53588.html.

Ji, Z., Zhao, Z., Wang, J., and Lv, Z. (2018). A flexible control strategy for shore-to-ship power system in terms of grid-connected and off-grid switch. *Pol. Marit. Res.* 25, 139–148. doi:10.2478/pomr-2018-0085

Jung, C., and Schindler, D. (2021). Distance to power grids and consideration criteria reduce global wind energy potential the most. *J. Clean. Prod.* 317, 128472–128512. doi:10.1016/j.jclepro.2021.128472

Karimi, S., Zadeh, M., and Suul, J. A. (2022). A multi-layer framework for energy efficiency assessment of shore-to-ship fast charging systems including onshore batteries. *IET Electr. Syst. Transp.* 12 (4), 269–286. doi:10.1049/els2.12052

Kizielewicz, J. (2023). Environmentally friendly cruise seaports in northern Europe – onshore power supply. *Int. J. Mar. Navigation Saf. Sea Transp.* 17 (2), 357–363. doi:10.12716/1001.17.02.12

Kizielewicz, J., and Skrzeszewska, K. (2021). Identifying actions to prepare electricity infrastructure in seaports for future power supplying cruise ships with energy from land. *Energies* 14 (23), 8173. No 8173. doi:10.3390/en14238173

Kumar, J., Kumpulainen, L., and Kauhaniemi, K. (2019). Technical design aspects of harbour area grid for shore to ship power: state of the art and future solutions. *Int. J. Electr. Power Energy Syst.* 104, 840–852. doi:10.1016/j.ijepes.2018.07.051

Kumar, N., Singh, B., and Panigrahi, B. K. (2018). *Grid synchronisation framework for partially shaded solar PV-based microgrid using intelligent control strategy*, 829–837. doi:10.1049/iet-gtd.2018.6079

Li, K., and Du, K. (2020). Research on onshore power supply system in port for ships. *Earth Environ. Sci.* 558, 052022–052025. doi:10.1088/1755-1315/558/5/052022

Martínez-Lopez, A., Romero-Filgueira, A., and Chica, M. (2021). Specific environmental charges to boost cold ironing use in the European short sea shipping transportation research Part D. *Transp. Environ.* 94, 1–14. doi:10.1016/j.trd.2021.102775

Mattsson, N., Verendel, V., Hedenus, F., and Reichenberg, L. (2021). *An autopilot for energy models – automatic generation of renewable supply curves, hourly capacity factors and hourly synthetic electricity demand for arbitrary world regions Energy Strategy Reviews 33*. Amsterdam, Netherlands: Elsevier, 2–9.

Najihah, N., Bakar, A., Bazmohammadi, B., Vasquez, J. C., and Guerrero, J. M. (2023). Electrification of onshore power systems in maritime transportation towards decarbonization of ports: a review of the cold ironing technology. *Renew. Sustain. Energy Rev.* 178, 1–16. doi:10.1016/j.rser.2023.113243

OPS Master Plan (2021). *OPS master plan for Spanish ports project*. Available at: http://poweratberth.eu/?page_id=219&lang=en.

Ortiz-Imedio, R., Caglayan, D. G., Ortiz, A., Heinrichs, H., Robinius, M., Stolten, D., et al. (2021). Power-to-Ships: future electricity and hydrogen demands for shipping on the Atlantic coast of Europe in 2050. *Energy* 228, 120660–120727. doi:10.1016/j.energy.2021.120660

Peng, Y., Dong, M., Li, X. D., Liu, H. K., and Wang, W. Y. (2021). Cooperative optimization of shore power allocation and berth allocation: a balance between cost and environmental benefit. *J. Clean. Prod.* 279, 123816–123818. doi:10.1016/j.jclepro.2020.123816

Port Technology International (2021). What is onshore power? Available at: http://www.porttechnology.org/news/what-is-onshore-power (Accessed May 7, 2023).

Puig, M., Azarkamand, S., Wooldridge, C., Selén, V., and Darbra, R. M. (2022). *Insights on the environmental management system of the European port sector 150550, Science of the Total Environment, 806*. Amsterdam, Netherlands: Elsevier, 2–12.

Qi, J., Wanga, S., and Peng, C. (2020). *Shore power management for maritime transportation: status and perspectives Maritime Transport Research, (1)*. Amsterdam, Netherlands: Elsevier, 1–11.

Qiong, S. Y., and Xiao, L. M. (2015). "Technology of uninterruptable shore-side power supply for berthing vessels and its application," in Proceedings of The 3rd International Conference On Advances, Energy and Environmental Science AER-Advances in Engineering Research, Vol. 31, Zhuhai, China, July 25-26, 2015, 371–375.

Qiu, J., Tao, Y., Lai, S., and Zhao, J. (2022). Pricing strategy of cold ironing services for all-electric ships based on carbon integrated electricity price. *IEEE Trans. Sustain. Energy IEEE Trans. Sustain. Energy Sustain. Energy, IEEE Trans.*13 (3), 1553–1565. doi:10.1109/tste.2022.3157645

Reusser, C. A., and Pérez, J. R. (2021). Evaluation of the emission impact of cold-ironing power systems, using a Bi-directional power flow control strategy. *Sustainability* 13 (1), 334. doi:10.3390/su13010334

Saxena, V., Kumar, N. N., Singh, B., and Panigrahi, B. K. (2012). An MPC based algorithm for a multipurpose grid integrated solar PV system with enhanced power quality and PCC voltage assist. *IEEE Trans. Energy Convers.* 36, 1469–1478. doi:10.1109/TEC.2021.3059754

Sciberras, E. A., Zahawi, B., and Atkinson, D. J. (2015). Electrical characteristics of cold ironing energy supply for berthed ships. *Transp. Res. Part D-Transport Environ.* 39, 31–43. doi:10.1016/j.trd.2015.05.007

