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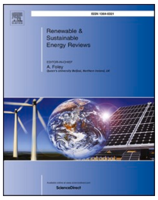

Electrification of onshore power systems in maritime transportation towards decarbonization of ports: A review of the cold ironing technology

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ABSTRACT

Cold ironing is a remarkable electrification innovation in the maritime industry for ship transportation, in which diesel engines driving ship generators for onboard load are switched to shore-supplied electricity during berthing. This facility serves not only as an alternative power supply for electric ships but also as part of the green port's strategy. Cold ironing installation is expected to be unavoidable in the long term for all port operators due to stringent emission policies. Even though cold ironing is used by a few ports across the world, it is still regarded as an underutilized technology due to the high upfront cost associated with the shoreside installation and ship's retrofitting, as well as unclear benefits for both sides. The involvement of diverse types of ships with different power requirements, various operational schemes, unpredictable berthing hours, uncertainty in the availability of local power sources, and synchronization issues among others make it very complex to coordinate for optimal cold ironing operations, which necessitate further investigations. This review gives an overview of cold ironing technology, including its operation, power requirement, standardization, challenges, and important assessment for evaluation. A cold ironing implementation strategy to achieve the ultimate seaport decarbonization goal through a synergy between cold ironing and seaport microgrid is also addressed.

1. Introduction

The rising shipping transportation caused by the global demand for trading activities implies higher emissions to the environment. Statistics of the seaborne trade from 1990 to 2020 show a drastically increasing trend, almost triple the volume of goods loaded in the port worldwide compare to 1990 [1]. Electrification of ships has been viewed as a prominent alternative for eliminating hazardous emissions. Thereby, a revolution in electric ships can be seen in diesel-electric, hybrid, and full-electric battery-driven propulsion systems. In a hybrid ship, the onboard battery for electric propulsion is recharged by diesel generators during the voyage across the sea. The Yara Birkeland, the first autonomous and all-electric drive container ship, is a pioneering project that eliminates crew on board and engage in zero-emission practice [2]. It was powered by a 6.7 MWh lithium-ion battery charged with green hydroelectric power and expected to replace roughly 40,000 diesel truck trips each year, reducing NO_x and CO_2 emissions [3]. The only real concern is the charging infrastructure is not even close to being ready. This cargo ship is indeed a very promising way of eliminating pollution, but the gigantic batteries of the ship are estimated to take a long charging time which requires fast charging technology. In this sense, the current research trend on battery swap technology (BST) [4] might be a potential solution for resolving this issue. However, further research for the ship application needs to be pursued as it is now only commercially used by electric vehicles, electric scooters, and electric bikes [5,6].

The electricity utilization on the shoreside is also an alternative to recharge the battery where the system is called as cold ironing (CI). The advantage offered by CI facilities is the ship's batteries can be recharged while running loading and unloading activities that generally last from a few hours to several days, thus long charging time is not an issue. In general, the ship that stops alongside the quay will switch off the main propulsion engines, however, some onboard applications require full functionality while in the port, necessitating the use of auxiliary engines for energy supply during idle mode. As a result, greenhouse emissions from auxiliary fuel generation are released into the atmosphere

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Nomenclature

Abbreviations

AES	All-electric ships
CI	Cold ironing
CMS	Cable management system
CO_2	Carbon dioxide
CHP	Combined heat and power
CSI	Clean shipping index
ESS	Energy storage systems
ESI	Environmental ship index
GHG	Greenhouse gas
HFO	Heavy fuel oil
HVSC	High voltage supply connection
LVSC	Low voltage supply connection
MGO	Marine gas oil
MG	Microgrid
NO_x	Nitrogen oxides
O&M	Operations and maintenance
OPS	Onshore power supply
PV	Photovoltaics
PEC	Power electronic converter
PM	Particulate matter
PBP	Payback period
RES	Renewable energy sources
SO_2	Sulfur dioxide
SSP	Shore-side power
TOU	Time-of-use
WT	Wind turbine

Indexes

j	Type of the cost
i	Type of the ship

Variables

C^A_{port}	Annual cost for CI establishment ($/year)
$C^A_{port,ins}$	Annual installation cost of the CI facilities ($/year)
$C^A_{port,O\&M}$	Annual operation and maintenance cost of the CI ($/year)
$C^A_{port,energy}$	Annual cost of the electricity purchased from the local grid to supply CI station ($/year)
$C^A_{port,ben}$	Annual benefit from CI installation ($/year)
C_{ii}	Initial investment ($)
C_{acf}	Annual cash flow ($/year)
C^A_{LSFO}	Annual cost of the ship without using CI ($/year)
C^A_{CI}	Annual cost of the ship using CI services ($/year)
C^A_a	Annual retrofitting cost for CI ($/year)
C^A_b	Annual operation and maintenance cost ($/year)
C^A_c	Annual electricity cost when visiting a port with CI ($/year)
C^A_d	Annual fuel cost when visiting a port without CI ($/year)
C^A_j	Annual cost of the ship for all type of cost j ($/year)
EC^{diesel}_n	Emission coefficient of particle n for diesel oil, (kg/kg)
EC^{grid}_n	Emission coefficient of particle n for the grid, (kg/kWh)
FC^{berth}_i	Diesel fuel consumption of ship i during berthing (kg)
P^{aux}_i	Auxiliary engines power of ship i, (kW)
PC^{berth}_i	Power consumption of ship i during berthing (kWh)
PP	Payback period (year)
$SFOC^{aux}_i$	Auxiliary specific fuel oil consumption of ship i, (kg/kWh)
$SE^A_{benefit}$	Socio-economic benefit ($/year)
$TE_{\varepsilon 1}$	Total emissions by using diesel auxiliary engines (kg)
$TE_{\varepsilon 2}$	Total emissions by using shore power from CI (kg)
t^{berth}_i	Average berthing duration of ship i, hours (h)
σ	Percentage of the visiting ships that use CI during berthing mode of operation (%)
ρ	Total number of visiting ships to the port in a year
γ_A	Electricity price of the shore power sold to the ship ($/kWh)
γ_B	Price of the purchased electricity by port from the local grid ($/kWh)
γ_C	Fuel price ($/kg)
ω	The health-cost externality of air pollution ($/kg)
l^A_i	Auxiliary load factor of the ship i during berthing mode of operation
α	Number of visiting ports in a year
δ	Percentage of visiting ports with CI

throughout berthing hours. The cabin crew and the local people within a close vicinity also suffer from noise and vibration pollution. Thus, CI facilities allow ships to plug into the shoreside electricity sources and turn off their auxiliary engines during berthing activity. The ship's power demand is then seamlessly shifted to the CI electricity power supply and suppressing the emission from the auxiliary engines. The CI's benefits entail not only the creation of cleaner ports, but also the introduction of innovative solutions that apply to all ships, encouraging the maritime sector's electrification advancement. Therefore, CI becomes an electrification game-changer in the maritime industry replacing fossil fuel-powered generators with technologies that use electricity as a source of energy. CI also well-known by other terms such as alternative maritime power (AMP), onshore power supply (OPS), shore-side electricity (SSE), shore-to-ship power (S2SP), and shore-side power (SSP) [7–11].

The purpose of the CI is not only to serve the electric ship but taking an important step toward zero carbon footprint in line with the global green port vision. Additionally, the pressure from regulatory policy regarding sulfur control from time to time emphasizes the importance of CI implementation. International Maritime Organization (IMO) in its most recent regulation restricted the sulfur substance in fuel to 0.1% reduced from 4.5% in 2000 [12]. Unfortunately, the desulfurization process entails high expenditures and is not still cost-effective [13]. Thus, it is not far from the expectation that CI may soon become mandatory at ports.

Existing CI installations in several ports such as the Port of Gothenburg, Port of Los Angeles, and Port of Stockholm give a perceptiveness into the CI market suitability [14]. Other CI stations in Europe with their detailed information can be found in the European alternative fuels observatory (EAFO) database [15]. Thalis Zis [16] has also made a compilation of existing and ongoing plans for CI facilities around the world. However, compared with the total number of ports globally, the existing installation of CI is considered underrated, primarily due to the high shore investment cost for port operators, and the huge retrofitting cost for ship owners. To justify CI deployment, apart from financial incentive support and regulation control, there are a lot of aspects that need further analysis to achieve benefits from CI. In early 2022, the Department of Transport UK issued a call for evidence on CI implementation with plenty of queries and concerns to address many unclear aspects, integration of relevant scattered information, and seek potential solutions to the arising issues [17]. Accordingly, a comprehensive and authentic overview of the enormous research on this topic, including past and ongoing activities are required.

In this regard, this review provides an overview of the CI integration in the seaport application, its operational, conceptualization, and standardization aspects. Besides, CI's influential factors, its current challenges, and fundamental assessment will be discussed. The contribution of this review is as follows.

1) First, this work gives a comprehensive review of the significant aspects of the CI technology discussed in both previous and current relevant academic studies (thesis and publications), technical reports, and government studies of the real cases. The purpose is to bridge the gaps between the previous concept, existing practices, and real concerns of the maritime industries by gathering information in one place. This review also identifies the main barrier that hinders the large-scale establishment of CI technology and provides opportunities that may inspire involved authorities for finding new solutions.
2) Second, this review discusses two key assessments in CI studies, namely economical and emissions aspects from the perspective of ports' operators and shipping lines that act as the main stakeholders in the CI establishment. The fundamental models are developed roughly to investigate the essential parameters and their impacts on the cost and emission analysis. The evaluation is to motivate stakeholders in the maritime industry to identify the shortfall and pursue an improved framework.
3) Third, further study of the two maritime electrification techniques, CI and microgrid, provides insights into how electrification combinations can boost the maritime industry to achieve emission neutrality. It emphasizes the maritime role in responding to the international treaty climate change of the Paris Agreement by 2050, as well as the port's detrimental influence on the environment and public health.

