energies

IMPACT FACTOR 3.0

CITESCORE 6.2

Article

Onshore Power Supply in Multi-Terminal Maritime Ports

Carmen Luisa Vásquez, Francisco António Borges, Lucas Marinho, Jesús C. Hernández and Teresa Batista

Special Issue
Advancements in Sustainable Energy Technologies: Innovations, Integration, and Impact

Edited by
Dr. Sunel Kumar, Dr. Dingkun Yuan and Dr. Xinlu Han

MDPI

https://doi.org/10.3390/en18102489

energies

Article

Onshore Power Supply in Multi-Terminal Maritime Ports

Carmen Luisa Vásquez [1,2], Francisco António Borges [1], Lucas Marinho [1], Jesús C. Hernández [2,3,*] and Teresa Batista [1]

[1] MED—Mediterranean Institute for Agriculture, Environment and Development, Change—Global Change and Sustainability Institute, Institute for Advanced and Research, Universidade de Évora, 7004-516 Évora, Portugal; carmen.vasquez@uevora.pt (C.L.V.); francisco.borges@uevora.pt (F.A.B.); lucas.marinho@uevora.pt (L.M.); mtfb@uevora.pt (T.B.)

[2] RIBIERSE-CYTED, Red para la Integración a Gran Escala de Energías Renovables en los Sistemas Eléctricos, Proyecto 723RT0150, Department of Electrical Engineering, University of Jaén, Campus Lagunillas s/n, Edificio A3, 23071 Jaén, Spain

[3] Department of Electrical Engineering, University of Jaén, Campus Lagunillas s/n, Edificio A3, 23071 Jaén, Spain

* Correspondence: jcasa@ujaen.es

Abstract: Depending on the type of fuels used by ships in maritime port operations, emissions may contribute more or less to the concentration of greenhouse gases in the atmosphere. The maneuvering of ships at maritime ports uses mainly auxiliary engines, resulting in a significant contribution to emissions. It is understandable that the energy transition in this sector brings benefits and is essential to sustainability, considering its economic and strategic importance. Among the measures established to ensure this transition is the onshore power supply and increased electrification in transportation operations. Maritime ports are not yet prepared for these adjustments, as their heterogeneity and contexts require further research, such as studying the impact of depth on energy consumption, terminal type, and others. The purpose of this paper is to quantify the reduction in greenhouse gas emissions achievable through the implementation of an onshore power supply at the Port of Sines, Portugal. Furthermore, it aims to identify the key factors influencing these adoptions to provide practical recommendations that can guide in advancing energy transition, reducing reliance on fuels, and fostering a sustainable future for the port industry.

Keywords: greenhouse gas emissions; maritime port; onshore power supply

Academic Editors: Sunel Kumar, Dingkun Yuan and Xinlu Han

Received: 1 April 2025
Revised: 28 April 2025
Accepted: 8 May 2025
Published: 12 May 2025

Citation: Vásquez, C.L.; Borges, F.A.; Marinho, L.; Hernández, J.C.; Batista, T. Onshore Power Supply in Multi-Terminal Maritime Ports. *Energies* **2025**, *18*, 2489. https://doi.org/10.3390/en18102489

1. Introduction

The importance of the oceans in regulating the climate [1], providing a carbon sink [2], and contributing to the global and local economy of countries is indisputable [3,4]. Their protection is vital, especially through maritime spatial planning (MSP) resources [5,6], which involves developing practical guidelines and fostering innovative solutions to address the multifaceted impacts of climate change on marine ecosystems and coastal communities [5], including the use of renewable energies within all maritime activities [7].

Ocean activity and the maritime industry are intrinsically linked, as maritime transport is responsible for moving 80% of the world's trade [8,9], which strengthens the global economy and the cooperation and interdependence between countries. Since 2006, China has been the most integrated country in the world's maritime transport networks, followed by the Republic of Korea, Singapore, the United States, and Malaysia [10]. By 2024, globally, the world fleet's carrying capacity reached 2.35 billion dead weight tons (dwt), an increase of 77 million dwt from the previous year [10]. All these integrations and activities pose challenges, which, in turn, have prompted a regulatory framework for reducing the risk of degrading ecosystems, among other aspects.

In terms of controlling emissions and energy consumption, international shipping is subject to an increasingly strict regulatory framework. This is aimed at reducing its environmental impact and contributing to the achievement of the goals proposed in the Paris Agreement [11] and to energy transition [12,13], among other guidelines [14]. This framework began with the signing of the International Convention for the Prevention of Pollution of the Sea by Oil (OILPOL) in 1954 [15]. In 1973, the International Convention for the Prevention of Pollution from Ships (MARPOL) was signed [16], which is the document currently used to regulate the impacts of pollution caused by ships in the maritime industry. This includes regulations aimed at preventing and minimizing pollution in six technical Annexes. In the same year, the Marine Environment Protection Committee (MEPC) was set up as a permanent body of the International Maritime Organization (IMO) with the responsibility of coordinating and supervising policies and measures to protect the marine environment from pollution caused by ships and the maritime industry. This includes the control of discharges into the sea and the atmosphere. Discharges to the atmosphere include emissions of greenhouse gases (GHGs) and other gases, volatile organic compounds (VOCs), and particulate matter (PM) from the use of fossil fuels and chemical compounds throughout the maritime industry.

In 2018, MECP.304 (72) [17] published the Initial IMO Strategy on Reduction of GHG Emissions from Ships with a Roadmap to achieve decarbonization of the maritime industry by 2050. In 2023, the MECP.377 (80) IMO Strategy on Reduction of GHG Emissions from Ships was published [18]. This strategy aims to achieve net-zero GHG emissions for all maritime industry and port activities [18]. Measures include shoreside/onshore power supply from renewable sources, infrastructure to support the supply of zero or near-zero GHG emission fuels and/or energy sources, and further optimization of the logistic chain and its planning, including ports [18]. Onshore power supply (OPS) and offshore power supply are considered measures to reduce emissions from the use of fossil fuels by ships while in berthing or anchoring operations within ports, respectively, if they are integrated from renewable sources [19].

While ships are maneuvering within a port's jurisdiction area, their main engines (MEs) operate at a lower load factor or are shut down. In this case, the auxiliary engines (AEs) mobilize the ship, where their load percentage varies depending on the type of maneuver. To maintain the functionality and safety of the ship during berthing, AEs provide the necessary power for critical systems. Depending on fuel type and technology, AEs can have even higher emission factors than MEs [20,21].

Depending on the type of fuels for use in marine diesel engines [22], emissions to the atmosphere include CO, CO_2, SO_2, NO_x, $PM_{2.5}$, PM_{10}, and total hydrocarbons (THSs) during ship berthing operations [23]. In the short term, these emissions can have an effect on the health of people who work at port terminals or live in nearby cities, even impacting the local economy [24,25]. However, their concentration can vary depending on wind speed and direction, location of the berthing point, use of emission-reducing technologies, and other ship parameters [26]. In the long term, these emissions contribute to the concentration of GHGs in the atmosphere and thus to global warming.

With the increase in cargo per ship worldwide, loading and unloading delays during berthing have increased. As a benefit, this brings a reduction in emissions per unit of cargo [27]. However, the energy consumption for the operation of cargo handling equipment has increased. This equipment has been replaced by electric components, as an additional measure to reduce the use of diesel [28].

OPS is presented as a suitable measure to reduce emissions in seaports and increase their efficiency, especially in those located in urban or coastal areas. This measure is driven by government regulations and incentives, including emission controls established by the IMO [29]. In addition to the term OPS, other terms can be used:

- Shore power (SP) [30];
- Coil ironing (CI) [31,32];
- Alternative maritime power (AMP) [33];
- Shore-to-ship power (SSP) [34];
- Shore-side electricity (SSE) [35];
- High-voltage shore connection (HVSC) [36].

These definitions refer to the supply of power from an onshore network to avoid running diesel engines when the ship is in port. The electrical power supply for the engines can be provided from the public grid, incorporating renewable energy sources (RESs) or energy storage systems (ESSs) [32]. During this maneuver, it requires a continuous and significant supply of electrical power [37].

OPS systems reduce the emissions from the use of fossil fuels in AEs to net-zero GHG emissions. However, the emissions are transferred to the power generation source [38]. Improvements in service continuity and a reduction in failure risks have been obtained by integrating OPS with RESs and microgrids [32].

Figure 1 shows a schematic of the overall electrical system of an OPS consisting of ship-side electrical systems (onboard receiving device), cable management system, shore-side electrical systems, and infrastructure [39,40]. HVSC can be realized at 6.6 or 11 kV [36,41], and low-voltage shore connection (LVSC) is realized at 440~380 V (50/60 Hz) [42].

