Journal of Sustainable Development Indicators

http://www.sdewes.org/jsdi

Year 2026, Volume 2, Issue 1, 2030696

Original Research Article

Modelling Cold-Ironing Potential in High-Density Ferry Quays: A Virtual Assessment for the port of Ancona

Nikolaos Sifakis[*1], *Dimitrios Cholidis*[1], *Alexandros Chachalis*[1], *Emina Melic*[2], *Samra Muratspahic*[2], *George Arampatzis*[1]

[1]Industrial and Digital Innovations Research Group (INDIGO), School of Production Engineering and Management, Akrotiri Campus, Technical University of Crete, 73100 Chania, Greece;

e-mail: nsifakis@tuc.gr, Enova d.o.o Sarajevo, Bosnia and Herzegovinia

Cite as: Sifakis, N., Cholidis, D., Chachalis, A., Melic, E., Muratspahic, S., Arampatzis, G., Modelling Cold-Ironing Potential in High-Density Ferry Quays: A Virtual Assessment for the port of Ancona, J. sustain. dev. indic., 2(1), 2030696, 2026, DOI: https://doi.org/10.13044/j.sdi.d3.0696

ABSTRACT

This study evaluates the shore-to-ship power (Cold Ironing, CI) potential of the Port of Ancona, a strategic Trans-European Transport Network (TEN-T) hub characterized by high-frequency Ro-Pax and ferry operations. Unlike container terminals with steady berth loads, ferry-dominated ports exhibit concentrated peak demand and significant grid stress, creating distinct infrastructural challenges for electrification. Five high-traffic quays were modeled to quantify aggregated berth-level electricity demand and assess the technical feasibility of phased CI deployment. Results indicate that full electrification would introduce an additional annual demand of approximately 52 GWh, primarily concentrated at three high-consumption terminals, thereby necessitating targeted medium-voltage grid reinforcement and centralized Static Frequency Converter (SFC) infrastructure. Transitioning from onboard auxiliary engines to shore power yields a 39% reduction in at-berth carbon emissions, corresponding to approximately 14,100 tonnes of CO_2 annually and 4,400 tonnes of marine fuel savings. Constrained rooftop photovoltaic (PV) integration contributes 1.27 GWh/year, enabling Net Zero land-side operations while the reinforced grid supports maritime loads. The study advances existing literature by moving beyond theoretical feasibility toward a demand-driven, phased implementation blueprint tailored to medium-sized, ferry-dominated TEN-T ports operating under spatial and infrastructural constraints. By integrating berth-level traffic prioritization, grid topology design, renewable optimization, and environmental scenario modeling, the proposed framework provides a replicable pathway for decarbonizing historic urban ports. Beyond emissions mitigation, the findings position shore power as a foundational infrastructure component for smart, regulation-compliant maritime mobility systems aligned with Sustainable Development Goals.

KEYWORDS

Cold-Ironing, Nearly zero energy ports, Port decarbonization, Maritime emissions, Photovoltaic system, Carbon footprint.

INTRODUCTION

The global maritime sector, an indispensable pillar of international commerce, is currently navigating a profound and necessary transition towards environmental sustainability [1]. Historically reliant on heavy fossil fuels, industry is a significant source of both greenhouse gases (GHG) and harmful atmospheric pollutants [2]. The emissions generated by shipping [3], particularly sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) [4], have

* Corresponding author

well-documented adverse effects on human health and marine ecosystems [5]. This environmental impact is mostly felt in and around port cities, where vessel operations are concentrated [6]. While ships are at berth, their continuous need for power is typically met by running onboard auxiliary diesel engines [7]. This practice, known as 'hoteling', transforms ports into significant stationary sources of local air pollution, directly impacting the quality of life for millions in coastal communities [8].

This transition is not merely voluntary but is increasingly mandated by stringent regulatory frameworks. At the European level, the "Fit for 55" package [9] and the Alternative Fuels Infrastructure Regulation (AFIR) have set aggressive targets, requiring major TEN-T ports to provide shore-side electricity for container and passenger ships by 2030 [10]. These policies aim to drastically reduce the maritime sector's reliance on fossil fuels, which currently accounts for a significant portion of global transport emissions [11]. Consequently, port authorities face the urgent challenge of upgrading their infrastructure to comply with these binding targets. This shifts the focus from theoretical feasibility to the practical necessity of integrating high-power electrical loads into existing, often constrained, port energy networks [12].

In response to this pressing challenge, a paradigm shift is underway, driven by international regulations from the International Maritime Organization (IMO) [13] and regional policies [14] like the European Green Deal [15]. Maritime ports are no longer viewed merely as logistical nodes but as active agents in the energy transition. This has given rise to the strategic vision of the nearly Zero Energy Port (nZEP) [16]. The nZEP concept represents a holistic approach to port development [17], aiming to minimize energy consumption through efficiency measures while meeting the remaining demand with locally produced renewable energy [18]. This ambitious goal involves integrating smart grid technologies, electrifying port equipment, and fundamentally reimagining the port's energy ecosystem to achieve a sustainable, low-carbon, and ultimately self-sufficient operational model [19].

A cornerstone technology in the journey towards transitioning to a nZEP is the electrification of berthed vessels [20]. To tackle the largest and most persistent source of port-side emissions, the implementation of cold-ironing, also known as shore-to-ship power, is essential [21]. The function of cold-ironing lies in a simple principle, instead of burning marine fuel in their auxiliary engines, docked vessels connect to the onshore electrical grid [22]. This transition to grid power offers the immediate and profound benefit of eliminating at-berth emissions of SO_x, NO_x, and PM, while also drastically reducing noise pollution [23]. As a foundational element of port electrification [24], cold-ironing is a critical first step in managing the port's energy load and paving the way for integration with renewable energy sources [25]. Cold ironing (CI) in ferry-dominated ports directly supports smart mobility by decarbonizing passenger flows, enabling integration with electrified hinterland transport, and facilitating digital coordination of vessel and port operations. This positions CI not only as an emissions mitigation tool, but also as a key enabler of sustainable, multimodal mobility chains in the Adriatic region [23].

While the technical standards for shore connection are established the operational implementation varies significantly by port type. Unlike container terminals, where vessels may remain at berth for days with steady power loads, ferry and Ro-Ro (Roll-on/Roll-off) terminals present a unique and dynamic operational profile [26]. These ports are characterized by high-frequency arrivals, short turnaround times, and intense power spikes required to maintain hotel services, heating, ventilation, and cooling, for thousands of passengers. This intermittent and fluctuating demand creates severe stress on the local electrical grid, distinguishing ferry-dominated ports from other maritime hubs [27]. Therefore, general models derived for cargo ports are often insufficient for assessing the grid impact on passenger-intensive hubs. Furthermore, the deployment of CI serves as a catalyst for the broader transformation toward the "Smart Port" paradigm [28]. By electrifying berths, ports evolve from simple transit points into sophisticated energy hubs capable of exchanging data and energy with the city grid. This integration necessitates the adoption of smart grid technologies to monitor consumption in real-time, balance loads, and optimize the use of distributed renewable energy resources [29]. In this context, CI is not an isolated technology but a cornerstone of port digitalization and decarbonization, enabling a symbiotic relationship between the port's energy demand and the urban environment's sustainability goals.

Despite increasing regulatory pressure and technological maturity of cold ironing systems, the transition from conceptual feasibility to practical implementation in ferry-dominated TEN-T ports presents a set of interrelated engineering, operational, and infrastructural challenges. (i) First, high-frequency Ro-Pax and Ro-Ro operations generate concentrated berth-level peak loads that substantially exceed the capacity of legacy medium-voltage port distribution networks, necessitating precise demand quantification and substation reinforcement strategies. (ii) Second, historic and urban-integrated Mediterranean ports are spatially constrained environments where large-scale ground-mounted renewable installations are infeasible, thereby limiting the potential for onsite energy autonomy and requiring realistic assessment of rooftop photovoltaic penetration limits. (iii) Third, the coexistence of a 50 Hz national grid with vessels designed for 60 Hz operation introduces a critical frequency mismatch, demanding centralized Static Frequency Conversion infrastructure capable of ensuring technical interoperability in compliance with IEC/ISO standards. (iv) Fourth, ferry-dominated ports exhibit pronounced demand volatility, including counter-cyclical seasonal peaks driven by winter hoteling heating loads rather than summer cooling patterns, complicating conventional grid dimensioning assumptions. (v) Finally, while prior studies address economic feasibility or renewable integration independently, there remains a structural absence of a phased, replicable implementation framework aligned with TEN-T electrification mandates and grounded in berth-level traffic realities.

In response to these challenges, this study pursues the following specific research objectives. (i) To quantify the aggregated annual and peak electricity demand associated with high-traffic ferry quays at the Port of Ancona using empirical berth-level traffic data and standardized vessel load assumptions. (ii) To design a technically compliant cold ironing system architecture centered on a centralized Static Frequency Converter (SFC) substation and multi-voltage distribution backbone tailored to the port's operational topology. (iii) To optimize constrained rooftop photovoltaic deployment through a multi-objective genetic algorithm that balances carbon footprint reduction and economic viability under strict spatial and grid export limitations. (iv) To evaluate the environmental implications of alternative operational scenarios through structured carbon footprint modeling, comparing onboard auxiliary generation, grid-powered cold ironing, and hybrid PV integration pathways. (v) To synthesize these technical, environmental, and infrastructural components into a phased, demand-driven implementation roadmap specifically applicable to medium-sized, ferry-dominated TEN-T ports operating under regulatory decarbonization mandates. By structuring the investigation around these explicitly defined challenges and objectives, the study advances cold ironing research beyond generalized feasibility assessments toward an integrated, engineering-grounded implementation methodology suitable for spatially constrained European ferry hubs.

LITERATURE REVIEW

To properly frame the specific application of CI technology within the context of the Port of Ancona, a thorough review of the existing scientific and technical literature is required. This section examines the current state-of-the-art by categorizing recent studies into three primary domains: economic and regulatory feasibility, socio-economic and health valuation, and technical integration with renewable energy microgrids. The following analysis identifies the established methodologies for shore power assessment while highlighting the specific research gaps regarding medium-sized, ferry-dominated ports.