The rest of this research is structured as follows. Section 2 is dedicated to presenting the general aspects related to the CI covering the typical configuration, demand from the onboard ship, standardization for quality control, available incentives for CI implementation, and challenges. In Section 3, key assessment is presented in terms of emission and economical aspects. Meanwhile, the evolution of the CI towards microgrid integration is highlighted in Section 4. Finally, the important findings are summarized in Section 5.

2. Cold ironing system overview

2.1. Typical structure, components, and topology

The operational principle of CI can be viewed as the process of transferring power supply from the ship's auxiliary engines to the local grid power at the shoreside via cable connection. This process is to serve the onboard load that need an energy while docked at the port. It receives power supply from the onshore utility grid and transmits it to voltages and frequencies that are matched with berthed ships. CI can be splits into three mains segment including the shore-side power supply, connection system (cables), and the shipside receiving electricity. The main idea is to curtail the emission that is released by the auxiliary engines during the berthing period as well as tackle noise and vibration problems. Low voltage supply connection (LVSC) and high voltage supply connection (HVSC) are the two main connections for the CI system on the shoreside. The difference between LVSC and HVSC lies in the cable requirements and supply capacity limitations. The first generation of CI systems operates on LVSC (typically 380–690 V), which requires many connection cables. For instance, the early LVSC installation in the Port of Stockholm consists of 9 connected cables in parallel to supply power up to 2500 kVA with 400 V at 50 Hz and 12 cables in another terminal to supply electricity at 690 V [14]. Recently, HVSC (typically 6.6–11 kV) become a favorable choice as it is easy to handle with only 1 or 2 high-voltage cables. In addition, HVSC has the flexibility to provide electricity to different ships with different voltage levels including low-voltage ships. However, an onboard transformer is needed to meet with the voltage level on the ship side. Besides, due to the high-voltage level, the cable weight is heavy, which necessitates the use of a cable management system (CMS), such as a crane. Alternative CMS technologies with standard specifications for connecting shore and ship can be found in Ref. [18]. Apart from facilitating easy handling of cables, CMS must ensure the adequacy of cable length, while the cable tension is also checked periodically. Fig. 1 shows the typical structure and the main components of CI. The function of the transformer is to step down the high voltage from the utility grid while the frequency converter is used to match the frequency to the required frequency by the ship, either 60 Hz or 50 Hz [19].

Previous studies in Refs. [20–24] categorize CI topologies into three clusters including centralized AC, distributed AC, and distributed DC. Rene Prenc et al. [25] examine all topologies in HVSC shore power supply and discuss the benefits and drawbacks of each topology. The centralized AC only has one central converter and double busbar, allowing the ship to connect at 50 Hz or 60 Hz. In the event of the converter malfunction, all the docks with 60 Hz system will lose electricity, only the 50 Hz line will remain accessible. In comparison, with distributed AC, each berth line has its converter for greater reliability, thus malfunctioning of one line will not affect other lines. However, the cost of the converter will be higher. Sanes SE [26] in his study, performs a simulation for two distribution architectures of the shore power supply, namely ramified and ring system, which result in interference in voltage variations in the form of harmonic distortions due to the high changes of the onboard load. Thus, the CI connection and disconnection process needs to be monitored to avoid an excessive voltage change. Meanwhile, DC distribution includes a DC busbar that provides the flexibility to integrate with energy storage systems (ESS) and renewable energy sources (RES) such as photovoltaics (PV). Fig. 2 illustrates all types of CI topologies.

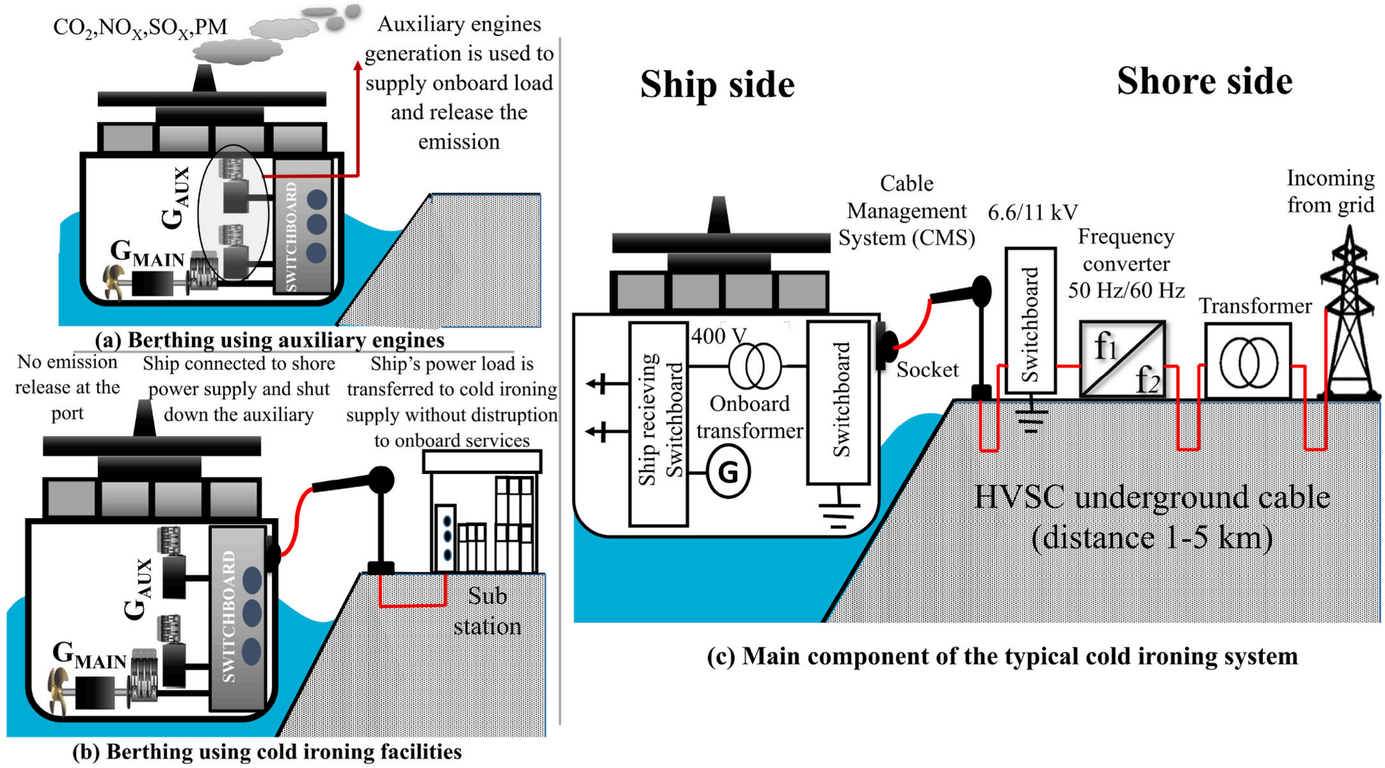
2.2. Power requirements at berth and influential factors

The important part for both planning and operation management to reduce unnecessary costs is by understanding the CI's power requirements. Before implementation (during the planning phase), identifying the load profile of the visiting ships is necessary to find out the ideal size and the right components of the CI facilities. While, after the establishment, the load profile will be used for operation management to utilize the facilities efficiently and economically. Therefore, it is significant to investigate the ship's load to comprehend CI's power usage.

Nevertheless, great challenges appear when it involves various types of ships that carry different loads. For instance, most of the cruise's onboard power demand is related to the hoteling load including accommodations, restaurants, bars, lounge, and theater to provide the passengers with a pleasant and comfortable trip. Meanwhile, container ships have machinery devices such as winches, heavy-lift derricks, or cranes at the port terminal for loading and unloading the cargo. This machinery is used on many container ships to reduce manpower requirements. Some of the containers are equipped with cooling storage that consumes high energy to preserve perishable foodstuffs during long journey transports. Common loads for most of the ships are lighting, alarm system, navigation lights, sensors, radio, steering gear, radars, communication devices, and loads in the crew living space. Other onboard loads that vary with the type of ship are ancillary services, refrigeration, hoteling requirement, seawater cooling pumps, fire pumps, HVAC for cooling and heating, and boilers [20,27,28].

Due to the difficulty to get the real data of the load profile unless by self-monitoring and measuring at the local port, many studies use the alternative to estimate the auxiliary consumption by utilizing a load factor. This load factor also known as a load coefficient. This auxiliary power will clarify how much supply is needed from the shoreside during the ships' stay. The general equation for energy consumption during berthing is provided in the following.

$$P_{CI}(kWh) = P_{auxi} * LF_i * t, \forall i \tag{1}$$

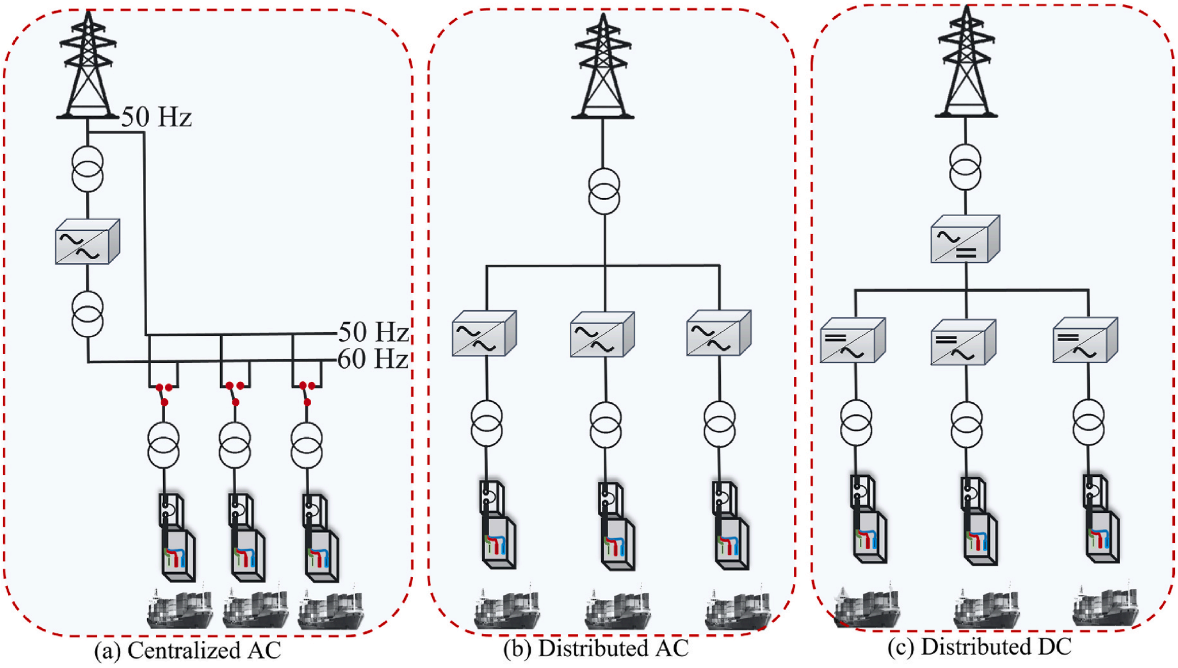


(a) Berthing using auxiliary engines

(b) Berthing using cold ironing facilities

(c) Main component of the typical cold ironing system

Fig. 1. Typical cold ironing structure and its main components.