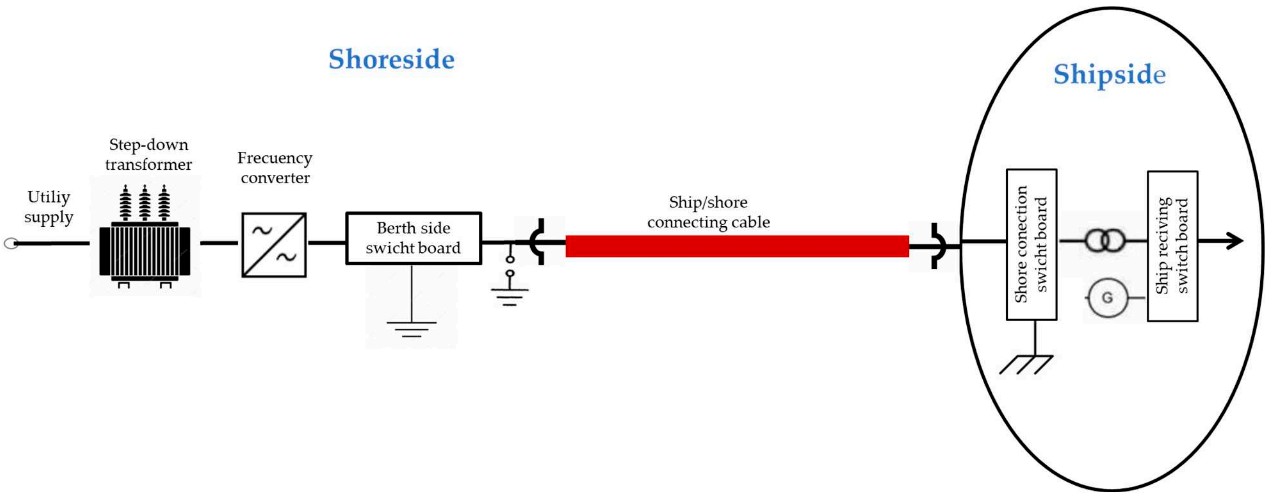

Figure 1. Generic requirements of OPS.

Some of the benefits of OPS include improvements in air quality and public health; increased efficiency; and reductions in noise, air emissions, fuel consumption, and carbon taxes [43]. Ports with renewable source systems [31,44] or with the use of green hydrogen as a vector [45] have demonstrated the achievement of these objectives. Despite the benefits, their implementation presents some of the challenges shown in Table 1.

As shown in Table 1, several challenges related to OPS must be addressed. These include the following:

1. Technical applications concerning energy supply and parameters: a previous case study highlights that the joint coordination between authorities and port operators

enhances energy independence, system efficiency, operational reliability, and the profitability of the microgrid [46].
2. Installation and retrofitting costs for ships, as well as potential subsidies: there is evidence supporting emission reductions when auxiliary engines are powered by the electrical grid [47].
3. Uncertainties regarding investment recovery in decarbonization projects: the cost of electricity is less volatile than that of fuel supply, making OPS a lower-risk alternative [48].
4. Finally, despite a variety of publications relating to the use of alternative fuels for emissions decarbonization, current global production cannot meet the necessary demand [49].

Table 1. Challenges of OPS systems [50,51].

Criteria	Sub-Criteria	Description
Technical application	Matching of the port and ship power supply	• It is necessary to ensure the matching of voltage and frequencies, and the compatible current phase when using the AMP.
	Direct power supply from the grid	• To achieve the direct grid power supply to berth ships, it is necessary to solve technical problems, including high-power electricity frequency conversion, equipment cooling, electromagnetic compatibility, and harmonic wave control.
	Power supply quality	• Technical issues of voltage stability and smooth transition between ships and the OPS.
	Technical standard	• Technical and standardization issues such as high-power frequency transformation, harmonic control, apparatus refrigeration, and compatibility of electromagnetism.
	Additional power capacity	• Not meeting the amount of power required by the ship, and the problem of the consistency of high-voltage and low-voltage interfaces.
	Coordination between the ship and the power supply	• Coordination between the port and regional grids, the extent of stakeholder apprehension, and the lack of electricity service rate grades.
Economic	Retrofit costs	• Power reception facility installation cost, existing ship renovation cost, ship power monitoring device installation, and repair cost.
	Operating costs	• Cost of managing and maintaining human resources, power, and power-using equipment when using OPS.
	Maintenance costs	• OPS management measures include establishment and improvement, cable safety maintenance, port cooperation failure prevention cost.
	Lack of economic benefits	• No economic benefit in cost–benefit analysis compared to fuel consumption.
Other	Policies and supporting systems	• Lack of safety agreements between ships and ports, and OPS implementation plans or guidelines issued by government departments.
	Subsidy/incentive	• Lack of policies on port financial subsidies and tax reductions.

Currently, there is scarce research related to the limitations that consider the increased risks that may occur when electrical energy is converted uncontrollably into heat or when uncontrolled flames, glows, or sparks occur [32,52,53], especially when the OPS involves high-voltage equipment [54]. Additionally, the process of ship berthing is considered crucial in the safety of seaports [55].

Notably, 31% of the risks in ship berthing activities in maritime ports are related to oil and its derivatives, chemicals, and natural gas [56]. Due to poor resilience of infrastructure [42] and losses, maritime terminals with the highest vulnerability are those storing chemicals (particularly chlorine, ammonia, methanol, nitrogen, sodium, etc.), liquefied natural gas (LNG), liquid and solid bulk [57], and general cargo [58] (especially roll-on/roll-off), as well as cruise terminals [59,60]. Hazardous events related to accidents during berthing may occur, such as explosions due to loading and unloading operations, and fires on ships/carriers during electrical installations and on cargo carriers during cleaning operations [61].

The purpose of this paper is to quantify the reduction in greenhouse gas emissions achievable through the implementation of an OPS at the Port of Sines, Portugal. Furthermore, it aims to identify the key factors influencing the adoption of OPS in multi-terminal ports and to provide practical recommendations that can guide port authorities in advancing energy transition, reducing reliance on fossil fuels, and fostering a sustainable future for the port industry.

The heterogeneity in port types and contexts implies that further empirical research is needed [62] and that smart approaches associated with efficient and clean energy use for port-to-ship pathways to reach net-zero GHG emissions in the maritime shipping sector need urgent research [63]. Finally, a cascade of challenges is observed, where research on operations can help the planning, making it possible to simulate future scenarios and reduce risk in investments [64].

2. Materials and Methods

The Port of Sines is a maritime infrastructure of vital importance for Portugal and other countries. The maritime area is 147.5 km^2 (Figure 2), with a maximum depth of 28 m. Presently, this port has five specialized terminals, including a sports and fishing port, with private concessions, which are included in Table 2.

Table 2. Identification, berths, depth, and cargo type from different terminals of the Port of Sines.

Terminal	Identification	Depth (m)	Cargo Type
Containerized cargo	SCT	17	Container
Liquid bulks	LBT	28	Crude oil, refined oil, liquefied petroleum gas (LPG), methanol, and chemical naphtha.
Liquefied natural gas	NGT	15	LNG
Petrochemical	PCT	12	Propylene, ethylene, butadiene, ethyl tertiary butyl ether, ethanol, methyl tertiary butyl ether, aromatic mixtures, and methanol
General cargo	GCT	18	Dry bulk, general cargo, and ro_ro
Others	Others	--	Sports and fishing port, tugboat service, and other services

In this study, we calculated the electrical energy consumption and emissions from the operation of equipment used for the unloading and loading of cargo at the terminals and the maneuvering of ships within the maritime jurisdiction area for the period 2018–2022. Only four terminals (LBT, NGT, SCT, and PCT) were considered, since the GCT started its operations only in August 2022.

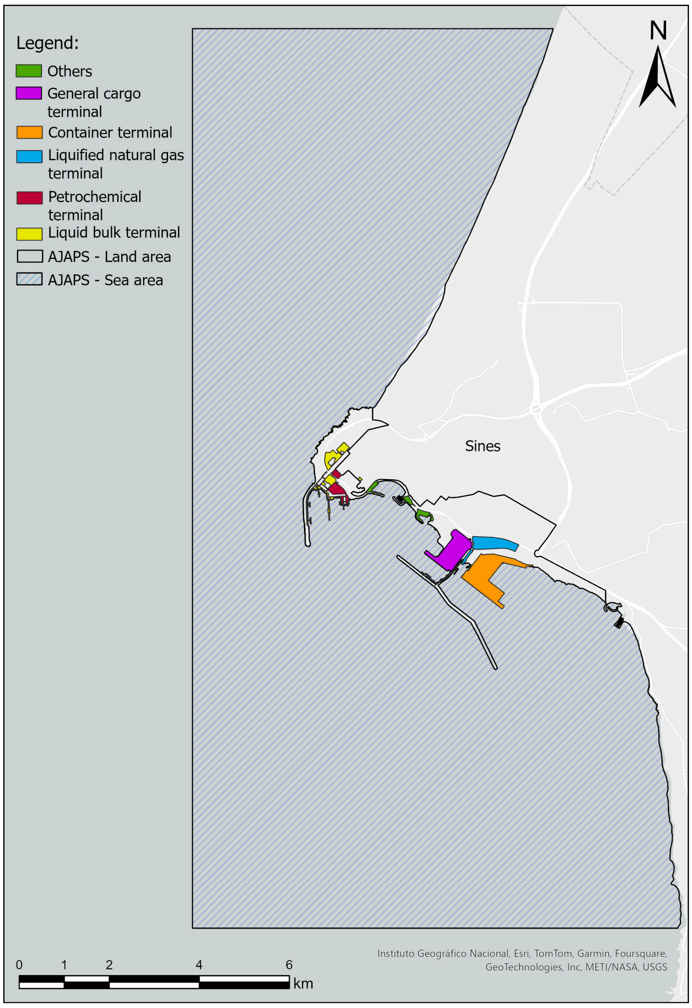

Figure 2. The jurisdiction area of the Port of Sines.