Recent studies provide a comprehensive framework for evaluating the prospects of CI as an emissions reduction technology. One such study developed a quantitative model to examine the economic and environmental feasibility of shore power from the perspective of both ship and terminal operators, demonstrating that a strong economic motivation often exists for its adoption, particularly under supportive regulatory conditions **[30]**. In particular, Zis **[30]** quantifies the break-even electricity pricing thresholds under different fuel cost scenarios and explicitly models the sensitivity of cold ironing viability to carbon pricing mechanisms. This contribution is critical because it translates environmental compliance into operator-level financial decision-making metrics, highlighting that regulatory certainty plays a decisive role in accelerating adoption. However, the study remains largely policy-driven and does not extend to infrastructure topology design or site-specific grid constraints. Further research has addressed the need to move beyond large ports by examining the unique challenges of installing CI in a medium-sized port with numerous small berths, using the Port of Aberdeen as a case study. That analysis involved designing a specific low-voltage system and conducting a social cost-benefit analysis, concluding that such projects are feasible when the value of external benefits, such as reduced health costs from emission savings, are considered in the investment case **[31]**. Innes and Monios **[31]** further contribute by identifying governance fragmentation and berth dispersion as non-technical barriers that can delay CI deployment in smaller ports. Their detailed assessment of infrastructure retrofitting requirements emphasizes that medium-sized ports face proportionally higher per-berth costs compared to large hub ports due to the absence of economies of scale. While this insight is highly relevant for regional ports, the study does not examine renewable energy coupling nor the operational volatility associated with high-frequency ferry services. *Although these studies offer robust frameworks for assessing the feasibility of CI in container and cruise terminals, a significant gap remains in the literature concerning a comprehensive implementation roadmap for medium-sized, strategic TEN-T ports whose operations are dominated by high-frequency ferry traffic, particularly one that integrates on-site renewable energy generation.*

From a socio-economic perspective, studies have focused on quantifying the societal benefits derived from reducing harmful air emissions in ports. One study analyzes the impact of hoteling cruise ships by calculating the potential reduction in external health costs through a detailed cost-benefit analysis. Using an advanced air pollution valuation model for a case study at the Port of Copenhagen, the research quantifies the significant annual savings in health costs and demonstrates that the large capital investment for cold-ironing infrastructure can be recovered from a societal perspective in just over a decade **[32]**. Ballini and Bozzo **[32]** notably apply damage cost functions linked to particulate matter and nitrogen oxides exposure, translating emission reductions into monetized public health benefits. Their methodological strength lies in connecting port decarbonization strategies with measurable improvements in urban respiratory and cardiovascular outcomes. Nevertheless, their focus remains centered on cruise ship hoteling patterns, which differ substantially from the shorter but more frequent connection cycles typical of Ro-Pax ferry operations. Expanding on this, more recent and expansive reviews have begun to position CI within a wider strategy of total port electrification. Another comprehensive review provides an overview of the technology's operation and challenges but notably frames it as a foundational component for achieving ultimate seaport decarbonization through synergy with a seaport microgrid. This approach highlights the potential for CI to integrate directly with on-site renewable energy sources, moving beyond simply reducing local ship emissions to create a sustainable and resilient port energy system **[33]**. Abu Bakar *et al.* **[33]** synthesize advancements in converter technology, power quality control, and distributed energy resource coordination, arguing that shore power infrastructure should be embedded within smart microgrid architecture rather than treated as a standalone intervention. Their review systematically categorizes voltage levels, harmonic mitigation strategies, and regulatory harmonization challenges. However, while technologically comprehensive, the study remains conceptual and does not quantify renewable penetration limits under strict spatial constraints or ferry-driven peak loads. *Although the literature establishes the socio-economic case for CI in cruise ports and presents a strategic vision for its integration with renewable energy, a clear gap exists in the form of a practical,* *technical feasibility study and implementation roadmap for a strategic renewable port focused on passenger ferries, specifically one which models the direct energy contribution from co-located photovoltaic (PV) systems.*

Building on the vision of integrated systems, some studies provide detailed technical models for powering CI entirely with dedicated renewable energy sources. One such study proposes a complete CI system for the Port of Barcelona, where the total electrical demand from berthed ships is met by a specifically sized combination of offshore wind turbines and *PV* panels; the research uses simulation to confirm the technical stability of such a system **[34]**. Rolán *et al.* **[34]** demonstrate that under conditions of high renewable penetration, voltage stability and frequency regulation can be maintained through coordinated inverter control strategies. Their work is technically rigorous and validates the theoretical possibility of full renewable supply for shore power loads **[35]**. Nevertheless, the proposed configuration assumes large offshore wind availability and extensive spatial deployment potential, conditions not universally applicable to compact, historically integrated Mediterranean ferry ports. Complementing this approach, other research conducts detailed techno-economic comparisons between different shore-based hybrid renewable configurations. A recent analysis, for instance, evaluates benchmarks PV/battery and novel PV/fuel cell systems, using hydrogen derived from different types of ammonia, against conventional grid power and onboard generation. This work provides a granular comparison of environmental performance (CO_2 eq. reduction) and economic viability (LCOE and payback period) for these advanced technological pathways **[36]**. Yuksel *et al.* **[36]** contribute by incorporating life-cycle emissions accounting and advanced fuel pathways into shore power system benchmarking. Their comparative framework highlights the trade-offs between capital-intensive hydrogen systems and more mature PV-based solutions. However, the analysis remains largely technology-oriented and does not explicitly address quay-level demand concentration, ferry-induced seasonal variability, or the practical sequencing of infrastructure deployment within an operational port environment. *While these detailed studies confirm the technical and economic viability of powering CI with dedicated renewable energy systems, they focus primarily on system design and modeling for container or large mixed-cargo ports. A gap therefore exists in providing a practical, phased implementation roadmap that addresses the unique grid and operational challenges of a strategic TEN-T port specializing in passenger and ferry services. Specifically, the literature lacks a demand-driven quay prioritization methodology, a grid reinforcement strategy tailored to aggregated ferry peak loads, and a quantified assessment of rooftop-constrained photovoltaic contribution under historic urban spatial limitations. Moreover, few existing studies integrates frequency conversion infrastructure (50/60 Hz mismatch), regulatory compliance pathways, renewable optimization, and phased deployment sequencing into a unified, replicable engineering blueprint for ferry-dominated Mediterranean ports.*

A review of the literature confirms that while frameworks for assessing CI are well-established, a significant and practical research gap exists. Existing studies focus on high-level assessment or system modelling, often for large container or cruise terminals. This reveals a clear gap in the literature: the scarcity of a holistic and replicable implementation blueprint tailored for a strategic TEN-T port dominated by high-frequency passenger, ferry and cargo traffic. More specifically, prior research tends to isolate individual dimensions of the problem, economic feasibility, renewable integration, health externalities, or converter technology, without integrating these dimensions into a unified engineering and operational framework applicable to real-world ferry-dominated ports.

While economic models establish conditional viability, and renewable simulations validate theoretical decarbonization potential, there remains a disconnect between conceptual feasibility and executable infrastructure sequencing within spatially constrained, urban-integrated ports. This study addresses this gap directly by providing a detailed, phased roadmap that integrates technical evaluations, including the strategic identification of the most traffic-heavy docks to tackle the core of the problem rather than pursuing a generalized, port-wide implementation, with grid load balancing tailored to a specific port's topology and energy offsets from PV input, all combined with crucial procedural steps like procurement, stakeholder alignment, and regulatory compliance.

The novelty of the present research lies not merely in evaluating cold ironing potential, but in structuring a demand-driven decarbonization pathway grounded in empirical berth-level traffic analysis. By quantifying aggregated ferry hoteling loads and explicitly modeling their impact on medium-voltage infrastructure, the study transitions from abstract emission reduction targets to actionable grid reinforcement requirements. This approach bridges the methodological divide between environmental modeling and electrical engineering design, a gap largely unaddressed in the existing literature. By using the Port of Ancona as a case study, this research provides a critical and practical guide for a common but under-researched category of European ports.

Furthermore, unlike studies that assume renewable energy sufficiency as a primary decarbonization mechanism, this work rigorously evaluates the physical and spatial constraints imposed by historic urban port environments. Through constrained photovoltaic optimization and peak-load modeling, it demonstrates the structural limitations of onsite renewable penetration and introduces the concept of functional decoupling – where landside operations approach Net Zero through rooftop PV, while maritime loads are supported through reinforced grid infrastructure. This reframing offers an alternative to prevailing narratives of full energy autonomy and replaces them with a context-sensitive, infrastructure-realistic decarbonization strategy.

Besides, this research distinguishes itself by incorporating frequency conversion infrastructure (50/60 Hz mismatch), dynamic load management considerations, and phased deployment sequencing aligned with TEN-T regulatory deadlines. Few prior studies have simultaneously integrated these technical, regulatory, spatial, and operational variables into a single replicable implementation blueprint tailored to high-density Ro-Pax and ferry operations. Thus, the principal academic contribution of this work resides in advancing cold ironing research from feasibility discourse toward implementation science, offering a structured, transferable methodology for ports facing high-frequency vessel turnover, constrained renewable deployment capacity, and mandatory electrification targets under European climate policy frameworks.

Table 1 presents a summary of the literature, comparing the contributions of previous research with those of the current study.

Table 1. Comparison of Recent Literature and Current Study Contributions

Ref	Scope & Objective	Port Type	Energy Source	Limitation / Gap Addressed
[30]	Model economic feasibility for operators	General / Mixed	Grid vs. Marine Fuel	Focuses on operator economics and regulation; lacks site-specific technical implementation.
[31]	Social Cost-Benefit Analysis (CBA)	Medium-sized (Aberdeen)	Low-Voltage Grid	Focuses on small berths; does not model renewable energy integration.
[32]	Health Cost Valuation Externalities	Large Hub (Cruise)	Grid (CI)	Specific to Cruise ships; focuses on societal/health valuation rather than grid/technical roadmap.
[33]	Technology Review Microgrids	General	Microgrid (Renewables)	Comprehensive review of concepts; lacks a specific, practical deployment roadmap for a case study.
[34]	Technical Simulation of Stability	Large Hub (Barcelona)	Offshore Wind + PV	Models a massive hub port; relies on offshore wind which is not viable for all constrained urban ports.

Ref	Scope & Objective	Port Type	Energy Source	Limitation / Gap Addressed
[36]	Techno-economic Benchmarking	General / Theoretical	Hybrid (H2, PV)	Focuses on advanced/future fuels; less emphasis on immediate grid integration challenges.
This Study	Phased Implementation Roadmap	Ferry-Dominated TEN-T	Grid + Constrained PV	Addresses high-frequency ferry peaks; Models specific grid load; Optimizes PV for constrained port land.