(a) Centralized AC (b) Distributed AC (c) Distributed DC

Fig. 2. Cold ironing topology.

Where i represents the ship index, P_{aux_i} is the auxiliary power of the ith ship in (kW), LF_i is the load factor of the ship i during berthing, and t is berthing duration in (h). Table 1 shows the common load factor values found in the studies, clustered by ship categories and modes of operation. A load factor of 1.0 indicates that 100% of the auxiliary capacity in a ship is consumed to supply onboard loads. Other load factor values show the percentage of the auxiliary capacity used in each type of ship during the cruise, maneuver, or berthing operation modes. However, these values are not fixed as the load factor varies with the actual capacity and ship's operations in real-time. Cengiz Deniz et al. [29] assume a universal load factor of up to 75% to represent all hoteling consumptions. Meanwhile, Aydın Tokuslu [30] suggests a load factor of 60% for tankers and 40% for other ships. Some studies consider a load factor of 19% for container ships which is higher than the value listed in

Table 1
Commonly-used load factors for auxiliary generators of various ships in different modes of operation [32–34].

Vessel type	Cruise	Maneuver	Berthing
Container	0.13	0.5	0.17
Bulk carrier	0.17	0.45	0.22
General cargo	0.17	0.45	0.22
Roro	0.15	0.45	0.3
Oil tanker	0.13	0.45	0.67
Cruise/passenger	0.80	0.8	0.64

Table 1 [31]. Fortunately, many ports are now moving toward digitalization in data storage and easily accessible data is expected in the future.

The voltage and frequency systems of the ship is another crucial aspect to design the shore power supply. A ship with a voltage level lower/higher than 1000 V is classified as a low/high voltage (LV/HV) ship [25]. Most of the ships use a 60 Hz frequency system, however, the number of ships that use 50 Hz is also not negligible. Thus, a power electronic converter (PEC) is required in the CI system to offer the flexibility of shore connection with different frequency levels. As a result, the establishment cost becomes very high as PEC constitutes almost 60% of the total capital cost [35]. Table 2 summarizes the system voltage, frequency, and average and peak power demand of various classes and lengths of ships. The assessment of the average and peak power demand in advance is to pursue energy reduction options while also ensuring that the system can offer enough power during peak intervals. According to Juan Gutiérrez Sáenz [14], the peak load of auxiliary engines take places before and after the propulsion engines are powered up or shut down when docking at the quay.

As the CI components have a big impact on the port's cost, it is important to specify the type of ships that are the focus of the project. CI has a greater potential for cost savings in ports with longer average ship handling periods [36]. Practically, ships with longer berthing hours should be prioritized as the emissions from auxiliary engines will keep emitting hazardous particles into the atmosphere. In existing implementation, high proportions of the CI are employed by container ships due to their long berthing duration, 21 h or more [21]. Recently, there has been a trend toward cruise ships since they consume high power for 'hoteling' services that need to be guaranteed over the duration of their stay at berth. The study in Ref. [37] estimated the ship's berthing timeframe for cold ironing by executing a data-driven approach over huge quantities and varying data from the ships. The goal is to formulate forecasting model with high degree of precision that can predict the ship berthing period for upcoming ships and plan an appropriate action for optimal operation. Among input parameters considered in the model that has a strong correlation with the berthing duration of the ships are the different type of ship, the size of the ship, the load capacity it carries, the hour of arrival, and the various ship's mode of operation.

Seasons also influence the power requirements of the CI. In 2015, Croatia's highest power consumption was 3.009 GW, measured around 13:00 h on July 22nd, which corresponds to the peak of cruise ship visits in the summer [25]. During this season, air-conditioning demand is high to cool the space. Based on the authors' observation at the Port of Aalborg, the season does influence the types of ships that visit the port. For instance, there is a strong increase in the number of pleasure boats during the summer while it's difficult to discern the same trend in other seasons, particularly winter. Cargo and tankers, in contrast, make regular port calls, because their goods must be transported regardless of the seasons. In these scenarios, cargo and tankers are the good prospects for the CI project in that port because of their consistent ship calling throughout the year. Ships may sail at different routes, yet they regularly visit the same ports for 3 or 4 years. J. Prousalidis e. al [28] highlights that CI is especially beneficial for ships that routinely visit the same port.

Apart from traffic arrival patterns, potential opportunities for CI may also vary depending on regional characteristics and local power station conditions [38]. The existing network at ports plays a vital role in the decision for LVSC or HVSC shore power systems. The power system must be strong enough to deliver the required energy for the existing port operations and the additional power needed by CI services. If not, the establishment of the new connection points imposes additional costs for new transmission lines. The major challenge of CI power demand stems from the uncertainty of sudden load increases due to the peak ship traffic and extra power requirement from big ships at the same time. In this circumstance, ensuring that the shore energy capacity is enough to cover the required power remains a critical concern. In this sense, HVSC is more flexible in providing energy to both high and low-voltage ships. However, the final decision relies heavily on how many berths are installed and the estimated power requirement at each berth with the worst-case consideration (peak demand). Meanwhile, the selection of a frequency converter is optional. If the system is planned to support one frequency system either 50 Hz or 60 Hz, a significant expense can be saved. The drawback is that it will become a constraint for ships with different frequency systems without PEC.

The CI system is designed based on various operational requirements and is not limited to long berthing ships only. It also applies to short-distance ferries that operate on a strict schedule with many trips between two terminals each day and has a limited time for charging, normally 10 min stops [39]. For instance, a large electric ferry known as MF Tycho Brahe and MF Aurora operating on high frequency on a 5 km route between Helsingør and Helsingborg with 22 trips per day, charge

Table 2
Power demand, frequency requirements, and voltage systems for various types and sizes of ships [32].

Ship type	Average power demand (kW)	Peak power demand (kW)	Peak power demand for 95% vessels (kW)	Frequency (%)		System voltage (%)							
						LVSC					HVSC		
				50 Hz	60 Hz	380 V	400 V	440 V	450 V	460 V	6.6 kV	10 kV	11 kV
Container vessels (<140 m)	170	1000	800	63	37	42	16	42	–	–	–	–	–
Container vessels (>140 m)	1200	8000	5000	6	94	6	79	–	3	–	12	–	–
Container vessels (total)	800	2000	4000	26	74	19	6	64	2	–	9	–	–
RoRo - and vehicle vessels	1500	2000	1800	30	70	–	30	20	43	7	–	–	–
Oil and product tankers	1400	2700	2500	20	80	13	–	40	47	–	–	–	–
Cruise ships (<200 m)	4100	7300	6700	36	64	14	18	59	9	–	–	–	–
Cruise ships (>200 m)	7500	11,000	9500	–	100	–	–	12	–	–	48	4	36

the batteries at both ends to extend battery life while passengers and cars are boarding or unloading [40]. Both ports are equipped with ultra-fast charging systems.

From reviewed studies, it can be concluded that various factors influence the CI establishment and its power requirement. Several important aspects to consider in both the planning and operation strategies of CI are summarized in the following.

1) Duration of berthing
2) Type of the ships
3) Ship traffic arrival (frequency of ships calling at the port)
4) Voltage and frequency system of the ships
5) Operational mode
6) Local grid characteristics at the port to decide on HV/LV system CI

2.3. *Cold ironing standardization*

An international standard for CI installation is crucial in providing harmonious global guidelines to ensure internationally synchronized implementation, quality, and safety while preventing global market gaps. Furthermore, because it is universally recognized, client confidence will be gained. IEC, ISO, and IEEE work collaboratively to develop a comprehensive CI standardization that addresses both the mechanical and electrical components of the system. This standard describes the design, installation of LV/HV shore distribution lines, CI connection and interface equipment, specification of plugs and socket outlets, as well as control, monitoring, and testing systems. Two main categories of LV and HV connections have been gathered in IEC/ISO/IEEE 80005: Utility connections in port [20]. Applicable standards and complimentary directives for CI are summarized in Tables 3 and 4.

2.4. *Incentives for cold ironing installation*

Due to the CI's potential for environmental control and its many advantages that apply to any scale of the ship, a various of economic incentives have been introduced to encourage the installation of shoreside power. These incentives are in several forms such as one-shot subsidies for construction, interesting pricing schemes (rebate in tariff), energy taxation (tax reduction or exemption), and environmental penalties. The design of this motivational framework is dependent on the aims it seeks to achieve and the bodies that profit the most from it, with the port operator and shipping firms being the two crucial parties involved in the investment. Authors of [43] also include the transfer of financial risk to the government as one of the CI encouragement strategies.