The electrical terminal load handling devices are as follows:

- Centrifugal pumps for liquid products of the oil and petrochemical industry in the LBT;
- Centrifugal pumps for petrochemical products of different viscosities and densities in the PCT;
- Cryogenic pumps for natural gas liquids at low temperatures in the NGT;
- Electric rubber-tired gantries (RTGs) and rail-mounted gantries (RMGs) in the SCT.

To calculate the electrical energy consumption of the terminals' equipment, the measurements of the electrical supply of the network were considered. Monthly records measured at the transformation points (TPs) in the LBT and SCT, managed by port authorities, were used. Additionally, the concessionaires that manage the NGT and PCT provided their energy consumption records for the same period. Emissions were calculated according to Equation (1), where the grid emission factors used are those indicated for each year by the APA [65]. Since 2005, the APA has been publishing annual emission factors used to calculate the emissions associated with Portugal's energy consumption. These factors are based on measurements and real data and consider the impact of renewable energy penetration. Their purpose is to establish or plan measures to reduce emissions (Lopes, 2023) [66]. These factors were used to estimate emissions from electricity consumption across all terminals.

$$Em = E * EF \quad (1)$$

where

Em: emissions due to the activity (tCO_2eq);
E: energy (MWh);
EF: emission factor (tCO_2eq/MWh).

Since 2005, the APA [65] has been publishing annual grid emission factors to calculate emissions linked to energy consumption in Portugal. These factors are grounded in actual measurements and data, accounting for the growing penetration of renewable energy sources. Their primary aim is to facilitate the establishment or planning of measures to reduce emissions [66]. Furthermore, these factors were applied to estimate emissions from electricity consumption across all terminals, aligning with methodologies from other studies [67].

The methodology shown in Figure 3 was used to calculate electrical energy consumption and emissions from ship maneuvers within the area of jurisdiction. The methodology involved the use of maritime transport information within the area of jurisdiction, maintained by the port authority.

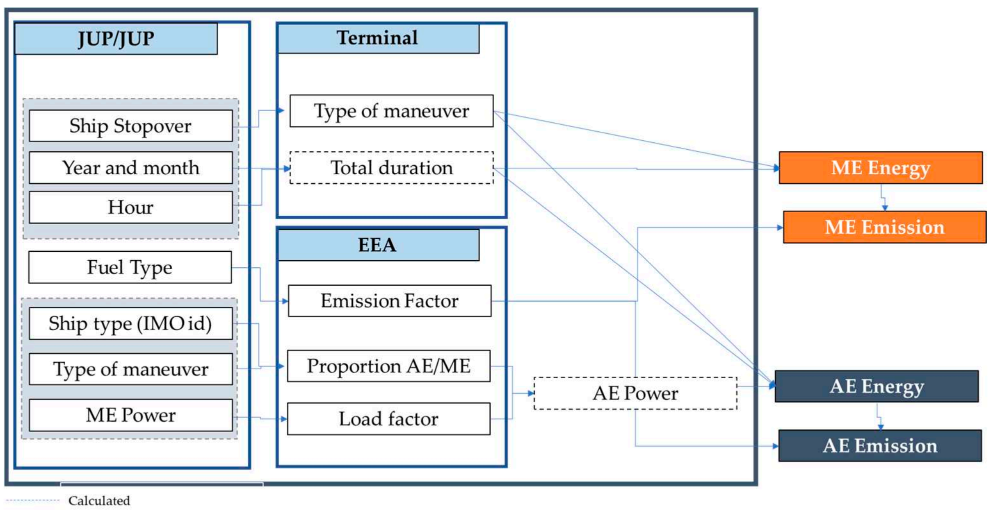

Figure 3. Methodology.

Regarding the ship movement data until 2019, they were collected using the maritime transport information from the Port Single Window (JUP). After 2020, the data were collected from the Logistics Single Window (JUL) [68] as a technological platform. The JUP and JUL include information on the scales of the ships, cargo, access to facilities, and operations in the terminals. Among the maritime transportation data are the type and times of maneuvers per terminal [69,70], which include the following:

- Passenger locator form (PLF)—entry;
- Anchoring;
- Suspending;
- Berthing;
- PLF—exit;
- Others.

The calculation was carried out based on information about the type of ship, the fuel used, and the time duration of the maneuvers, according to the methodology recommended by the European Environment Agency (EEA) [71–73]. This is based on the function of the power and load factors of the ME and AE of the ship and the execution time of each maneuver, the load factor, the proportion of the AE/ME, and the fuel type. In this methodology, the AE power is estimated as a percentage of the ME depending on the type of ship.

In total, 28,785 maneuvers were analyzed over the 5 years of the study; however, only 48% of these data included the power generated by the ME. For data completeness, missing ME power data [74] were assigned numerical values based on linear regression. In the literature, various methods for imputing missing data have been discussed. Among these, the statistical models utilizing direct data input based on dead weight tons (dwt) [75], twenty-foot equivalent unit (TEU) [76], or gross tonnage (GT) [74,77] stand out due to their advantages. These models consider the asymptotic nature of the data, offering moderate accuracy while ensuring high interpretability. Moreover, similar studies, applying empirical rules, have been used for estimating ship emissions in ports.

3. Results and Discussion

Figures 4–7 show the bubble chart of the dwt and power of ME by terminal, for the period 2018–2022. The ME power was divided into quartiles as a statistical tool to facilitate comparison and analyze trends in GT by year for each terminal. Given the different types, densities, and quantities of cargo and ships, this representation allowed for characterizing the trends in cargo/ship handling across the various terminals. From this analysis, the following observations emerged:

- In 2022, there was a significant increase in the ME power and GT in the LBT.
- Starting in 2019, the NGT managed ships with ME power in the third quartile (Q3). However, it was not until 2022 that it began to handle ships from this quartile with higher GT.
- Throughout the analyzed years, ships with ME power across all quartiles were observed. The only exception was the PCT, which during the same period, exclusively handled ships from the first quartile (Q1), regardless of GT.

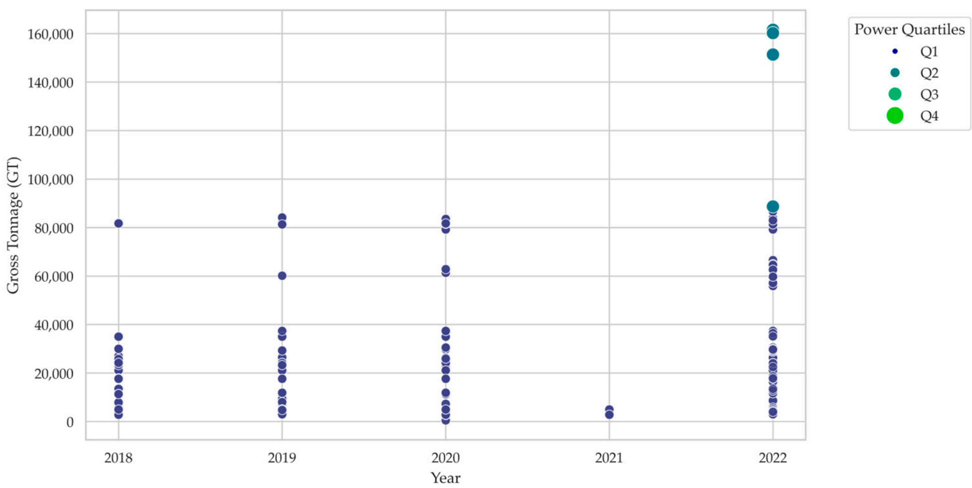

Figure 4. The dwt and power of ME in the LBT of the Port of Sines.