METHODS

The methodological framework adopted for this study aims to provide a comprehensive assessment of the technical, economic, and environmental viability of cold-ironing integration. The approach is structured into five distinct phases: establishing the operational baseline through case study analysis, defining the system architecture, simulating renewable energy integration, quantifying environmental impacts, and finally, synthesizing these elements into a phased implementation roadmap. The following sections detail the specific procedures applied at each stage.

Case Study Description

The case study for this research is the Port of Ancona, a strategic port situated in the Central Adriatic Sea. As a vital station for both passenger and freight movement, the port experiences high berth occupancy rates which contribute to significant local air quality pressures [37]. This study's intervention is specifically targeted at five of the port's busiest passenger quays, which are primary contributors to at-berth emissions due to high-frequency traffic. Data regarding specific vessel calls and duration of stay were obtained directly from the Ancona Port Authority. While the granular traffic logs are confidential and cannot be published, the modelling utilized aggregated average values derived from this dataset. To ensure reproducibility while maintaining confidentiality, the study adopted standard vessel class ranges for auxiliary power: Ro-Ro/Ro-Pax ferries were modelled with an average hoteling load of 1,500–2,200 kW and Cruise ships with 6,000 – 8,000 kW, consistent with the specific traffic profile of Ancona and verified against valid literature ranges.

The data reveals a distinct seasonal pattern in energy consumption, directly linked to the port's operational tempo with a total consumption of 1.2 GWh (**Figure 1**). Demand rises significantly during the summer months of July, August, and September, corresponding to the height of the passenger ferry season. During this period, the port's power demand frequently exceeds 250 kW hourly, reaching a maximum of approximately 280 kW, while demand is lowest during the spring months. This existing, fluctuating load profile provides the essential baseline upon which the new energy demand from the proposed CI system will be analysed.

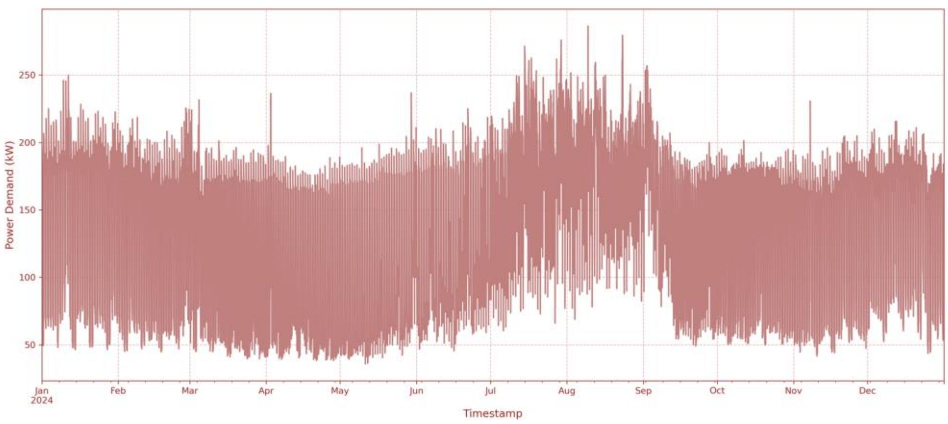

Figure 1. Ancona port facilities energy demand

The intervention for this study is specifically targeted at the port's busiest terminals: Quays 11, 13, 15, 16, and 26. These five quays were selected as accommodate the highest volume of vessel traffic. The operational tempo at these quays is intense and varied, characterized by a mix of short transit calls and longer turnaround stays where vessels remain docked for extended periods. This constant and dynamic traffic pattern makes these quays the primary source of at-berth emissions within the port, and therefore the ideal location for pilot CI implementation.

To evaluate the potential for offsetting this energy demand with on-site renewables, an analysis of the local solar resource is necessary. The clearness index is a key metric for this, quantifying the solar radiation that reaches the ground. As is expected for the Ancona region, the summer months exhibit the highest clearness index, indicating the most favorable conditions for PV installation. This period of maximum solar availability aligns perfectly with the port's peak energy demand from ferry traffic, creating a strong synergy for the proposed system. However, the on-site implementation of PV systems faces specific local constraints. The port's location near the historic city center imposes strict spatial limitations, precluding the installation of large ground-mounted solar arrays within the immediate port perimeter. Specifically, a detailed spatial analysis revealed that ground-level installations may be unfeasible due to critical land-use conflicts with freight logistics and significant dynamic shading caused by mobile harbor cranes and docked vessel structures. Consequently, the primary analysis focuses on the rooftops of existing terminal buildings and locations outside of the urban city. Nevertheless, to fully offset the significant energy demand of the cold-ironing system, the study also acknowledges the potential for off-site renewable generation. Areas outside the dense urban fabric of Ancona offer viable locations for larger PV installations, which could supply green energy to the port via the national grid or dedicated Power Purchase Agreements (PPAs), thereby overcoming the spatial limitations of the historic waterfront.

System Design

The technical configuration of the cold-ironing system was developed to address the specific infrastructural constraints and operational requirements of the Port of Ancona. A critical design constraint for this location is the frequency mismatch: the local Italian grid operates at 50 Hz, whereas many ocean-going ferries and Ro-Ro vessels calling at Ancona require 60 Hz. Consequently, the proposed architecture centers on the installation of a centralized Static Frequency Converter (SFC) substation. This unit is strategically located near Quay 15, the center of gravity for the port’s energy demand, to minimize transmission losses and cable runs.

To ensure global interoperability in compliance with IEC/ISO/IEEE 80005 standards **[38]**, the system is designed to provide a multi-voltage output tailored to the specific traffic mix identified at each target quay. Medium Voltage (11 kV/6.6 kV) infrastructure is deployed at Quays 15, 16, and 26. These terminals host large Ro-Pax ferries and cruise vessels with peak hoteling loads exceeding 5 MW, making high-voltage connections essential to minimize current draw and cable weight. Conversely, Low Voltage (440 V/400 V) infrastructure is deployed at Quays 11 and 13, which primarily serve high-speed craft and smaller service vessels with lower power demands (typically <1 MW).

The port’s existing electrical infrastructure is connected at the medium-voltage (MV) level, which requires careful load management for large-scale shore power deployment. To validate the electrical feasibility of the 11 MW peak demand, a simplified transformer sizing calculation was conducted. Assuming a worst-case aggregated peak load of P= 11MW and a target power factor of cosφ = 0.9, the required apparent power is calculated as $S = \frac{P}{\cos\phi} \approx$ 12.22 MVA. Consequently, the centralized SFC substation is designed with a standard 15 MVA step-up transformer to safely accommodate this demand **[39]**.

While precise, real-time upstream capacity data from the local Distribution System Operator is proprietary, the feasibility of accommodating this load can be validated through standard utility design principles. Strategic TEN-T ports like Ancona are typically serviced by primary urban substations equipped with multiple 40 MVA or 63 MVA transformers operating with N-1 redundancy. For the proposed system to be viable without requiring new high-voltage transmission lines, the local grid must provide an available capacity margin of at least 12.5 MVA. Given typical urban grid sizing, assuming this margin is available represents a realistic boundary condition for this feasibility study. Finally, to ensure thermal and voltage stability at the port connection node (assumed at the standard Italian 20 kV distribution level), the maximum drawn current is approximately $I = \frac{s}{\sqrt{3}v} \approx 353$ A. This falls well within the thermal ampacity limits of standard cables [40], [41].

Given the spatial constraints of Ancona's historic port area, where apron space is limited, the design prioritizes underground cable trenching over surface-mounted conduits. This approach ensures that the movement of heavy freight vehicles and passenger disembarkation remains unobstructed [42]. The system incorporates automated Cable Management Systems to safely handle the heavy connection cables and maintains a target power factor of 0.8 – 0.9 to ensure grid stability under the highly variable load profile of the ferries [43]. **Table 2** summarizes the technical specifications of the proposed system [30].

Table 2. Technical Specifications of the proposed Ancona Cold Ironing System

Parameter	Small Vessels	Medium Vessels
Voltage	400 V, 440 V, 690 V (LV)	6.6 kV, 11 kV (MV)
Frequency	50 Hz (Grid) or 60 Hz (Converted)	50 Hz (Grid) or 60 Hz (Converted)
Power Capacity	1 – 2 MW	2 – 8 MW
Power Factor	0.8 – 0.9	0.8 – 0.9
Cable Type	Low-voltage cables (400 V – 690 V)	6.6 kV – 11 kV
Target Vessels	High-Speed Ferries, Service Craft	Ro-Pax, Cruise Ships, Ro-Ro
Connector Standard	IEC/ISO 80005 (LVSC)	IEC/ISO 80005 (HVSC)
Typical Load	Lighting, small HVAC, communication	Refrigeration, HVAC, cargo handling

Simulation Modeling

The integration of a PV system within the constrained environment of the Port of Ancona presents a complex, non-linear optimization problem. Traditional deterministic sizing methods were deemed insufficient for this study due to the conflicting nature of the design objectives and the site-specific physical limitations. Consequently, a Multi-Objective Genetic Algorithm (GA) was developed to identify the optimal system configuration.

The primary reason for employing a GA lies in its ability to navigate a vast solution space where simple linear programming fails. Specifically, the algorithm seeks to resolve the trade-off between two competing objectives: minimizing the Levelized Cost of Energy (LCOE) to ensure economic viability and maximizing the Carbon Footprint (CF) reduction to achieve the port's sustainability goals. Crucially, the optimization is not performed in a vacuum but is bound by strict site-specific constraints identified during the case study analysis. First, spatial constraints dictate that ground-mounted arrays are prohibited due to the port’s location within a historic urban fabric; thus, the algorithm is restricted to placing modules solely on the rooftops of designated freight terminals and administrative buildings. Second, the model accounts for dynamic shading from mobile harbor cranes and docked vessel superstructures, which prevents the overestimation of energy yield common in standard models. Finally, the system size is capped by grid export limits to ensure peak generation does not exceed the thermal limits of the local medium-voltage substation transformers.