Many ports across Europe are developing HVSC shore power with EU funds, which significantly reduces their financial burden [25]. The Council Implementing Decision 2011/384/EU authorizes Sweden to impose a cheaper rate of energy tax on electricity supplied directly to vessels at berth in accordance with Article 19 of Directive 2003/96/EC [25]. It was reduced to EUR 5.79 per MWh from EUR 33.94 per MWh, applicable to ships with at least 380 V engines up to larger ships. The aim is to achieve widespread utilization of CI electricity covering most of the ships. The positive outcome from this scheme can be seen in the increasing number of CI facilities in Swedish ports from five to eight stations [44]. Reduction of energy taxation is also employed by Netherlands, and Denmark [45,46]. Furthermore, the government of the United Kingdom has revealed the Maritime 2050 policy that considers providing subsidies and investment funds to ports and ships to enhance the uptake of CI [43].

Table 3
Applicable standards for cold ironing technology [24,41].

Category	Applicable Electrical International standard	Power requirement		Onboard voltage	
LVSC/ HVSC	IEC/ISO/IEEE 80005–2:2016	Data communication for monitoring and control			
LVSC	IEC/ISO/IEEE 80005–3:2016	Low power consumption	≤1 MVA	Low voltage vessel	440V/ 690V
HVSC-low power	IEC/ISO/IEEE 80005–1:2019	Low power consumption	≤5 MVA	High voltage vessel	6.6/ 11 kV
HVSC-high power	IEC/ISO/IEEE 80005–1:2019	High Power consumption	≥5 MVA	High voltage vessel	6.6/ 11 kV

Table 4
Complimentary regulations and directives of cold ironing [14,42].

Standard Name	Standard description
IEC 62613–1:2018	Plugs, socket outlets, and ship couplers for HVSC
IEC 62613–2:2018	Requirements for dimensional compliance and interchangeability of products intended for use by different types of ships
IEC 62613	The need for HVSC accessory
IEC 60092–101:2018	Electrical installations in ships
IEC 60092–503:2007	Electrical installations in ships - Part 503: Special features
EU Directive 2003/96/EC	Framework for the taxation of energy products and electricity
EU Directive 2006/339/EC	Promotion of shore-side electricity
EU directive 2012/33/EC	The sulfur content of marine fuels
EU Directive 2014/94/EU	Deployment of alternative fuels infrastructure
EU Directive 2016/802/EU	Reduction in the Sulfur content of certain liquid fuels
IMO MARPOL Annex VI	Regulations for the prevention of air pollution from ships

Adoption of several environmental indices such as, the environmental ship index (ESI), green award (GA), the clean shipping index (CSI), and blue angel (BA), is an alternative option [47,48]. If the port's measurement index meets the benchmark value, these programs offer significant discounts on port dues. For instance, ships in Bremen with an ESI score of 30–40 get a 5% discount on port fees while those with a score of over 40 get a 10% discount. These rewards will encourage port organizations to upgrade their ports with shore electrification in order to earn additional port dues discounts [12]. However, future mechanisms would presumably not only reward clean ships but also penalize those that violate the allowed emissions boundaries. Table 5 summarizes other strategies to promote CI deployment.

2.5. *Challenges of cold ironing establishment*

This section discusses the significant challenges of implementing shore power technology. All arising issues should be investigated to find a feasible solution for future CI adoption. These barriers include, but are not limited to, the following.

2.5.1. *The high investment cost for port operators and retrofitting cost for ship owners*

Upfront costs for ports can be grouped into two categories: (1) development expenses for constructing CI facilities at the port, and (2) expenditures for coordinating to the power grid, which may include updating the existing port network connection, for instance by constructing new substations [17]. On the ship side, newly built ships are equipped with a transformer and socket outlet for shore connection, but existing ships need retrofitting to receive power from CI. According to the ports that have already implemented CI technology, the shoreside investment cost can range from $300000 to $4 million per berth [51]. On the shipside, the cost of the retrofitting is between $300,000 to $1–2 million per ship. In addition, operations and maintenance (O&M) costs for the shoreside can be up to 12% of the capital cost [38]. Further

Table 5
Strategies to promote cold ironing deployment.

Ref	Stage/Role	Solution	Description
[38]	Government initiatives and European Union (EU)'s grants	Financial grant (One-time funding for installation)	• Port of Los Angeles: California allocate $23.73 million to develop CI at 10 berths. • Port of Long Beach: California allocate $30 million to develop CI at 12 berths.
	Regulatory authority	Variable subsidies, tax exemption, tax reduction	Among the countries that receive this benefit are Sweden, Norway, and Germany.
[49]	Government	Mandatory order to use CI	• China's government mandated 50% coverage of CI by the end of 2020.
[35]	Government, municipality, public entities, and local port	Collaboration	• Collaboration between ports that have a regular route for ships to install CI, thus encouraging ship entities to retrofit their ship.
[50]	Port	Compensate ship for retrofitting	Port in Los Angeles has compensated ships with an amount of US $ 800,000 for installing the CI's onboard equipment. This program is particularly appealing to shipowners resulting in 52 new-built container vessels with CI receiver between 2005 and 2008.

investigations are necessary to clarify how costs should be distributed between ports and shipping companies.

2.5.2. *Competitive emission solutions*

As the shipping lines are obliged to use low-sulfur fuel at the port, marine gas oil (MGO) is the first choice. However, they have the option to install fuel gas cleaning known as scrubber technology, to avoid using expensive MGO and continue using cheaper heavy fuel oil (HFO) while achieving favorable environmental benefits. In a survey conducted by various shipping companies for the cruise's CI project in Copenhagen, most ship operators are focusing on installing scrubbers rather than CI because both solutions are expensive and there is a tendency to opt for just one technology [35]. Only a few shipping companies are prepared for CI solutions. The main reason behind this is that many visiting ports are not equipped with CI facilities. In addition, while shore electricity comes with a price and tax charge, oil is tax-free and hence cheaper [52].

2.5.3. *Frequency and voltage*

In the CI power supply, coordinating the frequency and voltage system between the ship and the shore sides is extremely crucial. However, there are differences in system frequencies, with most ships operating at 60 Hz, but Europe and most Asian countries operating at 50 Hz [53]. To solve this issue, PEC is required to feed both frequency systems, hence raising the infrastructure's cost.

2.5.4. *Synchronization*

Harmonization of the frequency, voltage, and phase of ships' onboard power and the shoreside power is essential to prevent severe inrush currents [39]. The inrush current is the maximum instantaneous current drawn by electrical equipment such as a diesel generator during the start-up. The worse situation can happen when a ship with a big diesel generator is suddenly connected to the CI. Hence, the inertia from the internal generator can cause a huge inrush current. Robert Smolenski et al. [42] develop shore-to-ship synchronization and load transfer formulas with the help of PECs on the shoreside rather than the shipside, to provide flexible management of load transfer and reduce the transient state during connection. Load transferring is the process of switching from the ship's generator to the shore electricity. Smooth load transfer is challenging in CI due to the high electromechanical time constants of the ship generators. In this case, the dynamic behavior during the CI connection is controlled by the electrical time constant from the PECs circuit in the range of milliseconds. In another study by Marcin Sedlak et al. [54], synchronization of ships' voltage and load transfer are performed in parallel instead of a short black-out. The result shows that the modification of the reference voltage signal can improve the load-transferring process. Table 6 provides a summary of the CI challenges identified in reviewed studies.

Among the mentioned barriers, financial concern is the biggest challenge for the CI establishment. In addition, the investment appears to have a long payback period. Hence, it requires a fair tradeoff in decision-making and determining whether the benefits will outweigh the costs. Thus, there is an urgent call to perform a feasibility study for a good financial framework for the regulator, government, port, and ship operator. These cost management studies can help to avoid unnecessary expenses while also guaranteeing that the maritime sector benefits from emission-free practices.

3. Key assessment in cold ironing

In the maritime industry, CI is not a new technology, and its provision has been a proven process for the past two decades. Nonetheless, CI implementation at ports around the world is progressing slowly as it needs significant investment and most of the ships are not still ready for this technology, resulting in low demand for CI. The sudden awakening of this technology a few years back is strongly due to the Paris Agreement (2015) on climate change, where the aim is to achieve climate neutrality by 2050 at the latest. It demands a political commitment to a legal obligation to take necessary actions. In complying with the Paris Agreement, the EU has set a target to reduce greenhouse gas (GHG) emissions by at minimum 55% below the 1990's level by 2030, making it a medium-term strategy leading to long-term planning by 2050. Thus, technology development and implementation must begin before 2030 to prepare for even more rapid change beyond then.

Accordingly, various complementary policies such as sulfur limitation from the ships are tightened to motivate the use of RES and low-carbon fuels. Thus, decarbonization technologies particularly for treating emissions from fossil fuels have become the highest concern in maritime transportation in recent years. With less than 30 years to go and considering the long lifespan of ships, the time is now to take the necessary measures toward this goal. Nevertheless, from the authors' perspective, emission control becomes stricter in the following years. The trend in Fig. 3 showing from 2010, the restriction on sulfur content in the fuel keep being lowered up to 0.1%. In another word, the visiting ship at the port must comply with the emission control requirements by using 0.1% low-sulfur fuel oil during mooring. Might be in the future, other particles will also face the tight restriction making CI employment unavoidable. Compared with other alternatives (MGO and scrubber), CI is not only best in the elimination of all types of emissions from HFO generation but also in its advanced technology. This is in line with the current development of the maritime industry toward electrification, shifting from burning fuel to electricity consumption. A big advantage of the CI technology is that it is capable of being integrated with RES in a microgrid system and offering emission-free sources. That makes the CI become a promising solution for both ports and ships providing a long-term return regardless of its high upfront cost.

Department of Transport in the United Kingdom released a call for evidence of shore power in 2022 to fill in the gaps and shortcoming in their understanding by acquire information on CI's gains and costs [17]. The trend for CI technology is growing, yet its greatest obstacle to large-scale implementation is financial issues. Therefore, this section will discuss two critical assessments in CI solutions: emission and

Table 6
Challenges of CI establishment [17,38,55–59], and [60].