Figures 8 and 9 show the average power consumption and emissions for each terminal. It is noteworthy that in the NGT, SCT, and PCT, the energy consumption per electrical energy (EE) was higher than the consumption of the AE in berthing operation. Additionally, these emissions were only surpassed by the emissions from the operation of the equipment in the LBT and SCT. The reason for this is multifaceted. One of the factors was that, in these terminals, there was an increase in per ship charge (Figures 4 and 7), berthing time (Table 4), and emissions (Table 5).

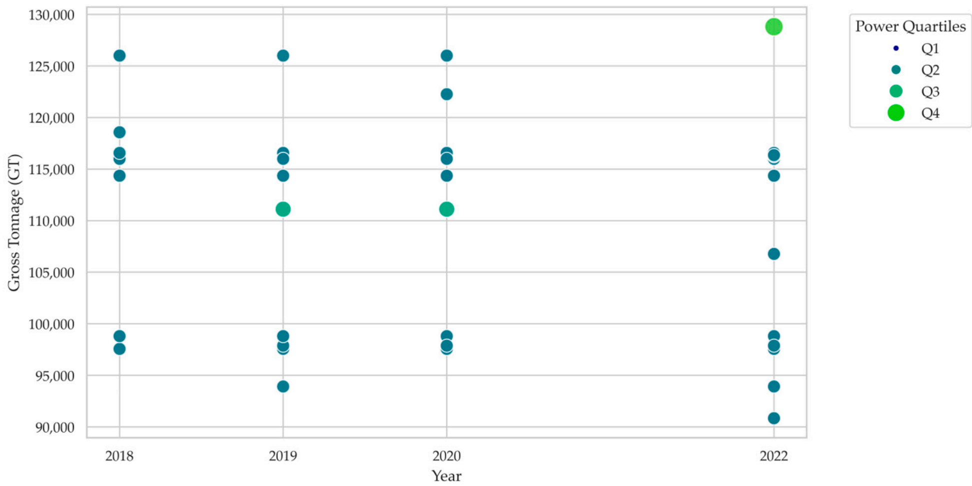

Figure 5. The dwt and power of ME in the NGT of the Port of Sines.

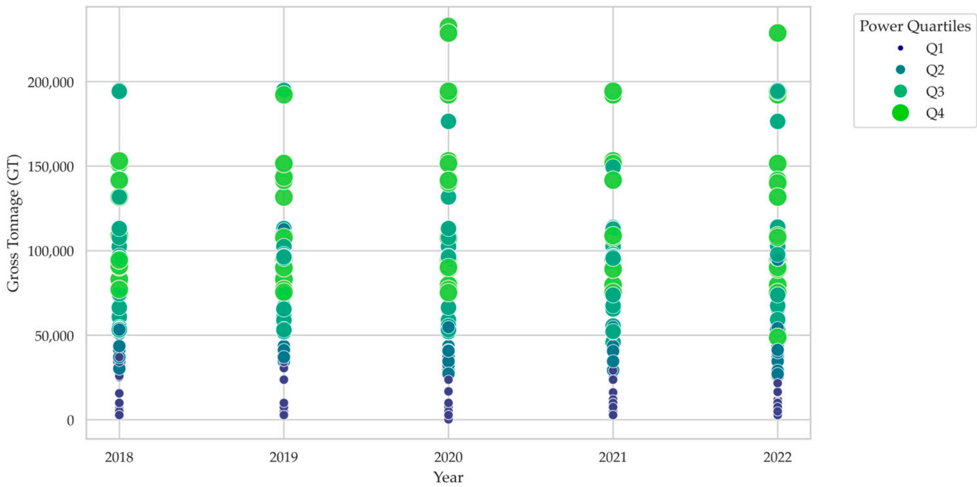

Figure 6. The dwt and power of ME in the SCT of the Port of Sines.

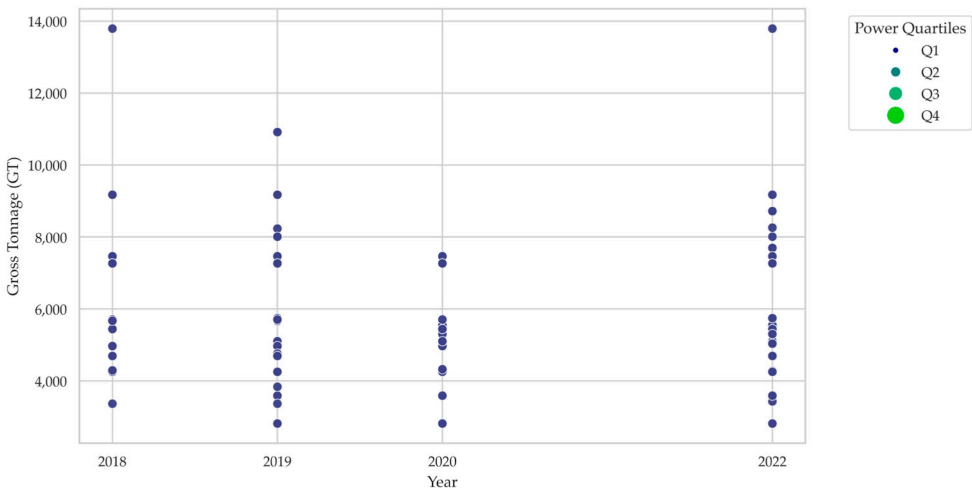

Figure 7. The dwt and power of ME in the PCT of the Port of Sines.

Tables 3 and 4 show the number of berths and time in the terminals for this period.

Table 3. Berths from different terminals of the Port of Sines.

Terminal	2018	2019	2020	2021	2022	Total
LBT	564	611	495	187	857	2714
NGT	23	29	20	--	55	127
SCT	649	672	791	540	644	3296
PCT	51	96	55	--	96	298
Total	1287	1408	1361	727	1652	6435

Table 4. Average time (hours) of berths from different terminals of the Port of Sines.

Terminal	2018	2019	2020	2021	2022	Average
LBT	16.03	17.54	16.25	10.27	19.06	15.83
NGT	23.52	23.28	23.61	--	22.33	23.19
SCT	16.37	14.80	15.34	19.04	23.36	17.78
PCT	26.15	23.66	24.62	--	24.27	24.68

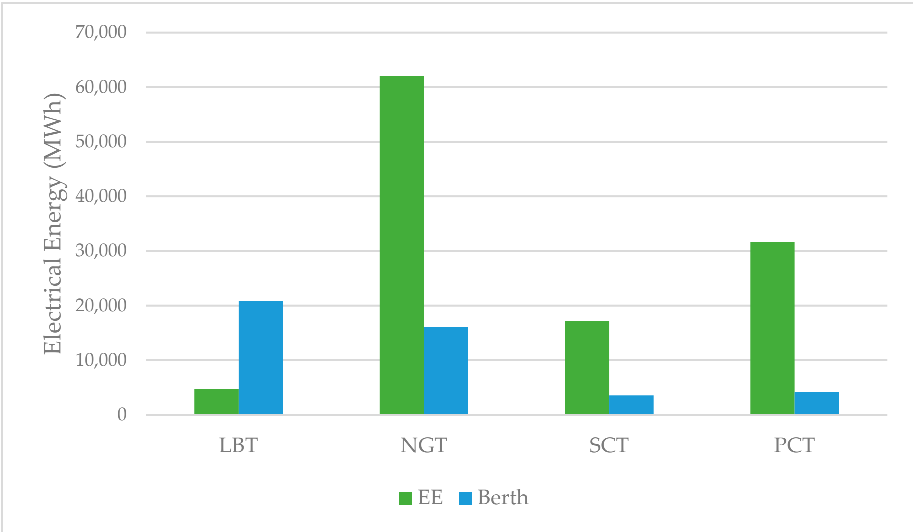

Figure 8. Electrical energy from different terminals of the Port of Sines.

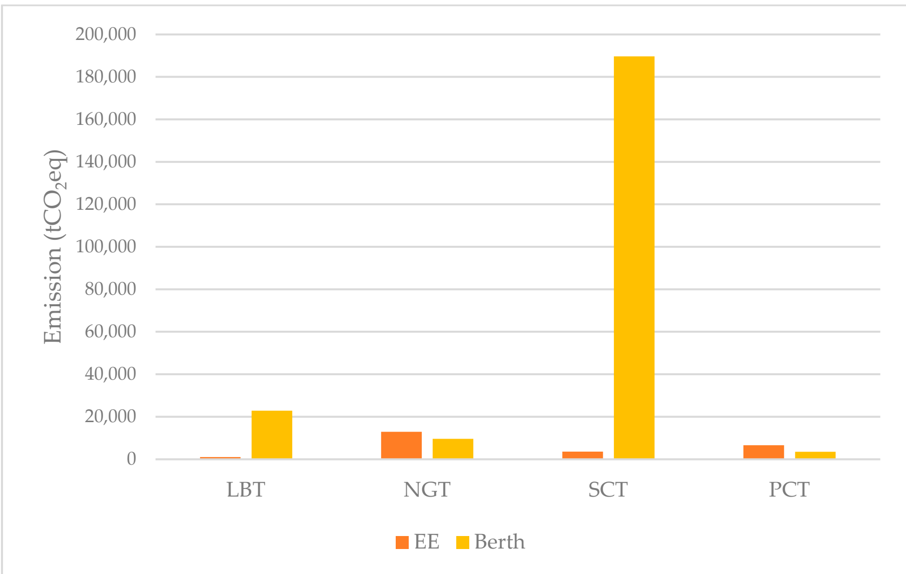

Figure 9. Emissions from different terminals of the Port of Sines.