Figure 2 illustrates the GA workflow. The algorithm iteratively evolves a population of candidate solutions, varying module type, tilt angle, and array size to converge on a Pareto-optimal frontier. To ensure the solution is both robust and reproducible, specific termination criteria and heuristic parameters were defined. The algorithm was initiated with a population size of 200 individuals to ensure sufficient diversity in the initial search space. Termination is governed by a dual-criterion approach: a maximum limit of 1000 generations serves as a hard stop, while a stall generation limit is applied to ensure convergence efficiency. Specifically, the algorithm terminates if the weighted objective function value fails to improve by a function tolerance of 1×10^{-6} for 200 consecutive generations. Furthermore, to prevent premature convergence at local optima, the algorithm utilizes a crossover fraction of 0.8 combined with an adaptive mutation function. This configuration allows the model to balance the exploration of new potential solutions with the exploitation of the best-performing candidates identified in previous generations.

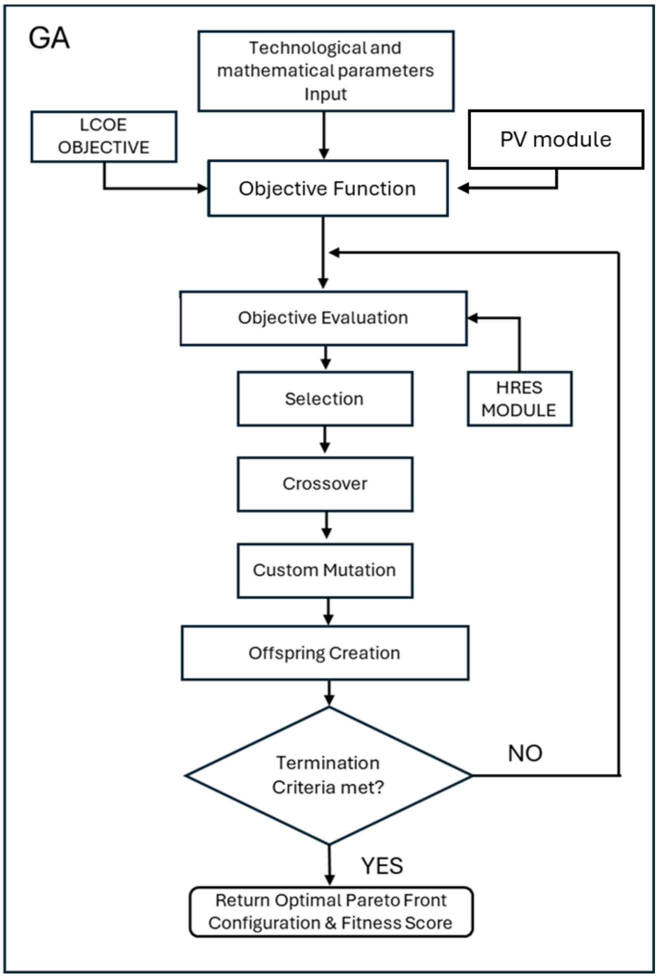

Figure 2. GA flowchart

Environmental Impact

To quantify the environmental benefits of the proposed intervention, the CF (expressed in tonnes of CO_2 equivalent per MWh) was modeled for three distinct operational scenarios. This approach allows for a direct comparison between the baseline conditions and the proposed system with CI and PV integration. The methodology for each scenario is based on calculating the total annual energy consumption and multiplying it by the appropriate Carbon Emission Factor [30].

First, the baseline emissions from the ships at berth were calculated. This scenario represents the current practice where vessels use their own auxiliary diesel engines for hoteling power. The total carbon footprint is a function of the total energy demand of the ships at the five target quays multiplied by the emission factor for marine fuel oil:

$$\text{CF VESSELS} = \text{Fuel Energy Ships} \times \text{CEF FUEL} \tag{1}$$

Second, the emissions for ships using CI were modeled. In this proposed scenario, the vessels' energy demand is met by the onshore electrical grid. The total carbon footprint is therefore calculated using the same energy demand but multiplied by the emission factor for the national grid, which is approximately estimated at 426 g CO_2/kWh:

$$\text{CF CI} = \text{Fuel Energy Ships} \times \text{CEF GRID} \tag{2}$$

Finally, the emissions for the port facilities integrated with a PV system were modeled. In this proposed scenario, the total carbon footprint is a composite of the reduced energy drawn from the grid and the near-zero emission energy generated by the PV installation:

$$\text{CF PORT PV} = (\text{Grid Usage} \times \text{CEF GRID}) + \text{PV production} \times (\text{CEF PV}) \tag{3}$$

By establishing the carbon footprint for each of these scenarios, this methodology provides a clear and robust basis for quantifying the precise environmental benefits of the proposed decarbonization pathway (**Figure 3**).

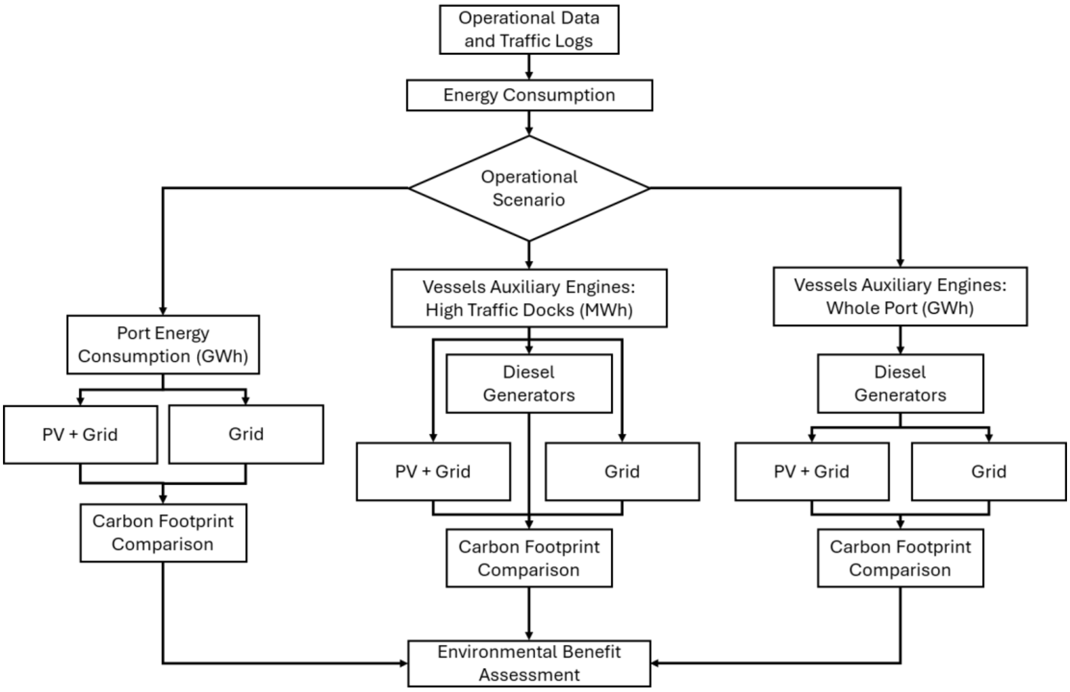

Figure 3. Flowchart of the environmental impact assessment methodology

Methodological Assumptions and Limitations

To ensure the transparency and replicability of the results, this study operates under a specific set of boundary conditions. The following key assumptions and limitations underpin the modeling framework:

- **Aggregated Power Loads:** Due to the confidentiality of high-resolution telemetry, vessel power demand is modeled using aggregated average hoteling loads (e.g., 1,500 –

2,200 kW for Ro-Pax ferries) derived from Port Authority data. While this creates a robust baseline for substation sizing, it simplifies the minute-by-minute fluctuations of onboard equipment.

- **Static Emission Factors:** The environmental impact assessment utilizes a constant annual average carbon intensity for the national grid. This conservative estimate does not account for hourly variations in the grid mix (e.g., lower emissions during high renewable production periods), potentially underestimating the dynamic benefits of shore power.
- **PV Generation Constraints:** The solar energy yield is calculated using standard Typical Meteorological Year (TMY) data for the Ancona latitude. The model prioritizes spatial constraints, specifically the exclusion of ground-mounted arrays due to shading from cranes and logistics operations, over theoretical maximums, but it does not factor in long-term panel degradation rates.
- **Grid Infrastructure Stability:** The feasibility of the proposed connection assumes the local medium-voltage grid has sufficient reserve capacity to accommodate the new 11 MW peak load without requiring upstream reinforcement beyond the substation level. Detailed power flow studies of the external distribution network were outside the scope of this port-focused analysis.
- **Scope of Emissions (TtW):** The environmental analysis focuses on Tank-to-Wake (TtW) emissions at the port to directly compare onboard combustion against grid usage. It does not conduct a full Well-to-Wake (WtW) lifecycle analysis, meaning it excludes upstream emissions associated with fuel production or the manufacturing of PV panels and battery systems.
- **Pathway Comparisons:** The comparative analysis between CI+PV and PV-only comparison assumes a fixed energy demand baseline. It serves to highlight the impact of 'seaside' versus 'landside' interventions, illustrating that maritime loads remain the dominant emission source.
- **CAPEX and Financial Modeling:** While the study acknowledges the 'essential' nature of grid reinforcement, it does not provide a primary-data-driven financial audit. Infrastructure costs are discussed based on literature benchmarks and regional averages. The focus remains on the technical feasibility and environmental impact as a prerequisite for future detailed financial planning.

RESULTS AND DISCUSSION

This section presents and discusses the results obtained from the proposed methodology, focusing on the implications of shore-side electrification for the Port of Ancona. The analysis addresses both the quantitative assessment of energy demand and the strategic considerations for infrastructure deployment. In particular, the results highlight how demand distribution across port facilities informs dock prioritization and supports the need for targeted grid upgrades.

The introduction of a CI system is projected to have a profound impact on Port of Ancona's overall energy profile. The analysis indicates that the total annual electricity demand from vessels at berth would be approximately 52 GWh. When added to the port facilities' existing baseline consumption of 1.2 GWh, the total demand represents a more than 40-fold increase. This substantial new load underscores the necessity of a robust grid analysis and a phased implementation strategy to ensure the port's electrical infrastructure can manage the new capacity requirements. It should be noted that this figure represents a 'full electrification' scenario, assuming 100% of eligible vessels connect; in practice, actual demand may be lower during the initial transition due to vessel retrofitting timelines and the gradual enforcement of regulatory mandates. The new energy demand is not distributed evenly across the port; it is concentrated at the busiest passenger terminals.