Aspects	Barriers	Descriptions
Economic	High expenditure on CI infrastructure and its operational cost	It is vital to ensure that the CI demand from shipping lines is high enough to cover the costs.
	High retrofitting cost for ships	The huge investment cost for ship modification results in low demand for shore solutions from shipping lines.
	Long return on investment (ROI)	Low revenue and high investment costs cause a long payback period. Thus, investors tend to not integrate the CI.
	Electricity cost and tax	By pursuing CI charging stations, ships need to pay for electricity costs including tax while diesel fuel is tax-free.
Technical	Synchronization frequency and voltage system	The use of frequency converters at the shoreside is required to provide flexibility to various types of ships, which further increases infrastructure costs.
	Cable management system	Long cable handling time during connect/disconnect process. Auxiliary usage in this period will release emissions.
	Electrocution risks managerial	Personnel or crew that handle the high-voltage cables are exposed to a high risk of electrocution.
	Complex decision-making for berth allocation	The decision on which berth terminal and how many berths should be considered for the installation of CI facilities is difficult. The stochastic ships' arrival must be properly forecasted using advanced algorithms.
Environmental	The effectiveness level of total emission clearance	The effectiveness level of emission treatment depends on the source of the local generation.
	The reduction of emissions is not applicable in all modes of ship operation	Emissions are only reduced when ships in berthing operation, and not during ship cruises.
	Emission from boiler	Auxiliary boilers that are needed to maintain the generated steam during berthing imply another type of emissions.
Management	Coordination failure and dilemma for implementation	Ports are reluctant to make investment in shore electricity networks until demand can be convincingly proven. On the other side, if the shore infrastructure is not widely available at ports, ship operators are not interested in investing in ship retrofitting.
	Presence of multiple stakeholders	Making a decision by several involved stakeholders with different roles and objectives is a complex process. Among the partners involved in the CI implementation project are policymakers, port authorities, terminal operators, shipping lines, research institutes, public authorities, intergovernmental, public, and engineering companies, as well as private transport companies.
	Limited available data	It is very difficult to obtain the data analysis from the ports with CI facilities and shipping lines to perform the required evaluation.
	Lack of market feedback	Due to the high upfront cost, evidence for the long-term establishment benefits of CI from existing ports with this technology is needed for a deep analysis of whether the investment is worthwhile in the long run.
Regulatory	No pressure on using CI	Without a global mandate for the compulsory use of CI, it is prone to demotivate both ports and ships for accelerating CI employment.

economic. There are some research studies on the technical aspects which can be found in Ref. [54]. However, those will not be covered in this study as the authors believe that establishment comes first and then will be followed by other aspects including technical issues. Recent articles are reviewed to provide the current perspective and potential opportunities of the CI. Reports and government studies are also included since they are closely related to the real concerns in the implementation process based on the actual feedback from involved entities.

3.1. Emission assessment

The most common harmful substances generated by ship generators are nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon dioxide (CO_2), and particulate matter (PM) [61]. Amongst these substances, CO_2 is the primary GHG that brings harm to global climate change. Meanwhile, SO_2, NO_x, and PM are substances that are detrimental to human health [62]. There are several categories of fuel to power the main and auxiliary engines including HFO, marine gas oil (MGO), and marine distillate oil (MDO) [63]. Table 7 represents the emission coefficients of different substances from various sources of emission. It is important to know the type of oil used by the ships to conduct an effective comparison with and without CI installation.

Considering that the CI's main purpose is to reduce emissions at berth, a thorough investigation is required to know the actual scale of ship emissions at port and the maximum potential of the CI to cut emissions. In this regard, auxiliary engines are important components for evaluation. In addition, there are several parameters to consider while examining the amount of ships emissions as follows.

1) Auxiliary power
2) Load factor of the ship during berthing
3) Berthing duration
4) Type of fuel used (HFO/MDO/MGO)
5) Emission coefficients

In the following, a simplified mathematical algorithm is presented to measure the emissions released with and without adopting CI technology.

$$TE_{\varepsilon 1} = \sum_i FC_i^{berth} * EC_n^{diesel} \forall n \in NO_x, SO_2, CO_2, PM \tag{2}$$

$$FC_i^{berth} = \left(P_i^{aux} * SFOC_i^{aux}\right) * l_i^A * t_i^{berth} \tag{3}$$

$$TE_{\varepsilon 2} = \sum_i PC_i^{berth} * EC_n^{grid} \forall n \in NO_x, SO_2, CO_2, PM \tag{4}$$

$$PC_i^{berth} = \left(P_i^{aux}\right) * l_i^A * t_i^{berth} \tag{5}$$

In most CI emissions evaluation studies, emissions produced by the local grid are considered. The emissions from using low sulfur fuel oil (LSFO), and shore electricity are compared. If $TE_{\varepsilon 2}$ is less than $TE_{\varepsilon 1}$, it demonstrates the positive environmental benefits of the shore electricity

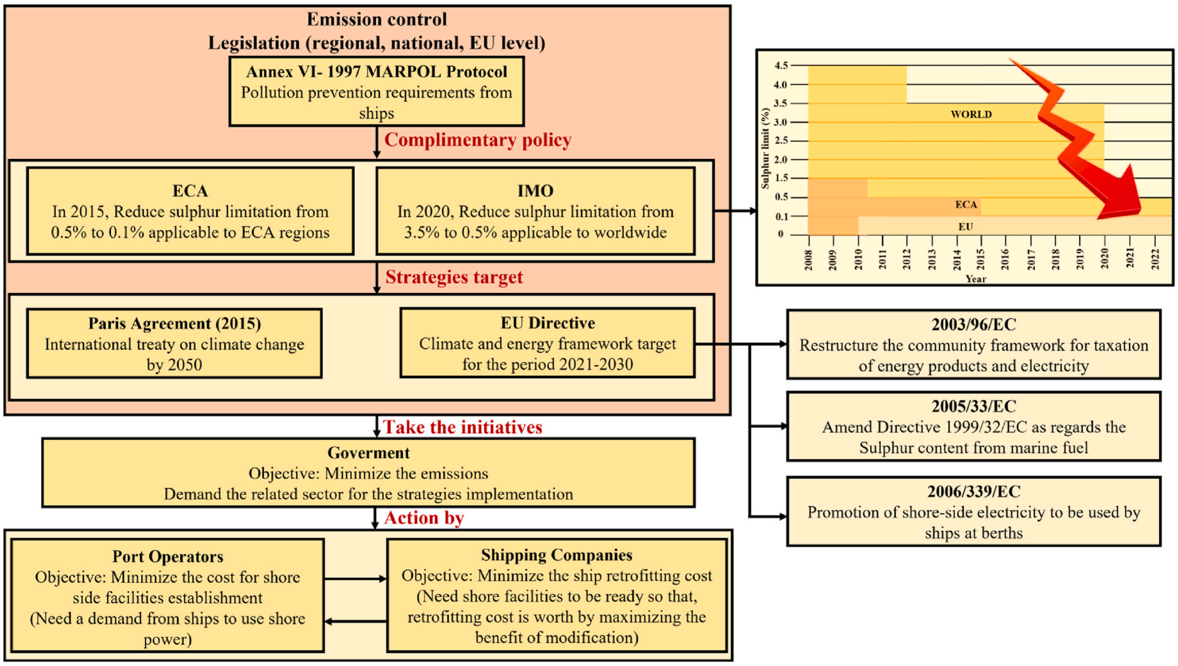


Fig. 3. Directive for the cold ironing action plan.

Table 7
Emission coefficients of different substances in various sources [64].

Emission sources	Ref	Emission coefficients (g/kWh)			
		NO_x	SO_2	CO_2	PM
HFO (3.5% sulfur)	[31]	14.9	11.1	722	1.5
HFO (2.7% sulfur)	[26,64]	12.47	12.3	722	0.8
LFO (0.1% sulfur)	[35]	13.2	0.2	645	0.207
LFO (0.5% sulfur)	[31]	13.9	2.12	692	0.38
Scrubber	[65]	12.4	0.03	690	0.19
Utility grid	[66]	0.32	0.07	426	0.03
Boiler	[14,67,68]	2.0	N/A	962	0.1

alternative and explains the necessity for CI employment. When ships are at port, especially the ports that are close to population centers, those emissions might have the greatest impact and the shore power has a huge potential to control toxic exhaust gases. Compared to utilizing LSFO, the additional benefit of CI is that it eliminates noise and vibration pollution, which benefits the surrounding population's mental and physical health as well as the coaster ecosystem [69]. Dutch authorities estimate to reduce the gas pollution from burning bunker fuels by 95% with the use of CI [46]. However, this valuation must be defined in a specific case, as 95% seems to be high when taking grid emissions into account. Nevertheless, it is achievable in the case that CI is powered by RES that generates electricity locally at ports [27]. In Ref. [59], the exhaust emissions from the shoreside are ignored since the main grid is located at a far distance from the port, and hence their emissions have no impact at the port. In contrast to the United States and Europe, where RES and natural gas account for the majority of overall power generation, China's power plants are still primarily coal-fired [70]. Thus, due to the less clean power generation resources, employing CI may result in increased emissions at ports. This issue needs to be addressed by investigate the potential solution to reduce emission risk at the port that primarily powered by coal.

While the available research suggests that CI can greatly decrease ship harmful emissions, it does not address all sources of emissions related [71]. For instance, the continuous emissions of the onboard boiler from the fuel combustion even after connecting to CI. In Ref. [68], it is mentioned that from three combustion sources of a ship (main and auxiliary engines and boiler), only the main and auxiliary engines are switch off during CI connection, while boilers continue to operate. Boilers help to keep the main engine's cylinders and fuel warm, to prevent damages caused by low-temperature contractions. Thereby, adding other sources of emissions to the quay. It is estimated that the boiler consumes about 50% of the total fuel burned at the berth [14]. Even though some ships no longer use boilers, a fair assessment to determine the maximal potential of the CI technology in eliminating emissions should also consider the gases emitted by boilers.