Table 5. Average emission (kCO_2eq) of berths from different terminals of the Port of Sines.

Terminal	2018	2019	2020	2021	2022	Average
LBT	9.59	12.41	11.54	4.00	16.61	10.83
NGT	93.27	98.52	89.46	--	84.29	91.39
SCT	48.22	42.53	46.78	58.34	73.49	53.87
PCT	16.79	14.53	12.33	--	13.09	14.19

To change an AE from a combustion to an electric engine, a series of steps must be followed [78–80]. This increases its efficiency and reduces losses. However, this improvement was not considered in this work. Figures 10–14 show the emissions of terminals in two cases: with an AE (case 1) powered by fossil fuels or electrically with connection to the public grid (case 2) [32].

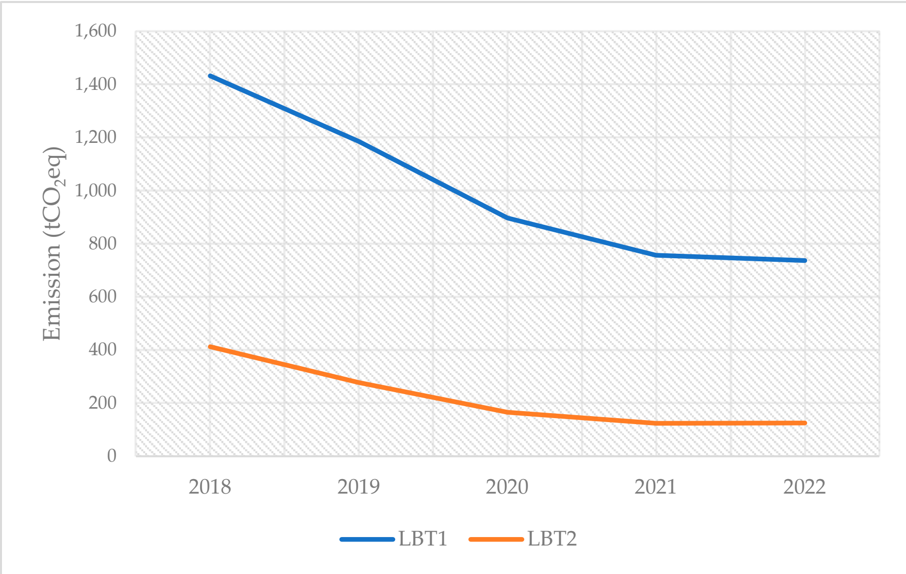

Figure 10. The LBT of the Port of Sines.

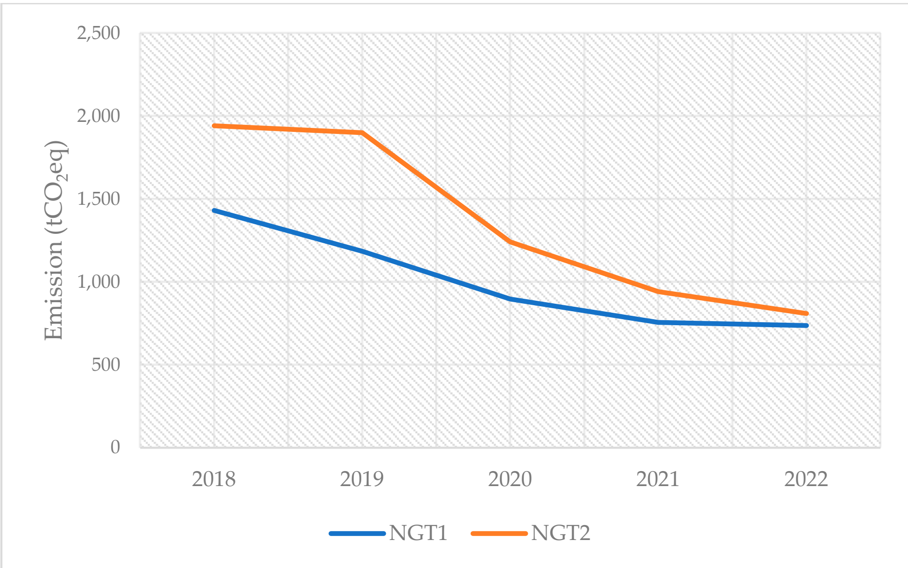

Figure 11. The NGT of the Port of Sines.

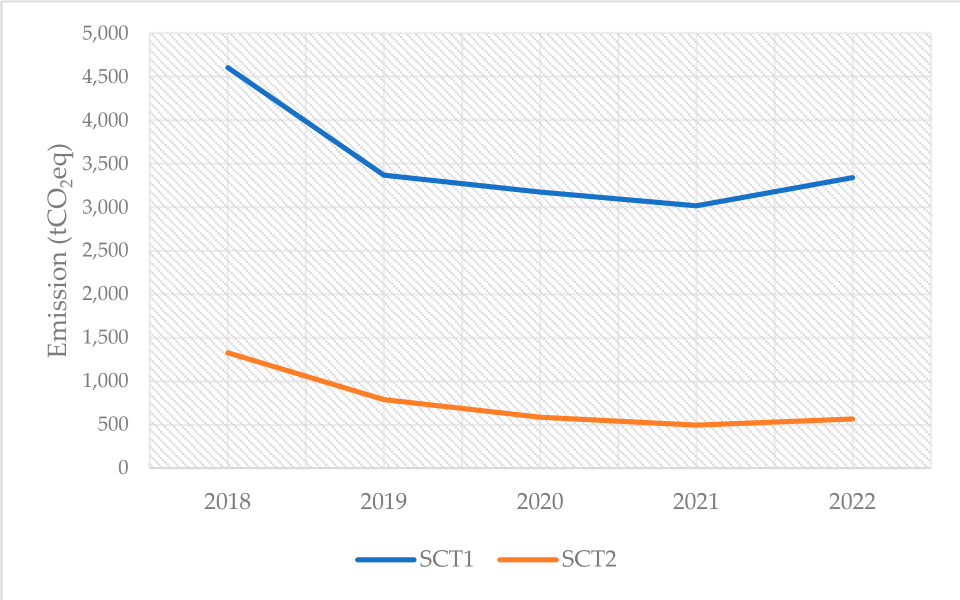

Figure 12. The SCT of the Port of Sines.

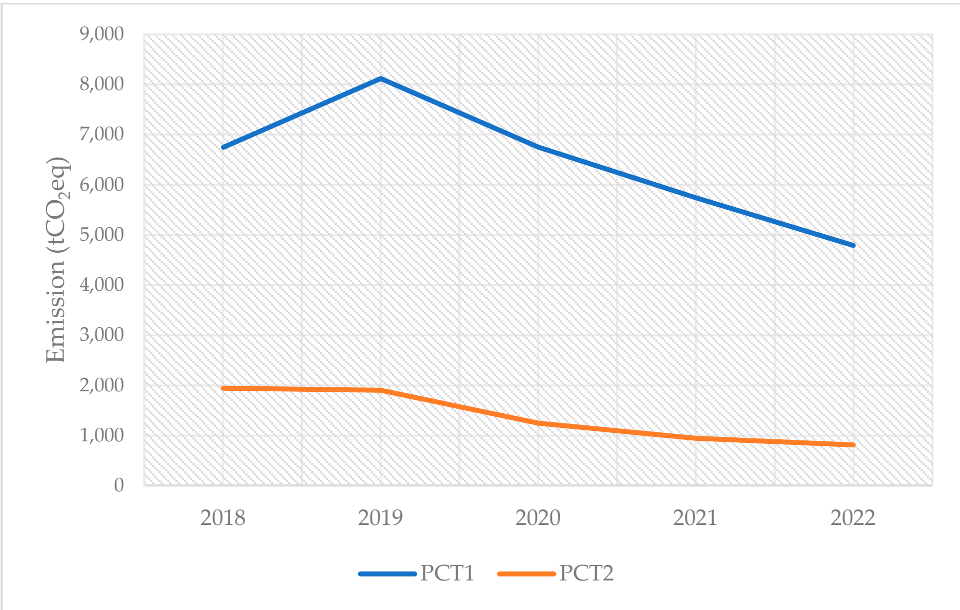

Figure 13. The PCT of the Port of Sines.