As illustrated in **Figure 4**, the energy audit reveals a clear hierarchy of demand. Quays 13, 15, and 26 emerge as "High Consumption Docks," collectively driving the vast majority of the port's energy needs. Although grouped in the lower consumption category in **Figure 4**, Quays 16 and 11 exhibit a consumption magnitude nearly double that of the next highest terminal (Quay 23), justifying their inclusion in the electrification plan. This Pareto-like distribution visually validates the study's scope: by targeting just these top five quays, the intervention addresses 72% of the total potential demand (approx. 37.5 GWh) while minimizing infrastructure complexity. This concentration of demand confirms that the centralized grid upgrades proposed in Section 3.2 are not just beneficial, but essential for avoiding grid congestion.

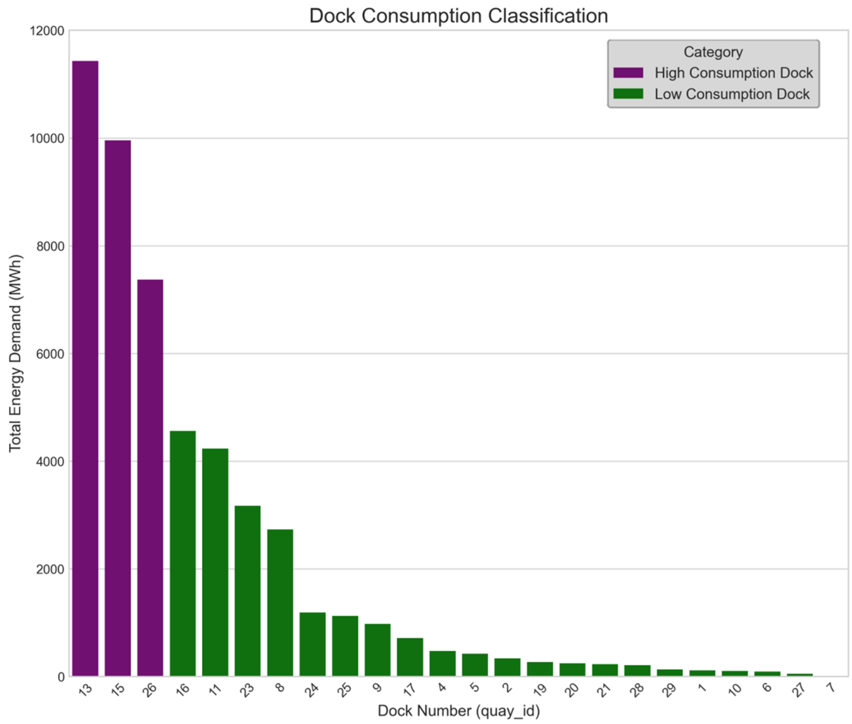

Figure 4. Dock Consumption Classification identifying the priority terminals for electrification

The breakdown of their annual energy consumption post-implementation is as follows in **Table 3**.

Table 3. Distribution of Cold Ironing Energy Demand Across High-Traffic Quays

Quay Number	Cold Ironing Total Consumption (MWh)
11	4,200
13	11,500
15	9,900
16	4,500
26	7,400
High Traffic Docks	37,500

To ensure the grid is sized correctly, it is essential to understand the operational drivers of this consumption. **Figure 5** decomposes the traffic specifically for the five selected high-consumption docks. The data confirms that Ro-Ro Cargo vessels are the dominant operational force, accounting for over 600 visits annually.

This dominance explains the "baseload" nature of the energy profile observed in the simulation; Ro-Ro vessels arrive frequently and have consistent hoteling requirements. In contrast, Container and Liquid Bulk vessels appear less frequently but introduce significant power spikes due to their high auxiliary loads (pumps and reefer units). This granular traffic insight, showing a mix of high-frequency Ro-Ro and high-power bulk carriers, confirms the necessity for the dynamic voltage support system proposed in the methodology. It further suggests that while Ro-Ro traffic provides a predictable revenue stream for the CI system, the sporadic but intense peaks from Liquid Bulk carriers will be the primary driver of grid dimensioning.

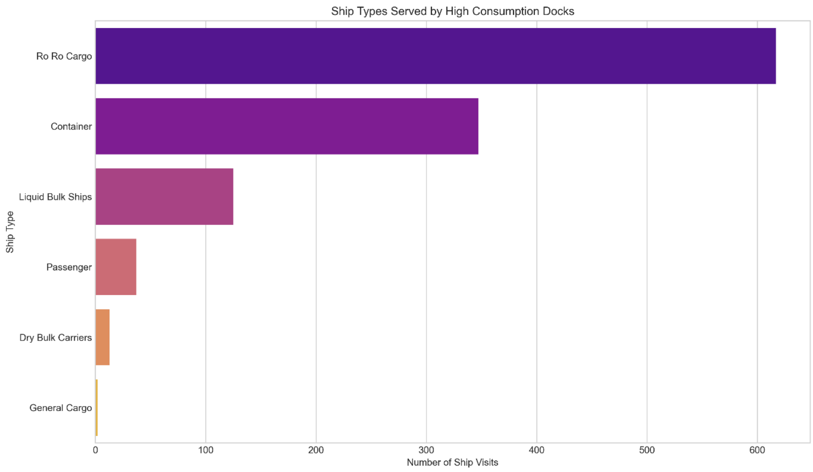

Figure 5. Distribution of ship types served specifically by the five high-consumption docks

Further granularity is provided by the seasonal analysis in **Figure 6**, which isolates the monthly energy demand specifically for the highest-consuming terminal, Quay 13. A critical finding is the divergence from the general port trend. While the port's baseline electricity consumption peaks in summer due to passenger terminal air conditioning (as noted in Section 3.1), the ship-side demand peaks in December (~1.7 GWh) and January.

This winter peak is driven almost exclusively by the consistent baseload of Ro-Ro traffic, likely due to increased onboard heating requirements during hoteling. Conversely, Liquid Bulk traffic shows an intermittent pattern, appearing primarily in late summer and autumn (August–December), creating sporadic load additions on top of the Ro-Ro baseload. This "counter-cyclical" profile is advantageous for grid stability, as the highest ship loads occur in winter when the port's building cooling loads are at their lowest.

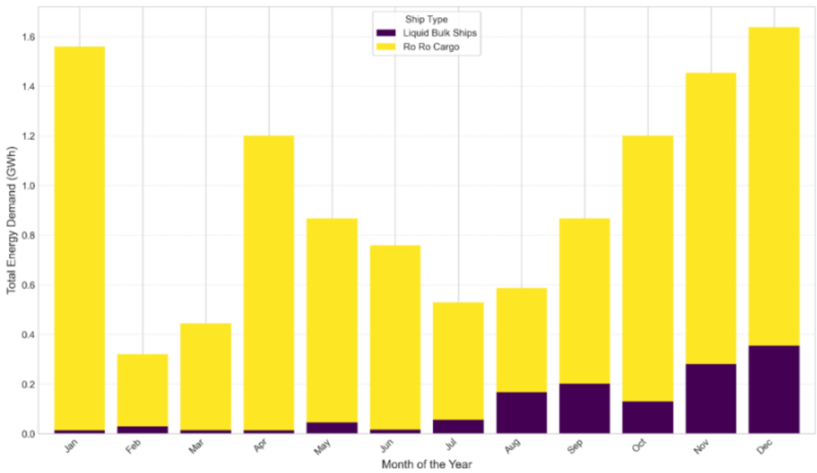

Figure 6. Seasonal profile of the projected Cold Ironing energy demand (Quay 13)

The application of the Multi-Objective GA demonstrates that while onsite renewable generation is feasible, its potential is strictly governed by the physical limitations of the port infrastructure. Constrained by the available rooftop surface area across administrative and freight terminals, the optimization process converged on a maximum installed capacity of 980 kWP. This configuration is projected to yield an annual energy generation of 1.27 GWh to cover the energy needs of the Ancona port facilities. However, when compared against the substantial energy requirements of high traffic docks CI, estimated at 37.5 GWh for those priority quays, the onsite PV system can meet only approximately 3.4% of the total energy demand. This disparity provides quantitative corroboration of the "spatial constraint" hypothesis, indicating that in historic, urban-integrated maritime hubs such as the Port of Ancona, achieving energy autonomy exclusively through onsite renewables is technically unfeasible without significant off-site generation or land reclamation.

The temporal characteristics of this generation capacity, as illustrated in **Figure 7**, exhibit a standard Gaussian irradiation curve consistent with the latitude of Ancona, reaching a peak production of approximately 7 MWh/day in July. This generation profile reveals a critical temporal mismatch with the load profile delineated in Section 4.2. Specifically, a seasonal misalignment is observed wherein solar generation peaks during the summer months, coinciding with the period of lowest ship-side demand and the absence of the "Winter Peak" associated with Ro-Ro heating requirements. Furthermore, a diurnal disparity is evident, as renewable generation is confined to daylight hours, whereas ferry hoteling loads persist continuously throughout the night.

Considering these constraints, the study concludes that the optimal role of the PV system is not to directly power the high-intensity ship-to-shore load, but rather to offset the port's baseload. The generated 1.27 GWh is sufficient to render the port's administrative buildings and logistical facilities Net Zero. This strategy effectively decouples "landside" operations from the grid, allowing the renewable infrastructure to function efficiently, even while "seaside" vessels remain dependent on the Static Frequency Converter (SFC) substation.

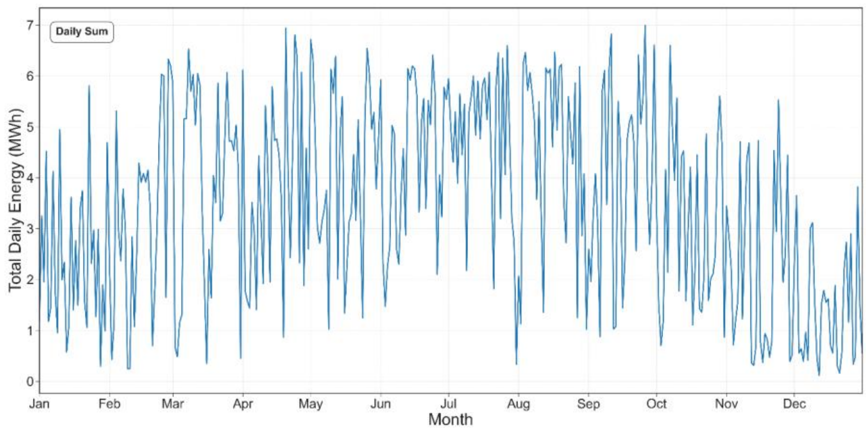

Figure 7. Projected Daily Energy Production for the Proposed Photovoltaic System for the port facilities

The environmental impact analysis quantifies the substantial reduction in the port's carbon footprint attributable to the implementation of the proposed CI and PV systems. Under the baseline scenario, defined by the reliance of vessels on onboard auxiliary engines, the total annual carbon footprint for the 52.18 GWh energy demand at the whole port is estimated at 36,354.7 t CO2 eq. This figure identifies hoteling vessels as the single largest source of emissions within the port boundary.