On the shoreside, the actual emission impact of using CI at ports is influenced by several factors. These factors include the various sulfur level of marine fuel that is used by ships, the size and type of the ships, the proportion of ships visiting at the port, the duration of ship docking, the location of the port, and how electricity is generated at the shore (diesel/utility/clean sources/mix of sources). Some studies also highlight another emission issue at the port during cable connection. Authors of [72] in their research estimate that the handling time for connecting and disconnecting cables from ship to shore takes 1 h (approximately 2 h for completing both). Within this process, auxiliary engines must continue to supply onboard load until the connection process is completed. Therefore, during this cable handling time, there will be emissions from auxiliary engines. The impact of CI on decreasing emissions at berth will vary when considering different aspects at various ranges. To the best of the authors' knowledge, there is no universal assessment to serve as a baseline in CI emission evaluation. Thus, the best practice is to conduct a case-dependent study at the specific port under consideration.

Apart from that, there are also competitive solutions for emission reduction at berth. Currently, shipping lines are provided with the option of utilizing LSFO, scrubber cleaning technology, or CI. All the alternatives have their pros and cons. There are several reports from governments that inquire about which technologies and fuels can aid in the reduction of ship emissions at ports, as well as their expenses, gains, and level of technology readiness [17]. The most common studies compare LSFO with CI technology and a comprehensive comparative study between all these competitive solutions is still lacking. This evaluation approach is significant as all the alternatives serve the same purpose of reducing emissions at ports but what distinguishes them from one another is their emission-eliminating level, the timeframe they belong to (short-term/medium-term/long-term), and the investment value which is unclear. These comparative studies can provide new insights into the available solutions and assist ports and ship owners and other related parties to adopt a good strategy considering their objectives and budget limitation. Table 8 presented the emission evaluation for ships during berthing activities by considering various sources of emissions for CI studies.

3.2. Economic assessment

Emission legislation and pressure from authorities drive the installation of shore-based CI technology. Accordingly, port operator and shipping lines are the two most affected parties. Meanwhile, municipal and legislative organizations play a supporting role in accelerating the implementation by providing attractive financial frameworks, supporting grants, or mandating the use of CI to visiting ships at local ports. For example, Californian ports have made a mandatory regulation for visiting ships to utilize CI during their stay at ports [80]. Hence, ships that regularly visit the California port need to be retrofitted and the port is also expanding its facilities on a large scale to provide CI services to the ships as much as possible.

A substantial part of the conducted research and reports from local ports and governments highlight the issue of high initial investments for the CI indicating that the most significant barrier to extensive CI employment is the economic concern. Typically, investors are hesitant to incorporate the technology due to the high upfront expenditures and the long payback period as well as unclear returns and benefits. Accordingly, further investigation of the cost distribution between the port and the ships, as well as a cost-benefit analysis is required. There is a growing trend in academia toward CI technology and several recent publications are dedicated to the economic investigation of CI projects with a variety of solutions from various perspectives and in different scenarios. This section will provide an overview of studies related to the CI economic assessment from two perspectives: port operators and ship owners.

3.2.1. Cost analysis from ports perspective

The prospect of capital cost savings as well as the financial benefits is the main considerations for port operators during CI's planning. If the gains outweigh the costs, their decision to adopt the technology is justified. In this section, a fundamental mathematical model to estimate the initial expenditure and perform a cost-benefit analysis for CI establishment is presented. The underlying assumptions comprise national tax is already included in electricity cost and technical infrastructures are known.

Annual investment cost:

$$C^{A}_{port} = C^{A}_{port,ins} + C^{A}_{port,O\&M} + C^{A}_{port,energy} \tag{6}$$

Annual cost-benefit analysis:

$$C^{A}_{port,ben} = \sigma * \rho * \left[PC^{berth}_{i} * (\gamma_A - \gamma_B)\right] + SE^{A}_{benefit} \tag{7}$$

Annual socio-economic analysis:

$$SE^{A}_{benefit} = \rho\left(TE^{A}_{\varepsilon 1} * \omega\right) - \sigma * \rho\left(TE^{A}_{\varepsilon 2} * \omega\right) \tag{8}$$

Payback period:

$$PP = \frac{C_{ii}}{C_{acf}} = \frac{C_{ii}}{C^{A}_{port,ben} - C^{A}_{port}} \tag{9}$$

There are three major parts of the investment involved to provide shore electricity to the ship which are infrastructure installation, operation and maintenance, and the cost of purchasing electricity from the local grid as illustrated in (6). The return on investment for the CI establishment is from selling electricity to the ships and the socio-economic benefit of reducing pollution. This model is extracted from Ref. [59], but with the addition of a socio-economic advantage in the return of investment, based on the assumption that external health costs would balance capital costs in a shorter payback period, as demonstrated in Ref. [66].

Ports are more likely to deploy CI if the benefits are worth the investment cost ($C^{A}_{port,ben} \geq C^{A}_{port}$). Authors of [81] classify cost analysis of ports decarbonization into two classes: cost minimization and profit maximization. Profit maximization can be achieved by increasing income from providing CI services to ships. However, to make the CI attractive to both ships and ports, the electricity price (γ_A) must be low enough to encourage ship owners to utilize CI instead of their auxiliary engines, but high enough to cover the costs of the port. Another factor for optimally using CI is the percentage of ships visiting a port that use shore power, σ. A survey conducted in Ref. [35] emphasizes the issue of a large portion of ships that are not ready for the use of CI due to high retrofitting costs. A low σ will result in a low annual financial benefit and cause a longer payback period. Thus, σ is a critical factor in the CI cost-benefit analysis as the port benefit increases with an increase in σ. Parth Vaishnav et al. [82] in their study reveal that by retrofitting between 25% and 66.6% of all ships that berthing at US ports will result in a \$70-\$150 million yearly air quality benefit.

The health cost savings from reducing pollutant substances from ship exhaust gases by employing CI is considered a socio-economic gain. The socio-economic benefit by definition is improvements in health corresponding to improvements in air quality. In order to measure this gain in monetary terms, the socio-economic is taken as the reduced external cost (human health) [70]. Higher $SE^{A}_{benefit}$ signifies that the benefits gained from CI technology rationalize its cost, whereas lower $SE^{A}_{benefit}$ indicates that the cost of installation is greater than the benefits it ultimately provides. Several studies perform socio-economic analysis with different methods and various scopes of study. Lei dai et al. [83] investigate the economic feasibility with an environmental benefit under three scenarios. According to their study, the income from pollution elimination has a small contribution, implying that the port must generate more profits from selling shore electricity to avoid severe economic losses. In contrast, Balinni and Bozzo [66] report significant earnings from the socio-economic benefit analysis when comparing the use of shore power with relying only on auxiliary engines using the air pollution model (EVA). However, their study is limited to the benefits of society's health and ignores the ports' or shipping companies' economic viability.

Cost minimization can be achieved by optimal design of the CI architecture and equipment as well as a suitable financial framework. As the frequency converter and transformer are necessary in specific cases, understanding the characteristics of the port, the local grid, and the demand from visiting ships is vital. According to the cost assessment in Ref. [35], frequency converter budgets contribute to nearly 50% of the overall expenditures. Hence, by excluding the frequency converter a significant amount of investment cost can be saved. Another approach is

Table 8

Berth emission evaluation under different emission reduction measures.

Reference and Year of publication	HFO	LSFO (0.5% or 1.0% sulfur)	Scrubber	Boiler	CHP	RES	Grid
[73] 2022	–	–	–	–	✓	✓	✓
[31] 2022	✓	✓	–	–	–	–	
[74] 2021	–	✓	–	–	–	–	✓
[75] 2021	–	–	✓	–	–	–	–
[76] 2021	–	✓	–	–	–	–	✓
[77] 2021	–	✓	✓	–	–	–	–
[14] 2019	–	✓	–	✓	–	–	✓
[78] 2018	✓	–	–	–	–	–	–
[79] 2015	✓	✓	–	–	–	–	–

to limit the CI installation to a small number of berths and ensure that these berths terminals have high occupancy. The facilities can be expended later when there is an additional budget or higher CI demand. Apart from that, the optimal design of the CI architecture that suits the load requirements will also help in reducing unnecessary costs. The CI's optimal sizing study in Ref. [19] illustrates a considerable reduction in emissions at the lowest net present cost (NPC) with the optimum architecture configuration and adequate size of components.

Regarding attractive financial frameworks, several publications consider financial incentives and pollution penalties in their economic analysis. Authors of [38] develop a hybrid economic framework with fixed and variable subsidies as well as emission subsidies considering regulators and port entities. The simulation result indicates that the proposed approach is capable to provide reasonable economic investment decision-making. However, it neglects the cost of shipping companies. In Ref. [43], subsidization plans are developed for the government to support CI promotion considering the huge environmental benefits of CI technology. Their proposed framework includes the three main involved parties, namely the government, ports, and ships with all parameters considered in their study are deterministic and constant. The main concern of applying this approach in practice is that the shore electricity and diesel fuel price fluctuate over time and are inconsistent. Future research should consider developing a subsidization framework that can withstand price volatility. Besides, a price sensitivity analysis is required. In addition, Ming Yin et al. [84] emphasize that special funding is more appropriate compared to subsidy programs as they are very costly and not sustainable. Xiaoyao Zhao et al. [85] alternatively combine the subsidy and penalty in their algorithm as they believe that the higher the penalty, the greater the loss that ports will encounter, thereby the higher willingness to implement CI. It can be concluded that all the measures that were successfully integrated would reduce the port's financial burden while also assisting in the promotion of the CI technology.