Figure 13 shows the reduction in emissions if the supply of electrical equipment is connected and, in addition, the SCT, since the latter has lower risks than those found to occur in the other three terminals, with a penetration of 10, 15, and 25% of RESs and an emission factor of 0 tCO_2eq for these types of energy [81].

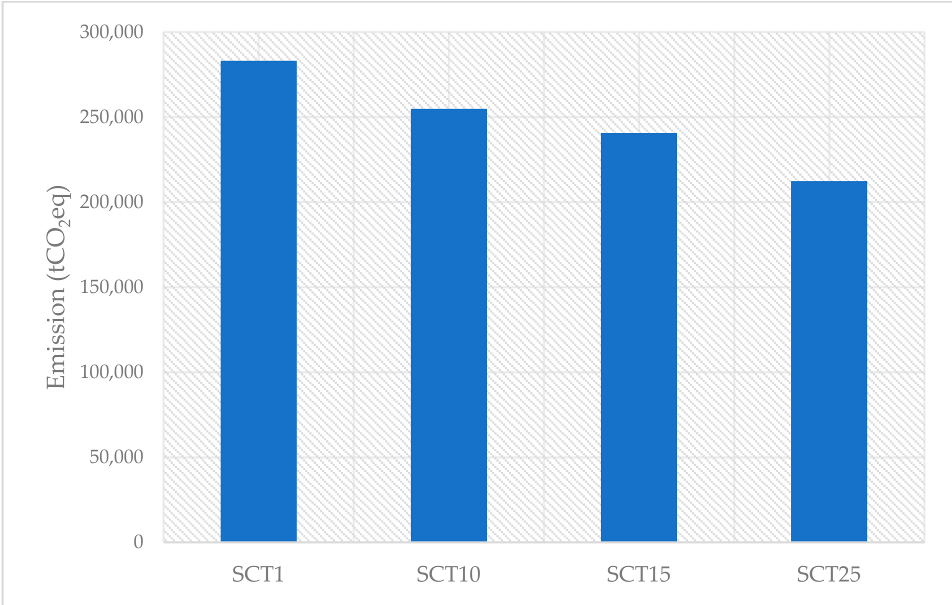

Figure 14. The SCT for different scenarios of the Port of Sines.

4. Conclusions

The implementation of onshore power supply (OPS) in multi-terminal seaports is a strategy for decarbonizing maritime transport and improving environmental quality in port areas. This study has shown that it offers environmental benefits despite the limits imposed by the presence of hazardous terminals.

OPS systems need to overcome several challenges. The integration of renewable energy in the supply and the adaptation of existing port infrastructure are critical aspects that demand attention. This work highlights the need to accelerate the implementation of OPS in multi-terminal ports. This is due to an increase in time and emissions due to the presence of ships with larger gross tonnage. Only through a concerted and coordinated effort can we fully reap the benefits of OPS systems and move toward a sustainable and environmentally friendly maritime future.

Given the critical nature of terminal operations, the application of renewable energy sources could be limited to powering ancillary equipment, such as ship loading and unloading systems, where intermittency and variability do not compromise safety. The integration of renewables into the main grid of these terminals may require advanced energy storage and management solutions, as well as reliable backup systems, to mitigate the risks associated with fluctuating renewable generation.

While the integration of renewable energies in the future would further optimize the benefits of OPS, connection to the public grid remains a valuable and affordable strategy. It allows ports and shipping lines to take a concrete step toward sustainability, demonstrating their commitment to reducing the carbon footprint of shipping. The widespread adoption of OPS, even in its most basic form, represents a crucial step toward a cleaner and more responsible maritime sector.

Author Contributions: Conceptualization, T.B., C.L.V. and J.C.H.; methodology, T.B. and C.L.V.; data curation, F.A.B.; writing—original draft preparation, C.L.V.; writing—review and editing, T.B., C.L.V., L.M., F.A.B. and J.C.H.; supervision, T.B.; project administration, T.B.; funding acquisition, T.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: Content produced within the scope of the Agenda "*NEXUS—Pacto de Innovação—Green and Digital Transition for Transport, Logistics and Mobility*", financed by the Portuguese Recovery and Resilience Plan (PRR), with no. C645112083-00000059 (investment project no. 53). The authors acknowledge the support provided by the Thematic Network 723RT0150 "*Red para la integración a gran escala de energías renovables en sistemas eléctricos (RIBIERSE-CYTED)*" financed by the call for Thematic Networks of the CYTED (Ibero-American Program of Science and Technology for Development) for 2022.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AE	Auxiliary engine
AJAPS	Port of Sines jurisdiction area
AMP	Alternative maritime power
APA	Portuguese Environment Agency
CI	Coil ironing
dwt	Dead weight tons
EEA	European Environment Agency
EE	Electrical energy
ESS	Energy storage system
GCT	General cargo terminal
GHG	Greenhouse gas
GT	Gross tonnage
HVSC	High-voltage shore connection
IMO	International Maritime Organization
JUL	Logistics Single Window
JUP	Single Port Window
LBT	Liquid bulk terminal
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
LVSC	Low-voltage shore connection
MARPOL	International Convention for the Prevention of Pollution from Ships
ME	Main engine
MEPC	Marine Environment Protection Committee
MSP	Maritime spatial planning
NGT	Natural gas terminal
OILPOL	Convention for the Prevention of Pollution of the Sea by Oil
OPS	Onshore power supply
PCT	Petrochemical terminal
PLF	Passenger locator form
PM	Particulate material
RESs	Renewable energy sources
RMGs	Rail-mounted gantries
RTGs	Rubber-tired gantries
ro_ro	Roll-on/roll-off
SCT	Container terminal
SP	Shore power
SSE	Shore-side electricity
SSP	Shore-to-ship power
TEU	Twenty-foot equivalent unit

THSs	Total hydrocarbons
TPs	Transformation points
VOCs	Volatile organic compounds

References

1. Archer, D.; Martin, P.; Buffett, B.; Brovkin, V.; Rahmstorf, S.; Ganapolski, A. The importance of ocean temperature to global biogeochemistry. *Earth Planet. Sci. Lett.* **2004**, *222*, 333–348. [CrossRef]
2. Ma, D.; Zhao, F.; Zhu, L.; Li, X.; Wei, J.; Chen, X.; Hou, L.; Li, E.; Liu, M. Deep learning reveals hotspots of global oceanic oxygen changes from 2003 to 2020. *Int. J. Appl. Earth Obs. Geoinf.* **2025**, *136*, 104363. [CrossRef]
3. Drufrénot, G.; Ginn, W.; Pourroy, M. Climate pattern effects on global economic conditions. *Econ. Model.* **2024**, *141*, 106920. [CrossRef]
4. Trueb, L.; Gacutan, J.; Phaphotjanaporn, T.; Alarcon, M.; Milligan, B. Identifying the institutional modalities for commencing Environmental-Economic Accounting for the ocean. *Mar. Policy* **2024**, *170*, 106410. [CrossRef]
5. Calado, H.; Cervera-Núnez, C.; Gutierrez, D.; Stojanovic, I. Forging ahead: Climate-smart maritime spatial planning for the future. *Mar. Policy* **2025**, *171*, 106503. [CrossRef]
6. Calado, H.; Santos, C.F.; Quintela, A.; Fonseca, C.; Gutierrez, D. The ups and downs of maritime spatial planning in Portugal. *Mar. Policy* **2023**, *154*, 105984. [CrossRef]
7. Cheng, J.; Choi, J.; Seo, Y. Environmental efficiency assessment of coastal ports in China: Implications for sustainable port management. *Mar. Pollut. Bull.* **2025**, *211*, 117436. [CrossRef]
8. UNCTAD. UN Trade&Devolopment. Available online: https://unctad.org/topic/transport-and-trade-logistics/review-of-maritime-transport (accessed on 9 December 2024).
9. STATISTA. Statista. 2024. Available online: https://www.statista.com/topics/1728/ocean-shipping/#topicOverview (accessed on 9 December 2024).
10. UN Trade&Devolopment, Maritime Transport. Data Insights. 2024. Available online: https://unctadstat.unctad.org/insights/theme/45 (accessed on 9 December 2024).
11. UN. Climate Action. 2015. Available online: https://www.un.org/en/climatechange/paris-agreement (accessed on 9 December 2024).
12. EUR-Lex. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions REPowerEU Plan. Document 52022DC0230. 2022. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2022:230:FIN (accessed on 16 December 2024).
13. Igliński, B.; Pietrzak, M. Renewable and Sustainable Energy—Current State and Prospects. *Energies* **2025**, *18*, 797. [CrossRef]
14. EUR-Lex. 'Fit for 55': Delivering the EU's 2030 Climate Target on the Way to Climate Neutrality. 2021. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0550 (accessed on 16 December 2024).
15. UN. International Convention (with Annexes) for the Prevention of Pollution of the Sea by Oil 1954 No. 4714. Available online: https://treaties.un.org/doc/Publication/UNTS/Volume%20600/volume-600-I-4714-English.pdf (accessed on 16 December 2024).
16. IMO. Final Act the International Conference on Marine Pollution. 1973. Available online: https://www.imo.org/en/KnowledgeCentre/ConferencesMeetings/Pages/MP_CONF_1973-Default.aspx (accessed on 17 December 2024).
17. IMO/MEPC. Resolution MEPC.304(72). Initial IMO Strategy on Reduction of GHG Emissions from Ships. 2018. Available online: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.304(72).pdf (accessed on 17 December 2024).
18. IMO/MEPC. Resolution MEPC.377(80). *2023 IMO Strategy on Reduction of GHG Emissions from Ships*. 2023. Available online: https://wwwcdn.imo.org/localresources/en/MediaCentre/PressBriefings/Documents/Resolution%20MEPC.377(80).pdf (accessed on 17 December 2024).
19. Kizielewicz, J. Onshore power supply–trends in research studies. *Front. Energy Res.* **2024**, *12*, 1383142. [CrossRef]
20. Su, P.; Hao, Y.; Qian, Z.; Zhang, W.; Chen, J.; Zhang, F.; Yin, F.; Feng, F.; Chen, D.; Li, Y. Emissions of intermediate volatility organic compound from waste cooking oil biodiesel and marine gas oil on a ship auxiliary engine. *J. Environ. Sci.* **2020**, *91*, 262–270. [CrossRef]
21. Zhou, S.; Sun, A.; Lou, C.; Zhou, P.; Xi, H.; Shreka, M.; Wang, H.; Zhu, Y.; Feng, Y. Gaseous and particulate pollutant emissions from ocean-going tankers in the context of carbon reduction: Main engine, auxiliary engine, and auxiliary boiler. *Energy* **2024**, *313*, 133831. [CrossRef]
22. *ISO 8217:2024*; Products from Petroleum, Synthetic and Renewable Sources—Fuels (Class F)—Specifications of Marine Fuels. ISO: Geneva, Switzerland, 2024. Available online: https://www.iso.org/standard/80579.html (accessed on 18 December 2024).