By transitioning these vessels to the proposed CI infrastructure, utilizing power drawn from the national grid, the carbon footprint for the equivalent energy demand is projected to decrease to 22,233.5 t CO2 eq. Furthermore, the specific implementation of cold ironing at the five high-traffic docks accounts for 16,033.8 t CO2 eq. of this total. This analysis highlights that these specific docks contribute the vast majority of the port's total cold-ironing emissions profile, validating the prioritization of these terminals.

The port's cold ironing transition represents a direct annual abatement of over 14,100 tonnes, or a 39% reduction, achieved by shifting power generation from inefficient marine diesel engines to the more regulated and diversified national energy mix.

Furthermore, the integration of the onsite PV system provides a complementary decarbonization strategy. In the "Hybrid Scenario," where the port's administrative and shoreside demands are met through a combination of onsite solar (1.27 GWh) and grid imports (0.84 GWh), the operational carbon footprint is minimized to 407.3 t CO2 eq. This confirms a dual-impact strategy: the primary emission source (vessels) is mitigated via electrification, while the carbon intensity of land-side operations is effectively reduced through renewable generation (**Table 4**).

To further validate the necessity of vessel electrification, a comparative analysis of the decarbonization pathways was performed. While the integrated CI and PV strategy achieves a 39% reduction in the port's total carbon footprint, a scenario involving only PV implementation for port facilities (excluding Cold Ironing) would result in a significantly lower abatement of approximately 27.47% relative to the total potential maritime emissions. This disparity quantitatively demonstrates that while onsite renewables are essential for achieving Net Zero land-side operations, they cannot significantly mitigate the port's primary environmental impact without the direct electrification of 'seaside' hoteling loads.

Table 4. Comparison of Annual Carbon Footprint (tonnes CO_2e) for Baseline and Proposed Scenarios

Scenario	Technology	Annual CF (t CO_2 equivalent)
Baseline: Ships at Berth	Fuel Auxiliary Engines	36,354.7
Cold Ironing: All Ships at Berth	Cold Ironing (Grid Power)	22,233.5
Cold Ironing: High Traffic Docks	Cold Ironing (Grid Power)	16,033.8
PV: Port Facilities	PV + Grid Hybrid System	407.3

The calculated carbon footprint of ~14,100 t CO2 eq. corresponds to an estimated annual saving of 4,400 tonnes of marine fuel, derived using the IMO/IPCC emission factor of 3.2 tonnes CO_2 per tonne of fuel. This metric underscores the thermodynamic efficiency gains realized by substituting shipboard combustion with centralized grid electricity. From an economic perspective, assuming an average Marine Gas Oil (MGO) price of 700 EUR/t, this fuel conservation translates into direct operating cost reductions of approximately EUR 3 million per year for ship operators. These savings strengthen the economic rationale for adoption, complementing the regulatory imperatives driving cold-ironing deployment.

From a societal perspective, the decarbonization pathway generates significant value through the internalization of external costs, specifically improved air quality and reduced climate impacts. Applying conservative social cost of carbon (SCC) estimates of EUR 50 – 150/t CO2, the avoided emissions correspond to EUR 0.7 – 2.1 million in annual societal benefits. These quantified benefits underscore the project's direct contribution to UN SDG 3. By eliminating 14,100 tonnes of CO2 and reducing associated SOx and NOx emissions, the intervention directly alleviates the respiratory and cardiovascular health burdens on the local Ancona community. Furthermore, the transition to a grid-integrated, renewable-supported model advances SDG 11 by reducing the environmental footprint of the port on the surrounding urban fabric, and SDG by delivering a measurable 39% reduction in greenhouse gas emissions. It must be noted that this valuation is likely a lower bound; if reductions in SOx and NOx, pollutants strongly correlated with respiratory and cardiovascular morbidity in coastal populations, were monetized, the external benefits would likely range between EUR 5 – 10 million annually given the population density of Ancona.

In summary, the environmental attractiveness of the grid-connected transition is validated by a granular comparison of emission intensities and thermodynamic efficiencies. For the study it is assumed a grid factor of roughly 426 g CO2/kWh to account for lifecycle/transmission. In contrast, onboard auxiliary engines operating on Marine Gas Oil (MGO) exhibit a significantly higher emission factor, typically cited at approximately 690 g CO2/kWh. Furthermore, the thermodynamic efficiency of centralized power generation, often exceeding 55% for combined-cycle gas turbines, far surpasses the 30 – 35% efficiency range characteristic of shipborne auxiliary combustion. Consequently, substituting onboard generation with centralized grid power not only eliminates localized pollutants but more than doubles the energy efficiency per unit of fuel consumed, rendering Cold Ironing a fundamentally superior environmental pathway for vessels at berth.

To validate the technical efficacy of the proposed decarbonization roadmap, the results of this study were benchmarked against three distinct European maritime case studies: the high-capacity renewable integration in the Port of Barcelona [34], the cold ironing feasibility study for Aberdeen [31], and the infrastructure survey of Croatian state-owned ports [44]. This comparison focuses on quantifiable CO2 eq. reduction and the feasibility of renewable energy integration.

These cases were selected to represent a diverse spectrum of port environments: a large-scale multi-purpose hub (Barcelona), a medium-sized specialized port (Aberdeen), and a regional administrative network (Croatian ports). This selection allows for a critical comparison across different implementation strategies, ranging from policy-driven readiness assessments to idealistic renewable microgrids.

A sharp contrast emerges regarding RES feasibility. The Barcelona study proposes an "integrated" self-sustaining microgrid, assuming massive spatial availability for wind and solar to meet a theoretical 100% RES goal. In contrast, this research highlights the "realistic" constraints of a medium-sized urban port. Due to limited spatial availability for PV, this study advocates for a "decoupled" strategy: utilizing grid reinforcement to handle the massive 52 GWh ship load, while reserving onsite PV specifically for port facilities (Net Zero buildings).

Unlike the Croatian study, which focuses on regional policy readiness, or the Aberdeen case, which targets smaller offshore support vessels (OSVs) with a reduction potential of 4,767 tonnes CO2/year, this study addresses the energy-intensive Ro-Pax sector. By targeting specific high-traffic quays, the Ancona roadmap achieves a significantly higher impact, with a projected reduction of 14,100 tonnes CO2/year.

Table 5 summarizes these structural and technical divergences, underscoring that while large hubs may pursue self-sustaining microgrids, ferry-dominated ports require a hybrid approach that balances grid reliance with targeted renewable integration.

Table 5. Comparative analysis of Cold Ironing strategies across different European port typologies

Metric	Barcelona Case [34]	Aberdeen Case [31]	Croatian Ports Case [44]	Ancona Port Case
Port Type	Large Size	Medium Size	Network of 6 ports	Medium Size
Vessel Focus	All types	OSV (Offshore Support Vessels) & Ferries	General	Ro-Ro & Ferries

Metric	Barcelona Case [34]	Aberdeen Case [31]	Croatian Ports Case [44]	Ancona Port Case
Scope	Entire Port	Small berths for support vessels	Regional readiness	High-Traffic Quays and port facilities
RES mix	Wind - PV	Grid	Grid	PV - Grid
Implementation Strategy	Integration (Self-sustaining microgrid)	Social benefit and health savings	Dual funding	Decoupling (PV for port facilities and Grid for CI)
Feasibility	Idealistic (Massive spatial needs to cover vessel demands)	Not addressed (Grid only)	Policy-focus (Grid only)	Realistic (Spatial constraints)
CO_2 emissions reduction	Theoretical 100% RES goal	4,767 tonnes/year	N/A	14,100 tonnes/year

The results of this study provide a critical quantitative validation of the challenges inherent in decarbonizing historic, urban-integrated ports. While the literature often presents the nZEP as a theoretical ideal, the specific case of Ancona demonstrates that for high-density ferry hubs, energy autonomy is constrained by a severe spatial dichotomy. The finding that onsite PV capacity, limited to 980 kWP by rooftop and limited non-urban availability, can cover only 3.4% of the ship-side demand fundamentally challenges the applicability of self-sufficiency models to medium-sized ports. This dictates a strategic shift from "total autonomy" to "functional decoupling," where limited renewable assets are allocated to shoreside facilities (achieving Net Zero for port operations), while the massive 52 GWh maritime load must inevitably be serviced by the national grid.

This heavy reliance on the grid underscores the unique operational profile of ferry-dominated TEN-T ports, distinguishing them from the container terminals typically analysed in existing studies. The identification of a "Winter Peak" driven by Ro-Ro heating requirements is a crucial operational insight. Unlike Mediterranean city grids, which typically face stress from summer cooling loads, the port's peak demand is counter-cyclical. This characteristic suggests that while the 40-fold increase in electrical load requires significant substation upgrades, it may not exacerbate the regional grid's summer peak stress events. This insight validates the necessity of the proposed frequency conversion infrastructure (SFC) not just for voltage compliance, but as a grid-balancing asset capable of managing these distinct seasonal fluctuations.

Furthermore, socio-economic analysis bridges the gap between operator feasibility and public benefit. The estimated EUR 3 million in annual fuel savings for ship operators provides a strong private economic incentive, potentially lowering the barrier for voluntary adoption. However, the study reveals that the true value of the infrastructure lies in the internalization of externalities. With societal benefits from avoided emissions estimated between EUR 0.7 and EUR 2.1 million annually and potentially reaching EUR10 million when broader health impacts are considered, the rationale for Cold Ironing shifts from a purely commercial investment to a critical public health intervention. This supports the argument for public-private funding models, as the infrastructure delivers substantial unmonetized value to the surrounding urban population.

This economic framework highlights a classic 'split-incentive' challenge in maritime decarbonization. While the Port Authority bears the high capital expenditure (CAPEX) for grid reinforcement and Cold Ironing infrastructure, the direct operational savings from avoided fuel consumption accrue primarily to ship operators. To bridge this gap, the proposed model assumes a service-based recovery system where vessels pay the port for the electrical energy consumed at berth. This allows the port to recoup infrastructure costs over time while providing operators with a price-stable alternative to marine fuels. It must be noted, however, that this study focuses on technical and environmental feasibility; a detailed calculation of specific energy tariffs, infrastructure procurement costs, and the resulting payback periods for the port was outside the current research scope.