Siu, J. Y., Kumar, N., and Panda, S. K. (2022). Command authentication using multiagent system for attacks on the economic dispatch problem. *IEEE Trans. Industry Appl.* 58 (4), 4381–4393. doi:10.1109/TIA.2022.3172240

Spengler, T., and Tovar, B. (2021). Potential of cold-ironing for the reduction of externalities from in-port shipping emissions: the state-owned Spanish port system case. *J. Environ. Manag.* 279, 111807. doi:10.1016/j.jenvman.2020.111807

Stolz, B., Held, M., Georges, G., and Boulouchos, K. (2021). The CO2 reduction potential of shore-side electricity in Europe. *Appl. Energy* 285, 116425–116512. doi:10.1016/j.apenergy.2020.116425

Su, S., Li, W., Mou, J., Garg, A. R., Gao, L., and Liu, J. (2023). A hybrid battery equivalent circuit model, deep learning, and transfer learning for battery state monitoring. *IEEE Trans. Transp. Electrification* 9, 1113–1127. doi:10.1109/tte.2022.3204843

Sun, Y., Zhu, L., Xu, Z., Xiao, L., Zhang, J., and Zhang, J. (2019). Characteristic analysis and forecast of electricity supply and demand in APEC. *Glob. Energy Interconnect. V.* 2 (6), 413–422. doi:10.1016/j.gloei.2019.11.016

Tarnapowicz, D., and German-Galkin, S. (2018). International standardization in the design of "shore to ship" - power supply systems of ships in port. *Manag. Syst. Prod. Eng.* 26 (1), 9–13. doi:10.2478/mspe-2018-0001

The Port of Bremen (2023). Cruise Terminal, modern, secure, purpose-built. Available at: https://www.bremenports.de/en/ports/bremerhaven.

Vaishnav, P., Fischbeck, P. S., Morgan, M. G., and Corbett, J. J. (2016). Shore power for vessels calling at U.S. Ports: benefits and costs. *Environ Sci. Technol.* 50 (3), 1102–1110. doi:10.1021/acs.est.5b04860

Viana, M., Hammingh, P., Colette, A., Querol, X., Degraeuwe, B., Vlieger, I., et al. (2014). Impact of maritime transport emissions on coastal air quality in Europe Atmospheric Environment. *Atmos. Environ.* 90, 1–9. 96e105. doi:10.1016/j.atmosenv.2014.03.046

Vlachokostas, A., Prousalidis, J., Spathis, D., Nikitas, M., Kourmpelis, K., Dallas, S., et al. (2019). "Ship-to-grid integration: environmental mitigation and critical infrastructure resilience," in 2019 IEEE Electric Ship Technologies Symposium (ESTS), Washington, DC, 542–547. doi:10.1109/ESTS.2019.8847858

Wang, L. F., Liang, C. J., Shi, J., Molavi, A., Lim, G., and Zhang, Y. (2021a). A bilevel hybrid economic approach for optimal deployment of onshore power supply in maritime ports. *Energy* 292, 264–274. doi:10.1016/j.apenergy.2021.116892

Wang, X. Y., Chen, Y. Z., Liu, Z. Q., Zhang, H. W., Li, Q. Y., Wang, J. X., et al. (2021b). High-density memristor-CMOS ternary logic family. *IEEE Trans. Circuits Syst. I Regul. Pap.* 68 (1), 264–274. doi:10.1109/TCSI.2020.3027693

Wang, Y., Ding, W., Dai, L., and Jing, D. (2020). How would government subsidize the port on shore side electricity usage improvement? *J. Clean. Prod.* 278 (7), 123893–123896. doi:10.1016/j.jclepro.2020.123893

Williamsson, J., Costa, N., Santen, V., and Rogerson, S. (2022). Barriers and drivers to the implementation of onshore power supply-A literature review. *Sustainability* 14 (10), 2–16. doi:10.3390/su14106072

Winkel, R., Weddige, U., Johnsen, D., Hoen, V., and Papaefthimiou, S. (2016). Shore side electricity in Europe: potential and environmental benefits. *Energy Policy* 88, 584–593. doi:10.1016/j.enpol.2015.07.013

World Port Sustainability Program (2021). *Hamburg port authority – onshore power supply*. Available at: https://sustainableworldports.org//project//port-of-hamburgonshore-power-supply-ops//.

Yang, Z. M., and Chai, Y. (2016). A survey of fault diagnosis for onshore grid-connected converter in wind energy conversion systems. *Renew. Sustain. Energy Rev.* 66, 345–359. doi:10.1016/j.rser.2016.08.006

Yu, J. J., Voss, S., and Song, X. Q. (2022). Multi-objective optimization of daily use of shore side electricity integrated with quayside operation. *J. Clean. Prod.* 351, 1–7. doi:10.1016/j.jclepro.2022.131406

Yu, M. D., Huang, W. T., Tai, N. L., Zheng, X. D., Ma, Z. J., and Wang, Y. (2017). Advanced microgrid and its multi-objective regulation strategy for shore supply. *J. Eng.* 2017 (13), 1590–1594. doi:10.1049/joe.2017.0600

Zhang, H., Tomasgard, A., rage Rugstad Knudsen, B. R., Svendsen, H. G., Bakker, S. J., and Grossmann, I. E. (2022). *Model. analysis offshore energy hubs Energy* 261, 1–17. Part A. doi:10.1016/j.energy.2022.125219

Zis, T. P. V. (2019). Prospects of cold ironing as an emissions reduction option. *Transp. Res. Part A* 119, 82–95. doi:10.1016/j.tra.2018.11.003