23. Gao, X.; Yu, Q.; Dai, W.; Chen, Q. Examining the influence of port ship activities on pollutant emissions in port environments. *Heliyon* **2025**, *11*, e41208. Available online: https://www.cell.com/heliyon/fulltext/S2405-8440(24)17239-8?uuid=uuid:7c4d4b3e-e3a0-4441-8245-cb6d91da76ea (accessed on 18 December 2024). [CrossRef] [PubMed]
24. Nunes, R.; Alvim-Ferraz, M.; Martins, F.; Sousa, S. Local mortality and costs from ship-related emissions in three major Portugueses ports. *Urban Clim.* **2024**, *53*, 101780. [CrossRef]
25. Manqele, N.; Moolha, R.; Frost, L. The health and economic impacts of exposure to marine mobile emissions from ships in Durban port, South Africa. *Atmos. Environ. X* **2024**, *23*, 100277. [CrossRef]
26. Boikos, C.; Rapkos, N.; Ioannidis, G.; Oppo, S.; Armengaud, A.; Siamidis, P.; Tsegas, G.; Ntziachristos, L. Factors affecting pedestrian-level ship pollution in port areas: CFD in the service of policy-making. *Build. Environ.* **2024**, *258*, 111594. [CrossRef]
27. Nguyen, P.; Woo, S.; Kim, H. Ship emissions in hotelling phase and loading/unloading in Southeast Asia ports. *Transp. Res. Part D Transp. Environ.* **2022**, *105*, 103223. [CrossRef]
28. Yu, D.; Li, D.; Sha, M.; Zhang, D. Production, Manufacturing, Transportation and Logistics Carbon-efficient deployment of electric rubber-tyred gantry cranes in container terminals with workload uncertainty. *Eur. J. Oper. Res.* **2019**, *275*, 552–569. [CrossRef]
29. Wang, J.; Li, H.; Yang, H.; Ge, Y. Shore power for reduction of shipping emission in port: A bibliometric analysis. *Transp. Res. Part E Logist. Transp. Rev.* **2024**, *188*, 103639. [CrossRef]
30. Tan, Z.; Sheng, D.; Yin, Y. Shore-power capacity allocation in a container shipping network under ships' strategic behaviors. *Transp. Res. Part B Methodol.* **2025**, *192*, 103151. [CrossRef]
31. Ling-Chin, J.; Roskilly, A. Investigating the implications of a new-build hybrid power system for Roll-on/Roll-off cargo ships from a sustainability perspective—A life cycle assessment case study. *Appl. Energy* **2016**, *181*, 416–434. [CrossRef]
32. Abu, N.; Bazmohammadi, N.; Vasquez, J. Electrification of onshore power systems in maritime transportation towards decarbonization of ports: A review of the cold ironing technology. *Renew. Sustain. Energy Rev.* **2023**, *178*, 113243. [CrossRef]
33. Wang, Q. Charting a greener course: China's recent legal strategies in shore power promotion for achieving maritime emission targets. *Mar. Policy* **2024**, *170*, 106386. [CrossRef]
34. Sheng, J.; Tang, L.; Yang, Z.; Yu, M.; Liu, X. Strategies of stakeholders' selection of shore-to-ship power in China. *Transp. Res. Part D Transp. Environ.* **2023**, *119*, 103729. [CrossRef]
35. Yue, M.; Wang, Y.; Guo, S.; Dai, L.; Hu, H. A multi-objective optimization study of berth scheduling considering shore side electricity supply. *Ocean Coast. Manag.* **2025**, *261*, 107500. [CrossRef]
36. Prenc, R.; Vucetic, D.; Cuculic, A. High Voltage Shore Connection in Croatia: Network configurations and formation of the connection point to the Utility power grid. *Electr. Power Syst. Res.* **2018**, *157*, 106–117. [CrossRef]
37. Wang, W.; Liu, K.; Peng, Y.; Yu, Q.; Guo, J.; Yu, T. Investigating relationships between shore power utilization and characteristics of ships and berths. *Transp. Res. Part D* **2024**, *136*, 104446. [CrossRef]
38. Herrero, A.; Ortega, A.; Díaz-Ruíz-Navamuel, E.; Gutierrez, M.; López-Diaz, A. Influence of the Implantation of the Onshore Power Supply (OPS) System in Spanish Medium-Sized Ports on the Reduction in CO_2 Emissions: The Case of the Port of Santander (Spain). *J. Mar. Sci. Eng.* **2022**, *10*, 1446. [CrossRef]
39. Kim, A.; Seo, J.; Seo, Y. Key barriers to adopting onshore power supply to reduce port air pollution: Policy implications for the maritime industry in South Korea. *Mar. Policy* **2023**, *157*, 105866. [CrossRef]
40. Mahdi, H.; Hoff, B.; Ostrem, T. A Review of Power Converters for Ships Electrification. *IEEE Trans. Power Electron.* **2023**, *38*, 4680–4697. [CrossRef]
41. *IEC/IEEE International Standard 80005-1-2019*; Utility Connections in Port—Part 1: High Voltage Shore Connection (HVSC) Systems—General Requirements. IEC/IEEE: Piscataway, NJ, USA, 2019. Available online: https://ieeexplore.ieee.org/document/8666180 (accessed on 6 January 2025).
42. Zhu, X.; Wang, K.; Yang, J.; Huang, L.; Shen, B.; Sun, M. Research on the control strategy of grid connection between shore power supply and ship power grid. *Energy Rep.* **2022**, *8*, 638–647. [CrossRef]
43. Xiang, Z.; Xin, X.; Zhang, T.; Chen, K.; Liu, M. Asia-Europe liner shipping network design model considering Arctic route and black carbon tax. *Ocean Coast. Manag.* **2025**, *261*, 107492. [CrossRef]
44. Gutierrez-Romero, J.; Esteves-Pérez, J.; Zamora, B. Implementing Onshore Power Supply from renewable energy sources for requirements of ships at berth. *Appl. Energy* **2019**, *255*, 113883. [CrossRef]
45. Pivetta, D.; Armi, C.; Sandrin, P.; Bogar, M.; Taccani, R. The role of hydrogen as enabler of industrial port area decarbonization. *Renew. Sustain. Energy Rev.* **2024**, *189*, 113912. [CrossRef]
46. Zhang, Y.; Liang, C.; Shi, J.; Lim, G.; Wu, Y. Optimal Port Microgrid Scheduling Incorporating Onshore Power Supply and Berth Allocation Under Uncertainty. *Appl. Energy* **2022**, *313*, 118856. [CrossRef]
47. Albo-Lopez, A.; Carrillo, C.; Díaz-Dorado, E. Contribution of Onshore Power Supply (OPS) and Batteries in Reducing Emissions from Ro-Ro Ships in Ports. *J. Mar. Sci. Eng.* **2024**, *12*, 1833. [CrossRef]
48. Amaral, M.; Amanor, N.; Arsénio, P. Methodology for Assessing Power Needs for Onshore Power Supply in Maritime Ports. *Sustainability* **2023**, *15*, 16670. [CrossRef]