Beyond the operational 'split-incentive,' the high CAPEX required for grid reinforcement remains a primary barrier to implementation. For a high-density hub like the Port of Ancona, the installation of a centralized SFC substation, medium-voltage step-up transformers, and approximately 1.5 km of underground cabling represents a significant investment. Based on recent technical reports and European TEN-T port benchmarks **[45]**, the comprehensive capital CAPEX for such infrastructure typically ranges from EUR 1.5 to EUR 2.5 million per MW of installed capacity. This benchmark estimate is fully inclusive of the primary system components, specifically the SFC equipment, medium-voltage step-up transformers, extensive civil works (such as quay excavations and cable trenching), and the required underground cabling. This places the initial investment for the proposed 11 MW system in the range of EUR 16.5 – 27.5 million.

While these upfront costs are substantial, they are increasingly mitigated through EU-level funding instruments, such as the Connecting Europe Facility (CEF) or the Interreg programs, which recognize shore power as a critical public health infrastructure rather than a purely commercial venture. Nonetheless, a high-fidelity financial audit remains a necessary next step to define the precise procurement costs and long-term amortization schedule.

Finally, the Pareto-like distribution of energy demand, where five quays drive the majority of consumption, validates the proposed phased implementation roadmap. By targeting Quays 13, 15, and 26, the port can address the core of its emissions problem without the immediate need for a port-wide overhaul. This "demand-driven" approach offers a replicable blueprint for other constrained European ports, demonstrating that effective decarbonization does not require solving the entire energy equation simultaneously, but rather strategically targeting the high-impact nodes where the operational and environmental returns are highest.

Regarding the robustness of these projections, three key areas of uncertainty must be acknowledged. First, concerning vessel simultaneity, the model assumes standard scheduled overlaps. However, in a 'worst-case' scenario where multiple heavy-load Ro-Pax vessels connect simultaneously, peak demand could spike beyond the 11 MW aggregate. This uncertainty justifies the proposed centralized SFC architecture, which allows for dynamic load shedding between berths to prevent substation overload. Second, seasonal variability introduces a distinct sensitivity; as noted, the ship-side demand peaks in winter (due to onboard heating), effectively balancing the port's summer-peaking cooling loads. This suggests the grid stress is less than a simple linear addition of maximums would imply. Third, the emissions analysis relies on an annual average grid carbon intensity. In reality, this factor fluctuates hourly. Future dynamic studies could refine these savings by correlating vessel connection times with real-time grid generation mixes, though the current annual average provides a conservative baseline for decision-making.

CONCLUSION

This study investigated the design, implementation, and environmental impacts of a Cold Ironing (CI) pilot project at the Port of Ancona, providing a critical assessment for strategic TEN-T ports characterized by high-frequency ferry traffic. The results confirm that while full implementation introduces a substantial new electrical load of approximately 52 GWh annually, it achieves a 39% reduction in the carbon footprint from berthed vessels, corresponding to an abatement of approximately 14,100 tonnes of CO2 eq. per year. This reduction represents not only a significant environmental improvement but also a measurable shift in the operational energy paradigm of ferry-dominated ports. Furthermore, the analysis validates a dual-pronged decarbonization strategy: while the massive ship-side demand necessitates targeted grid reinforcement and medium-voltage infrastructure upgrades, the integration of onsite Photovoltaics (PV) to power shoreside facilities proves to be a highly synergistic complement. By generating 1.27 GWh annually, the PV system effectively decouples land-side operations from the grid, rendering administrative and logistical functions Net Zero while the reinforced grid infrastructure supports the heavy maritime load.

The primary academic contribution of this research lies in advancing cold ironing studies beyond theoretical feasibility assessments toward a structured, engineering-grounded implementation blueprint for the under-researched archetype of ferry-dominated TEN-T ports. By strictly prioritizing the most traffic-intensive quays, the study challenges generalized, port-wide electrification models and demonstrates that a demand-driven intervention can address the core emission sources without unnecessary infrastructure dispersion. The identification of a Pareto-like demand concentration confirms that strategic targeting of high-impact terminals yields disproportionate environmental returns. While the specific energy autonomy results are inherently shaped by Ancona's spatial limitations, the proposed “targeted decoupling” methodology – combining grid-supported maritime electrification with constrained rooftop PV for landside autonomy – is directly transferable to other historic, urban-integrated Mediterranean ports where land-use conflicts restrict large-scale renewable deployment.

However, these findings must be interpreted within clearly defined modeling boundaries. The projected emissions abatement assumes a full electrification scenario in which 100% of eligible vessels connect to shore power, an outcome contingent upon vessel retrofitting timelines, interoperability compliance, and regulatory enforcement. Additionally, the limited contribution of rooftop PV – covering only 3.4% of total CI demand – quantitatively demonstrates the structural constraint faced by dense urban ports: full energy autonomy through onsite renewables is frequently unfeasible. Consequently, the study reframes port decarbonization not as a renewable sufficiency challenge, but fundamentally as a grid integration and infrastructure reinforcement challenge. The results thus emphasize that medium-sized ferry hubs require robust substation capacity expansion and frequency conversion systems as prerequisites for meaningful emissions reduction.

Crucially, based on the spatial constraints and empirically derived load profiles identified in this analysis, the study proposes a structured three-phase “Roadmap for Decarbonization” to guide practical deployment. Phase I (Strategic Prioritization) focuses on targeted electrification of Quays 13, 15, and 26, identified as the operational center of gravity for emissions, thereby maximizing environmental return on investment while minimizing capital dispersion. Phase II (Infrastructure & Grid Integration) precedes vessel connection and centers on the installation of the centralized Static Frequency Converter (SFC) substation, medium-voltage backbone reinforcement, and underground cable trenching. This phase resolves the 50Hz/60Hz mismatch inherent to international Ro-Pax fleets and establishes the digital monitoring architecture required for stable operation. Phase III (Operational Synchronization) integrates real-time PV generation data with dynamic load management strategies to offset shoreside baseloads and maintain grid stability under stochastic ferry demand peaks. Together, these phases transform CI from an isolated technology intervention into a coordinated infrastructure transition strategy.

Future research should extend this work through post-implementation monitoring to validate modeled peak-load assumptions, seasonal variability impacts, and real-world grid performance under simultaneous vessel connections. A comprehensive life-cycle cost analysis and tariff structuring study is also recommended to assess long-term financial sustainability and address the split-incentive dynamic between port authorities and vessel operators. Finally, the integration of BESS warrants further investigation to enhance peak shaving, improve renewable utilization, and strengthen resilience against grid volatility.

This study demonstrates that effective decarbonization of ferry-dominated TEN-T ports does not depend on achieving full renewable autonomy, but rather on strategically integrating reinforced grid infrastructure with constrained renewable assets through a phased, demand-driven implementation framework. By bridging environmental modeling, electrical engineering design, and operational sequencing, the research contributes a replicable methodology for transforming high-density Mediterranean ferry hubs into structurally decarbonized, regulation-compliant maritime energy nodes.

ACKNOWLEDGMENT

The authors would like to thank the Central Adriatic Ports Authority (Ancona) for providing the essential traffic data and operational insights that made this study possible. This research was conducted within the framework of the AIMPRESS project, funded by the Interreg IPA ADRION Programme. The authors gratefully acknowledge the valuable support and collaboration of all consortium partners for their contributions to advancing research on sustainable port energy systems.

REFERENCES

1. Harahap, F., Nurdiawati, A., Conti, D., Leduc, S. and Urban, F., Renewable marine fuel production for decarbonised maritime shipping: Pathways, policy measures and transition dynamics, *Journal of Cleaner Production*, Vol. 415, p. 137906, 2023, https://doi.org/10.1016/j.jclepro.2023.137906.
2. Chen, J., Fei, Y. and Wan, Z., The relationship between the development of global maritime fleets and GHG emission from shipping, *Journal of Environmental Management*, Vol. 242, pp 31-39, 2019, https://doi.org/10.1016/j.jenvman.2019.03.136.
3. Monteiro, A., Russo, M., Gama, C. and Borrego, C., How important are maritime emissions for the air quality: At European and national scale, *Environmental Pollution*, Vol. 242, Part A, pp 565–-575, 2018, https://doi.org/10.1016/j.envpol.2018.07.011.
4. Zisi, V., Psaraftis, H. N. and Zis, T., The impact of the 2020 global sulfur cap on maritime CO2 emissions, *Maritime Business Review*, Vol. 6, No. 4, pp 339-357, 2021, https://doi.org/10.1108/MABR-12-2020-0069.
5. Papadopoulos, C., Kourtelesis, M., Moschovi, A. M., Sakkas, K. M. and Yakoumis, I., Selected Techniques for Cutting SOx Emissions in Maritime Industry, *Technologies*, Vol. 10, No. 5, p 99, Oct. 2022, https://doi.org/10.3390/technologies10050099.
6. Cammin, P., Yu, J., Heilig, L. and Voß, S., Monitoring of air emissions in maritime ports, *Transportation Research Part D: Transport and Environment*, Vol. 87, p 102479, 2020, https://doi.org/10.1016/j.trd.2020.102479.
7. Aakko-Saksa, P. T., Lehtoranta, K., Kuittinen, N., Järvinen, A., Jalkanen, J.-P., Johnson, K., Jung, H., Ntziachristos, L., Gagné, S., Takahashi, C., Karjalainen, P., Rönkkö, T. and Timonen, H, Reduction in greenhouse gas and other emissions from ship engines: Current trends and future options, *Progress in Energy and Combustion Science*, Vol. 94, p 101055, 2023, https://doi.org/10.1016/j.pecs.2022.101055.
8. Sifakis, N., Vichos, E., Smaragdakis, A., Zoulias, E. and Tsoutsos, T., Introducing the cold-ironing technique and a hydrogen-based hybrid renewable energy system into ports, *International Journal of Energy Research*, Vol. 46, No. 14, pp 20303-20323, 2022, https://doi.org/10.1002/er.8059.
9. Schlacke, S., Wentzien, H., Thierjung, E.-M. and Köster, M., Implementing the EU Climate Law via the 'Fit for 55' package, *Oxford Open Journals*, Vol. 1, p oiab002, 2022, https://doi.org/10.1093/ooenergy/oiab002.