3.2.2. *Cost analysis from shipping lines perspective*

Retrofitting cost is the main concern for ship owners to use CI services [70]. Among the costs involved are the modification expenses, operation and maintenance, and the cost of purchasing electricity from the shore. Ships' priority is to minimize associated costs and maximize potential revenues. Thus, the interest in retrofitting is higher if this technology can guarantee their economic benefits while complying with pollution limits during berthing alongside the quay. Equations (10) and (11) are formulated to perform a comparison between the cost of using auxiliary engines and CI services.

$$C_{LSFO}^{A} = FC_{i}^{berth} * \gamma_{C} * \alpha \tag{10}$$

$$FC_{i}^{berth} = \left(P_{i}^{aux} * SFOC_{i}^{aux}\right) * l_{i}^{A} * t_{i}^{berth} \tag{11}$$

$$\sum_{j} C_{j}^{A} \quad j \in \{a, b, c, d\} \tag{12}$$

$$C_{CI}^{A} = C_{a}^{A} + C_{b}^{A} + C_{c}^{A} + C_{d}^{A} \tag{13}$$

$$C_{c}^{A} = PC_{i}^{berth} * \gamma_{A} * \delta * \alpha \tag{14}$$

$$PC_{i}^{berth} = \left(P_{i}^{aux}\right) * l_{i}^{A} * t_{i}^{berth} \tag{15}$$

$$C_{d}^{A} = FC_{i}^{berth} * \gamma_{C} * (1 - \delta) * \alpha \tag{16}$$

The ship's cost analysis in Ref. [86] only considers electricity cost and ignores the fuel cost. Therefore, it can be used in the scenario that all ports visited by the ship can provide the shore power or if the exact number of visiting ports with CI is already known. However, in practice, CI services are not available at all ports, suggesting that ships must use their auxiliary engines while visiting ports without CI service.

To identify the actual investment cost of using shore power, it is more realistic to include the proportion of visiting ports that do not provide shore power. Thus, $(1 - \delta)$ is introduced in the model representing the proportion of the port that not providing CI service. All ships moored in these ports are required to utilize auxiliary engines with LSFO, which implies the fuel cost of LSFO. LSFO is considered in this model due to the strict regulations prohibiting HSFO usage during berthing. If the value of δ is high, retrofitting is a viable solution, especially for those ships that visit the same ports. However, the weakness of the CI compared to other solutions is the technology readiness, as many ports do not have CI facilities that demotivate ships to make a large investment for retrofitting when they can use it only in limited ports. Most shipping companies choose to use LSFO or scrubber technology not only because of financial concerns but also because it is ready to be used in every berth right after installation. Hence, it is an opportunity to investigate the suitable financial framework that benefits both ship owners and governments to encourage retrofitting of ships. The dilemma is that the ports would not establish CI until enough ships can use shore services, and shipping lines resist retrofitting unless enough ports can provide CI services. This issue can only be solved by compulsory commands to use the CI [16]. Another solution is to ensure that each port provides shore-to-ship power facilities even with limited capacity. At the same time, ports can also build the CI facilities considering their budget limitation and expand them in the future if necessary. Small capacity of CI facilities may increase the waiting time of ships to use shore power but will encourage more ships to use it services in long term. Zheng Wan et al. [76] clarify in their study that despite having a long waiting time at anchorage, ships still gain high economic benefits from CI since the berthing time at the port is generally longer than the waiting time at anchorage. Other studies that consider the waiting time for using CI services can be found in Refs. [78, 87], and [88].

In a comparative analysis with and without installation of CI's power receiver, if $C_{CI}^{A} < C_{LSFO}^{A}$, there is a high chance that ship owners decide to retrofit their ships. To achieve this goal, several actions can be taken. For instance, the shorter the period a ship stays at berth, the less likely that ship owners be willing to retrofit their ship for using shore power as using LSFO is a more practical solution. With longer berthing hours (t_{i}^{berth}), ships benefit more from CI services as during long berthing duration, more power is consumed (PC_{i}^{berth}) from the shoreside, and significant elimination of emission from bunker fuel can be achieved. It also satisfies the purpose of CI installation to optimally utilize services after a huge investment. Accordingly, it is suggested that containers and cruise ships become the front runners that utilized CI [17]. Indeed, in existing CI applications, the major types of ships that use CI are container ships, passenger ships (cruise and ferry), tankers, and RORO ships. According to the authors' observations through a live update of ship traffic at the Port of Aalborg [89], cargo and tankers spend the longest time at the port among others. Their monthly visits to the port are consistent regardless of the season and have frequent ship callings. This makes them the best candidate for CI integration. The list of the real CI stations around Europe with specific information on the type of visiting ships, number of the berth with CI at each port, voltage system, system categories (HVSC/LVSC), and power usage can be found in Ref. [15].

The advancement in ship manufacturing has offer the new ship that are readily equipped with CI power receivers. This progressive development is another solution for shipowners in the case of retrofitting is irrelevant if the remaining service life of their ship is short. Retrofitting the ships which are approaching retirement will cause severe financial loss and greatly reduces the potential benefits of the investment. However, building new ships with CI equipment needs also a relatively long time, typically up to three years [59].

Another important aspect of a ship cost assessment is the shore electricity price, γ_{A}. In this aspect, relatively low γ_{A} and high fuel price, γ_{C} result in $C_{CI}^{A} < C_{LSFO}^{A}$, showing a higher potential for increasing demand from ships to use CI. The high oil price volatility creates an opportunity for serious consideration of retrofitting by shipping lines. Current sentiment on the Russia-Ukraine war in February 2022 had a huge impact on oil prices, with Brent oil rocketing to $120.65/barrel from $21.49/barrel in 2020, nearly 6 times higher in just two years [90].

Jingjing Yu et al. [70] develop a strategic retrofit planning for ships by using an improved multi-objective genetic algorithm (NSGA-II) with the main objectives of minimizing the payback period and maximizing environmental gains. The retrofitting is considered advantageous if the payback period (PBP) is less than the whole project planning time, which is set at 15 years. A subsidy framework is applied, and results show that PBP varies between 2.25 and 7.14 years being highly dependent on the high frequency visiting of ports with CI. The substantial economic benefits and short PBP are achieved by ships that have a high proportion of visiting ports with readily accessible CI infrastructure. Table 9 shows the relevant publications that evaluate the CI technology cost.

4. Synergy of the cold ironing and microgrid system

The greatest advantage of the CI in reducing emissions over other competitive solutions (LSFO and scrubber) is its ability to integrate with microgrid systems. The conceptualization and operation of seaport microgrids with CI integration can be found in Ref. [12]. A microgrid is a local energy network aggregating distributed energy resources (DER), RES, ESS, and loads with the possibility to connect with the main grid, to provide a cost-effective and sustainable power supply [96,97]. The main role of joint seaport microgrid and CI is to address the arising issue of emissions generated by the local grid that supplies CI. Although CI is a means to minimize ship emissions, the fact that it receives power from the main grid which mostly relies on fossil fuel-based resources is a disadvantage. The amount of emission released by the main grid is highly dependent on the grid generation mix. Thus, the effectiveness of decarbonization strategies at ports using CI toward achieving emission neutrality is possible with high penetration of RES from MG. Fig. 4 illustrate the concept of cold ironing and microgrid in the port site.

The establishment of seaport microgrids means another investment cost factor for the port operators. However, given the considerable number of existing ports with microgrids, the synergy between CI and microgrid is a viable solution without imposing additional costs. For instance, the Port of San Diego has implemented the microgrid solution to power its Tenth Avenue Marine Terminal with 700 kW of solar panels, 700 kW of ESS, and CI infrastructure [93]. Many European ports have invested in RESs, such as wind turbines (200/45/28.2 MW in Rotterdam, Antwerp, and Amsterdam, respectively), solar farms (11 GWh/750 MWh/55 MWh in the Ports of Amsterdam, Rotterdam, and Gothenburg, respectively), and wave/tidal energy [98]. Due to the uncertainty of RES output power and its stochastic nature, CI may also need to utilize energy from the grid at some intervals. Hence, the precise amount of emission reduction highly depends on the proportion of RES used for the shore power. Further investigation on the CI and MG integration considering technical and economic aspects, emission reduction effectiveness, system stability, optimal sizing, and practical configurations are required to provide a feasible solution to the maritime industry.

Yue Zhang et al. [93] propose a scheduling approach for two of the outstanding maritime electrification combination, CI and MGs, and analyze the impacts of six different CI capacities. The terminal with all berths supplied by maximum capacity of CI facilities also offers the best operational performance. The overall handling time is decreased from 44 to 42 h and emissions are significantly reduced (CO2, SO2, NOX, PM10, and PM2.5 reduced by around 85%, 94%, 99%, 99%, and 100%, respectively) when compared to a terminal without CI. Meanwhile, RES and ESS in the MG lower the port operation costs by importing electricity from the main grid during off-peak hours and using MG power during intervals with high market prices. Besides, the excess generation from MG resources is exported to the grid network during peak period to reduce the main grid's burden. The overview of the charging station

Table 9
Cold ironing cost analysis strategies from ports' and ships' points of view.