49. Manuel-López, F.; Diáz-Gutierrez, D.; Camero-Orive, A.; Parra-Santiago, J. Iberian Ports as a Funnel for Regulations on the Decarbonization of Maritime Transport. *Sustainability* **2024**, *6*, 862. [CrossRef]
50. Chen, J.; Zheng, T.; Garg, A.; Xu, L.; Li, S.; Fei, Y. Alternative Maritime Power application as a green port strategy: Barriers in China. *J. Clean. Prod.* **2019**, *213*, 825–837. [CrossRef]
51. Yin, M.; Wang, Y.; Zhang, Q. Policy Implementation Barriers and Economic Analysis of Shore Power Promotion in China. *Transp. Res. Part D Transp. Environ.* **2020**, *87*, 102506. [CrossRef]
52. Wang, N.; Mu, W.; Ma, R. A Systematic understanding of the risk development process for port authority. *Mar. Policy* **2024**, *167*, 106243. [CrossRef]
53. Costa, P.; Agreira, C.F.; Pestana, R.; Cao, Y. European Ports Transition—A new Approached of a8 Load Model, Consumption Integration of Renewable Energy Sources and Energy Storage Systems Profiles. In Proceedings of the IEEE Conference on Vehicle Power and Propulsion (VPPC) 2024, Washington, DC, USA, 7–10 October 2024. [CrossRef]
54. Uzun, D.; Okumus, D.; Canbulat, O.; Gunbeyaz, S.; Karamperidis, S.; Hudson, D.; Turan, O.; Allan, R. Port energy demand model for implementing onshore power supply and alternative fuels. *Transp. Res. Part D Transp. Environ.* **2024**, *136*, 104432. [CrossRef]
55. Khan, R.; Yin, J.; Mustafa, F.; Shi, E. Factor assessment of hazardous cargo ship berthing accidents using and ordered logit regression model. *Ocean Eng.* **2023**, *284*, 115211. [CrossRef]
56. Lecue, M.; Darbra, R. Accidents in European ports involving chemical substances: Characteristics and trends. *Saf. Sci.* **2019**, *115*, 278–284. [CrossRef]
57. Ronza, A.; Carol, S.; Espejo, V.; Vilchez, J.; Arnaldos, J. A quantitative risk analysis approach to port hydrocarbon logistics. *J. Hazard. Mater.* **2006**, *128*, 10–24. [CrossRef]
58. Lalla-Ruiz, E.; López-Plata, I.; Expósito-Izquierdo, C.; Barrios-Fleitas, Y.; González-Ramírez, R. Greening container terminals through optimization: Through optimization: A systematic review on recent advances. *Curr. Opin. Environ. Sustain.* **2024**, *71*, 101490. [CrossRef]
59. Styhre, L.; Winnes, H.; Black, J.; Lee, J.; Le-Griffin, H. Greenhouse gas emissions from ships in ports—Case studies in four continents. *Transp. Res. Part D* **2017**, *54*, 212–224. [CrossRef]
60. Romero-Faz, D.; Camarero-Orive, A. Risk assessment of critical infrastructures—News parameters for commercial ports. *Int. J. Crit. Infraestruct. Prot.* **2017**, *18*, 50–57. [CrossRef]
61. Rao, P.; Raghavan, K. Hazard and risk potential of chemical handling at ports. *J. Loss Prev. Process Ind.* **1996**, *9*, 199–204. [CrossRef]
62. Steen, M.; Ystmark, K.; Hansen, L.; Seter, H. Implementing decarbonisation measures in Norwegian ports. *Transp. Res. Interdiscip. Perspect.* **2024**, *23*, 100993. [CrossRef]
63. Hoang, A.; Foley, A.; Nizetik, S.; Huang, Z.; Ong, H.; Olcer, A.; Pham, V.; Nguyen, X. Energy-related approach for reduction of CO_2 emissions: A critical strategy on the port-to-ship pathway. *J. Clean. Prod.* **2022**, *355*, 131772. [CrossRef]
64. Christiansen, M.; Fagerholt, K.; Pisinger, D. Fifty years on maritime transportation. *EURO J. Transp. Logist.* **2025**, *14*, 100148. [CrossRef]
65. APA. Fator de Emissão de Gases de Efeito de Estufa para a Eletricidade Produzida em Portugal. Available online: https://apambiente.pt/clima/fator-de-emissao-de-gases-de-efeito-de-estufa-para-eletricidade-produzida-em-portugal (accessed on 7 January 2025).
66. Lopes, D.; Graca, D.; Rafael, S.; Rosa, M.; Relvas, H.; Ferreira, J.; Reis, J.; Lopes, M. An exploratory approach to estimate point emission sources. *Atmos. Environ.* **2023**, *312*, 120026. [CrossRef]
67. Chen, J.; Chen, H.; Shi, J.; Shi, M.; Xu, J.; Jiang, H.; Xiang, J.; Liu, X.; Chen, H. AIS data-driven assessment of shore side electricity's emission reduction potential in China. *Transp. Policy* **2025**, *167*, 130–144. [CrossRef]
68. PGDLISBOA.PT. Ministério Público de Portugal. 2019. Available online: https://www.pgdlisboa.pt/leis/lei_mostra_articulado.php?nid=3188&tabela=leis&ficha=1&pagina=1&so_miolo (accessed on 8 January 2025).
69. Santos, S.; Lima, L.; Castelo, M. Corporate sustainability of Portuguese seaports. *J. Clean. Prod.* **2022**, *380*, 136057. [CrossRef]
70. Gil, R.; Borges, R.; Maritna, A.; Macebo, B.; Teixeira, L. A Simulation Tool to Forecast the Behaviour of a New Smart Pre-Gate at the Sines Container Terminal. *Sustainability* **2025**, *17*, 163. [CrossRef]
71. EEA. EEA Report No 13/2019. *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019. Technical Guidance to Prepare National Emission Inventories.* Available online: https://www.eea.europa.eu/en/analysis/publications/emep-eea-guidebook-2019 (accessed on 16 January 2025).
72. EEA. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023. Available online: https://www.eea.europa.eu/en/analysis/publications/emep-eea-guidebook-2023 (accessed on 16 January 2025).
73. EEA. European Maritime Transport Environmental Report. 2021. Available online: https://www.eea.europa.eu/en/analysis/publications/maritime-transport#:~:text=This%20report%20provides%20a%20factual%20analysis%20of%20the,to%20reduce%20the%20sector's%20impact%20on%20our%20environment (accessed on 16 January 2025).
74. Run, S.; Abouarghoub, W.; Demir, E. Enhancing data quality in maritime transportation: Apractical method for imputing missing ship static data. *Ocean Eng.* **2025**, *315*, 119722. [CrossRef]

75. Abramowski, T.; Cepowski, T.; Zvolenský, P. Determination of regression formulas for key design characteristics of container ships at preliminary design stage. *New Trends Prod. Eng.* **2018**, *1*, 247–257. [CrossRef]
76. Cepowski, T. Regression Formulas for the Estimation of Engine Total Power for Tankers, Container Ships and Bulk Carriers on the Basis of Cargo Capacity and Design Speed. *Pol. Marit. Res.* **2019**, *26*, 82–94. [CrossRef]
77. Batista, T.; Vásquez, C.; Ramírez-Pisco, R.; Marinho, L.; Borges, F.; Araujo, J. Energy Consumption and Carbon Footprint of the Port of Sines: Contribution to Maritime Transport Sustainability. *Sustainability* **2025**, *17*, 3382. [CrossRef]
78. Baldi, F.; Larsen, U.; Gabreilii, C.; Andersson, K. Analysis of the influence of the engine, propeller and auxiliary generation interaction on the energy efficiency of controllable pitch propeller ships. In Proceedings of the International Conference of Maritime Technology, Glasgow, UK, 7–9 July 2014. Available online: https://core.ac.uk/download/pdf/70610846.pdf (accessed on 18 January 2025).
79. Pamik, M.; Nuran, M. Increasing ship energy efficiency and emission reduction with diesel electric propulsion system. *World J. Environ. Res.* **2020**, *10*, 50–60. [CrossRef]
80. Kolios, A. Retrofitting Technologies for Eco-Friendly Ship Structures: A Risk Analysis Perspective. *J. Mar. Sci. Eng.* **2024**, *12*, 679. [CrossRef]
81. Lozano, J.; Pérez-Baez, S.; Leon-Zerpa, F.; Mendieta-Pino, C.A. Alternatives for the Optimization and Reduction in the Carbon Footprint in Island Electricity Systems (IESs). *Sustainability* **2024**, *16*, 1214. [CrossRef]