Ref	Case study (port/ type of ship)	Cost evaluation side	Cost factors	Cost-benefit	Financial strategies	Sensitivity analysis	Description
[91]	General port terminal with five berth station	Port	1-Different cost coefficient 2-Different emission coefficient	N/A	Emission limitation and Emission penalty	Increasing in load demand from ship	Analysis on different environmental dispatch strategies
[92] 2022	1-Port: N/A 2-Ship: General AES	1-Port 2-Ship	1- CI Electricity 2- Carbon tax	1-Price incentive 2-Social welfare	TOU-pricing	1- Port capacity 2- Number of AES	Investigating the AES's voyage planning, the CI's profit, and the power system dispatch
[93] 2022	Ship: Container ship, quay cranes, yard cranes	1-Port 2-Ship	1- Operational cost 2- Transaction cost between MG and utility	N/A	Penalty cost for the ships not arriving and departing on time	N/A	Studying the impact of different CI capacity
[94] 2021	Ship: AES ferry	Ship	1- O&M cost 2- CI Electricity 3- AES fuel	N/A	Day-ahead economic dispatch	N/A	Addressing the impacts of fluctuations in electricity price along the ship's route
[95] 2021	1- Port: port of Houston 2- Ship: Cruise, reefer	Port	1- Power grid electricity (CI) 2- Startup & shut-down cost of DGs 3- Additional energy 4- Fuel	N/A	Dynamic pricing mode	N/A	Addressing the strategy of dynamic pricing mode by purchasing more electricity during low-price intervals
[85] 2021	Involves several ports with general ships	1- Government 2- Port 3-A another port operators	1- CI Implementation 2- Active government supervision 3- Passive government supervision	1- Income from shipping 2- Government benefit	1-Subsidy incentive 2-Government fines	1- Different government fine values 2- Subsidy parameter	Studying strategies of different stakeholders
[88] 2021	Port: Involves several ports in China Ship: Cargo	1- Energy operator 2- Government 3- Port 4- Ship	1- Bunkering of ship 2- Retrofitting and maintenance cost	N/A	N/A	1- Volatility of electricity price 2- Availability of CI facilities at ports	Discussing the interests of stakeholders in the CI

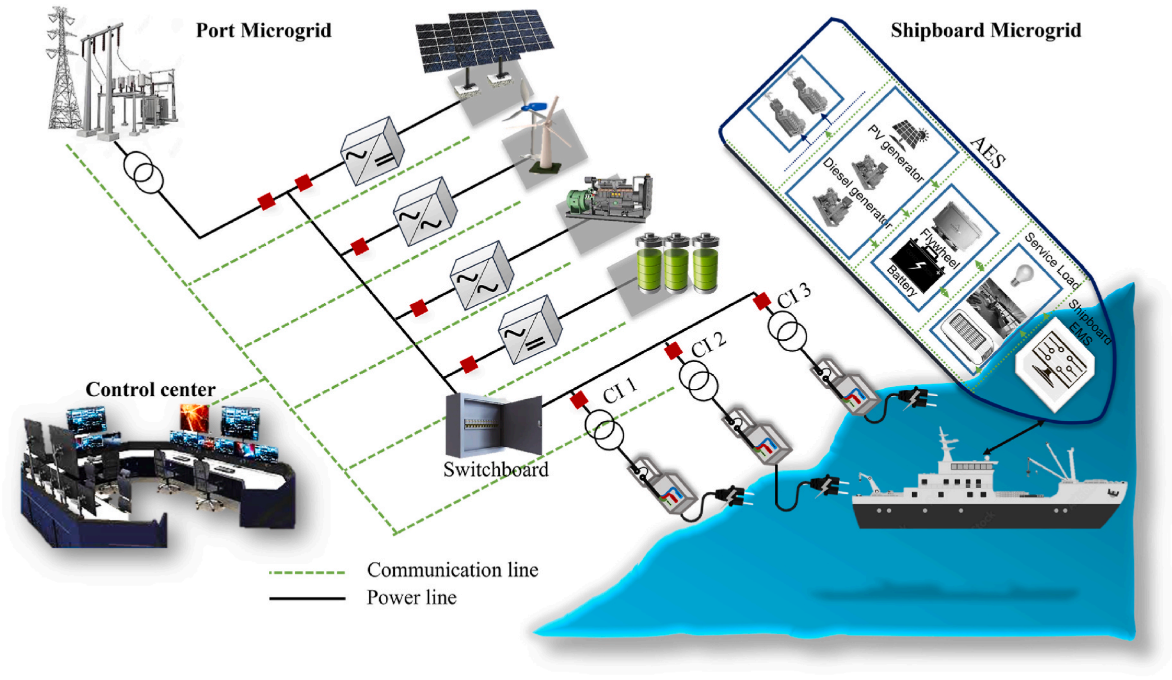


Fig. 4. Coordination between cold ironing and microgrid system.

configuration in Ref. [99] suggests that the integration of RES and ESS will reduce the pressure on the grid performance during peak demand. ESS arrangement is not only beneficial to store and release the energy for grid balancing issues but also advantageous to cover the deviation from the uncertainty of solar farms and wind turbines output power. However, establishing high-capacity CI facilities implies a greater investment cost to the port operator.

In [100], the impact of CI on the output power of diesel generators with the MG system on the ship side (shipboard MG diesel-PV-ESS-CI) instead of considering MG on the shoreside is investigated. While other studies only focus on either shipboard MG or CI alone, this study evaluates the combination of CI and shipboard MG considering that all-electric ships (AES) may purchase the required power from the shore to charge the onboard ESS. The results from the CI and shipboard-MG demonstrate a decrease in diesel generators' consumption both during berth and after berthing interval, signifying the use of ESS charged by CI during berth. Consequently, total operating costs are reduced by 7% and show a significant emissions curb. Jing Qiu et al. [92] study a problem formulation for the CI using time-of-use (TOU)-based pricing with MG integration on both shore and ship sides. Other related studies for CI and MG integration are summarized in Table 10. Based on the existing publications, coordination between CI and MG studies can be classified into three categories: 1) MG on the shore side, 2) MG on the ship side (shipboard microgrid), and 3) MG on both shore and ship sides.

The collaboration between CI and MG can be summarized from the following perspectives.

1) Economical: The diversity of resources in a MG allows CI to operate flexibly by dispatching the ESS during peak hours and purchasing energy from the main grid to support CI services during intervals with a low electricity price. The surplus energy produced from RES can be sold back to the utility. Another benefit of harvesting energy locally is that it can cut the price of grid transmission cable and utility expansion to meet the demand from CI [106].
2) Environment control: Emission curtailment from the ships with CI strategy during their stay at the port can be group into local emissions control and global emission control. Due to the external emission from the shoreside resources, CI only eliminates the emissions from the ship but not from the shore (local emission control). The seaport microgrid provides the opportunity for CI to achieve global emission control (ship and shore sides) moving towards the zero-emission maritime target.
3) Energy security: The port itself is a complex system with numerous heavy machineries. Hence, high power consumption of CI facilities due to continuous supply to the ships during their stay especially during the peak demand caused by increased ship traffic arrival and simultaneous demand from large ships may lead to power outages and disruptions. In this regard, local ports' power generation from RES-based MGs which can operate independently during utility failures, ensures electricity security for seamless port operations.

5. Conclusion

This review provides a comprehensive overview of CI technology from different technological, economic, environmental, social, and regulatory framework viewpoints. The contributing factors driving the adoption of shore power are outlined and research directions that are worth investigating are presented. Apart from published articles, the technical reports, and government research on the shore power supply are also reviewed, highlighting the actual growing concerns of CI adoption. Mitigating shipping emissions in the maritime sector entails the coordination of different parties including legislation bodies, government, energy operators, ports, and shipping lines. Even though they have different roles and aims, the collaboration between them can make the technology deployment feasible. CI is undeniably beneficial to emission reduction, including also noise and vibration. However, the underlying issues of the costly installation, long payback period, and ship retrofitting costs have become the main obstacles to its wider adoption. Thus, a strategic framework for financial support which can provide mutual benefit to all parties involved is urgently needed. In addition, external pressure from higher levels will also enforce the quick development of CI technology. Therefore, financial initiatives, regulatory frameworks, and hybrid approaches appear to be able to promote CI which is also an opportunity for further research.

Another significant concern is the actual scale of the emission reduction from the CI execution, which is highly dependent on the end

Table 10
Cold ironing-Microgrid related studies (WT: wind turbine).

Ref	Year	MG components	Allocation of the MG	Evaluation aspect
[101]	2022	PV, ESS, Hydrogen (grid-connected MG)	Shoreside	- Emission
[92]	2022	Shore side- PV, WT (grid-connected MG) Ship side- Diesel, PV, ESS	Shore and ship side	- Economic (pricing strategy) - Emission
[87]	2022	grid-connected MG	Shoreside	- Emission - Processing time at berth
[102]	2022	PV, ESS	Shoreside	- Voltage control - Stability - Sensitivity analysis in penalty factor
[93]	2022	PV, WT, ESS, Diesel	Shoreside	- Economical - Emission - Handling time at port - Energy consumption
[103]	2022	Diesel, ESS	Shipside	- Electrical characteristic - Sensitivity analysis of energy storage cost
[104]	2022	Diesel, ESS	Shipside	- Forecasting CI electricity price - Economical - Emission - Ship navigation time
[94]	2021	Diesel, ESS	Shipside	- Forecasting CI electricity price - Economical - Emission - Ship navigation time
[95]	2021	PV, WT, ESS, CHP (grid-connected MG)	Shoreside	- Economic
[19]	2021	Diesel, PV, WT, ESS (grid-connected MG)	Shoreside	- Economic - Emissions - Sensitivity analysis
[100]	2021	Diesel, PV, ESS	Shipside	- Economic - Emission - Sensitivity analysis of different variable cost
[39]	2020	ESS	Shoreside	- Fast charging evaluation
[27]	2019	PV, WT	Shoreside	- Frequency deviation
[105]	2013	Flywheel ES	Shoreside	- Power quality

sources of shore power. Emission neutrality is possible with high utilization of renewable energy through the incorporation of CI and MG power systems. The good coordination between these two promising electrification alternatives in the maritime industry will not only curtail the emission to the maximum level but also serve as a platform for better operational management. The flexibility provided by integrating CI with MG becomes the added value of CI compared to other competitive solutions (LSFO and scrubber). In addition, CI is not limited to sulfur control only but is capable to reduce all kinds of air pollutants, vibration, and noise from ship activities. Due to its numerous benefits, further research directive on CI and MG integration may provide the maritime sector with new insights to assist them in making better decisions.

Credit author statement

NNA Bakar. Conceptualization, Data curation, Writing - original draft, Visualization, Investigation. N Bazmohammadi. Supervision, Writing – review & editing. JM Guerrero. Supervision, funding acquisition. JC Vasquez.; Supervision.

Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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Appendix A. Supplementary data

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