10. Řehák, D., Vlkovský, M., Maňas, P., Apeltauer, J., Apeltauer, T. and Hromada, M., Sustainability of the Trans-European Transport Networks Land Infrastructure to Address Large-Scale Disasters: A Case Study in the Czech Republic, *Sustainability*, Vol. 17, No. 6, 2025, https://doi.org/10.3390/su17062509.
11. Papadaki, A., Savvakis, N., Sifakis, N. and Arampatzis, G., Analysis of Hybrid Renewable Energy Systems for European islands: Market Dynamics, Opportunities and Challenges, *Sustainable Futures*, Vol. 9, p 100601, 2025, https://doi.org/10.1016/j.sftr.2025.100601.
12. Mohite, A. A. and Mathew, E., Exploring the necessary upgrades in port infrastructure to accommodate and support the operation of the next-generation green ships, *Marine Systems & Ocean Technology*., Vol. 20, No. 2, p 26, 2025, https://doi.org/10.1007/s40868-025-00171-2.
13. Christodoulou, A. and Echebarria Fernández, J., Maritime Governance and International Maritime Organization Instruments Focused on Sustainability in the Light of United Nations' Sustainable Development Goals, in: *Sustainability in the Maritime Domain: Towards Ocean Governance and Beyond*, A. Carpenter, T. M. Johansson, and J. A. Skinner, Eds., Springer International Publishing, pp 415-461, Cham, Switzerland, 2021, https://doi.org/10.1007/978-3-030-69325-1_20.
14. Groenleer, M., Kaeding, M. and Versluis, E., Regulatory governance through agencies of the European Union? The role of the European agencies for maritime and aviation safety in the implementation of European transport legislation, *Journal of European Public Policyy*, Vol. 17, No. 8, pp 1212-1230, 2010, https://doi.org/10.1080/13501763.2010.513577.
15. deManuel-López, F., Díaz-Gutiérrez, D., Camarero-Orive, A. and Parra-Santiago, J. I., Iberian Ports as a Funnel for Regulations on the Decarbonization of Maritime Transport, *Sustainability*, Vol. 16, No. 2, p 862, 2024, https://doi.org/10.3390/su16020862.
16. Cholidis, D., Sifakis, N., Savvakis, N., Tsinarakis, G., Kartalidis, A. and Arampatzis, G., Enhancing Port Energy Autonomy Through Hybrid Renewables and Optimized Energy Storage Management, *Energies*, Vol. 18, No. 8, 2025, https://doi.org/10.3390/en18081941.
17. Cholidis, D., Sifakis, N., Chachalis, A., Savvakis, N. and Arampatzis, G., Energy Transition Framework for Nearly Zero-Energy Ports: HRES Planning, Storage Integration, and Implementation Roadmap, *Sustainability*, Vol. 17, No. 13, 2025, https://doi.org/10.3390/su17135971.
18. Parhamfar, M., Sadeghkhani, I. and Adeli, A. M., Towards the application of renewable energy technologies in green ports: Technical and economic perspectives, *IET Renewable Power Generation*, Vol. 17, No. 12, pp 3120-3132, 2023, https://doi.org/10.1049/rpg2.12811.
19. Zhang, Z., Song, C., Zhang, J., Chen, Z., Liu, M., Aziz, F., Kurniawan, T. A. and Yap, P.-S., Digitalization and innovation in green ports: A review of current issues, contributions and the way forward in promoting sustainable ports and maritime logistics, *Science of The Total Environment*, Vol. 912, p 169075, 2024, https://doi.org/10.1016/j.scitotenv.2023.169075.
20. Reusser, C. A. and Pérez, J. R., Evaluation of the Emission Impact of Cold-Ironing Power Systems, Using a Bi-Directional Power Flow Control Strategy, *Sustainability*, Vol. 13, No. 1, p 334, 2021, https://doi.org/10.3390/su13010334.
21. Sulligoi, G., Bosich, D., Pelaschiar, R., Lipardi, G. and Tosato, F., Shore-to-Ship Power, *Proceedings of the IEEE*, Vol. 103, No. 12, pp 2381-2400, 2015, https://doi.org/10.1109/JPROC.2015.2491647.

22. Sandy Thomas, C. E., Transportation options in a carbon-constrained world: Hybrids, plug-in hybrids, biofuels, fuel cell electric vehicles, and battery electric vehicles, *International Journal of Hydrogen Energy*, Vol. 34, No. 23, pp 9279-9296, 2009, https://doi.org/10.1016/j.ijhydene.2009.09.058.
23. Anyanwu, J. O., Nze, I. C., Obed, N., Onyemechi, C., Okorefe, C. O. and Okoronkwo, N. C., Comparative study of alternative marine power (cold ironing) application as an air pollution mitigation technology in Nigeria seaports, *International Journal of Frontiers in Engineering and Technology Research*, Vol. 3, No. 1, pp 029-036, 2022, https://doi.org/10.53294/ijfetr.2022.3.1.0027.
24. Ramsay, W., Fridell, E. and Michan, M., Maritime Energy Transition: Future Fuels and Future Emissions, *Journal of Marine Science and Application*, Vol. 22, No. 4, pp 681-692, 2023, https://doi.org/10.1007/s11804-023-00369-z.
25. Kumar, D. and Zare, F., A Comprehensive Review of Maritime Microgrids: System Architectures, Energy Efficiency, Power Quality, and Regulations, *IEEE Access*, Vol. 7, pp 67249-67277, 2019, https://doi.org/10.1109/ACCESS.2019.2917082.
26. Abu Bakar, N. N., Uyanik, T., Arslanoglu, Y., Vasquez, J. C. and Guerrero, J. M., Two-stage energy management framework of the cold ironing cooperative with renewable energy for ferry, *Energy Conversion and Management*, Vol. 311, p 118518, 2024, https://doi.org/10.1016/j.enconman.2024.118518.
27. Sifakis, N., Sarantinoudis, N., Tsinarakis, G., Politis, C. and Arampatzis, G., Soft Sensing of LPG Processes Using Deep Learning, *Sensors*, Vol. 23, No. 18, p 7858, 2023, https://doi.org/10.3390/s23187858.
28. Heikkilä, M., Saarni, J. and Saurama, A., Innovation in Smart Ports: Future Directions of Digitalization in Container Ports, *Journal of Marine Science and Engineering*, Vol. 10, No. 12, 2022, https://doi.org/10.3390/jmse10121925.
29. Sadiq, M., Su, C.-L., Terriche, Y., Alfaro Aragon, C., Ali, S. W. and Buzna, Ľ., Toward Next-Generation Smart Ports: A Case Study on Seaport Microgrids Customized for Islands, *IEEE Transactions on Industry Applications*, Vol. 60, No. 5, pp 7681-7692, 2024, https://doi.org/10.1109/TIA.2024.3425800.
30. Zis, T. P. V., Prospects of cold ironing as an emissions reduction option, *Transportation Research Part A: Policy and Practice*, Vol. 119, pp 82-95, 2019, https://doi.org/10.1016/j.tra.2018.11.003.
31. Innes, A. and Monios, J., Identifying the unique challenges of installing cold ironing at small and medium ports - The case of aberdeen, *Transportation Research Part D: Transport and Environment*, Vol. 62, pp 298-313, 2018, https://doi.org/10.1016/j.trd.2018.02.004.
32. Ballini, F. and Bozzo, R., Air pollution from ships in ports: The socio-economic benefit of cold-ironing technology, *Research in Transportation Business & Management*, Vol. 17, pp 92-98, 2015, https://doi.org/10.1016/j.rtbm.2015.10.007.
33. Abu Bakar, N. N., Bazmohammadi, N., Vasquez, J. C. and Guerrero, J. M., Electrification of onshore power systems in maritime transportation towards decarbonization of ports: A review of the cold ironing technology, *Renewable and Sustainable Energy Reviews*, Vol. 178, p 113243, 2023, https://doi.org/10.1016/j.rser.2023.113243.
34. Rolán, A., Manteca, P., Oktar, R. and Siano, P., Integration of Cold Ironing and Renewable Sources in the Barcelona Smart Port, *I EEE Transactions on Industry Applications*, Vol. 55, No. 6, pp 7198-7206, 2019, https://doi.org/10.1109/TIA.2019.2910781.
35. Sifakis, N., Resilient Control Strategies for Urban Energy Transitions: A Robust HRES Sizing Typology for Nearly Zero Energy Ports, *Processes*, Vol. 14, No. 3, p 549, 2026, https://doi.org/10.3390/pr14030549.

36. Yuksel, O., Bayraktar, M. and Seyhan, A., Environmental and economic analysis of cold ironing using renewable hybrid systems, *Clean Technologies and Environmental Policy*, Vol. 27, No. 8, pp 3489-3517, 2025, https://doi.org/10.1007/s10098-024-03065-w.
37. Toscano, D., The Impact of Shipping on Air Quality in the Port Cities of the Mediterranean Area: A Review, *Atmosphere*, Vol. 14, No. 7, p 1180, 2023, https://doi.org/10.3390/atmos14071180.
38. S Sanes, S. E., Casals-Torrens, P., Bosch Tous, R. and Castells, M., Comparative Analysis of Cold Ironing Rules, *Naše more, International Journal of Maritime Science & Technology*, Vol. 64, No. 3, pp 100-107, 2017, https://doi.org/10.17818/NM/2017/3.4.
39. Ren, H., Dobson, I. and Carreras, B. A., Long-Term Effect of the n-1 Criterion on Cascading Line Outages in an Evolving Power Transmission Grid, *IEEE Transactions on Power Systems*, Vol. 23, No. 3, pp 1217-1225, 2008, https://doi.org/10.1109/TPWRS.2008.926417.
40. Corsi, S., Pozzi, M., Sabelli, C. and Serrani, A., The coordinated automatic voltage control of the Italian transmission Grid-part I: reasons of the choice and overview of the consolidated hierarchical system, *IEEE Transactions on Power Systems*, Vol. 19, No. 4, pp 1723-1732, 2004, https://doi.org/10.1109/TPWRS.2004.836185.
41. Lorenzo, G. D., Stracqualursi, E., Araneo, R. and Cecere, R., Smart Tests for Medium Voltage Cables in Renewable Energy Plants: The Case Study of a PV Plant Located in Italy, *IEEE Transactions on Industry Applications*, pp 1-11, 2026, https://doi.org/10.1109/TIA.2026.3661946.
42. Paul, D., Peterson, K. and Chavdarian, P. R., Cold Ironing Power System design and electrical safety, in: *2012 Petroleum and Chemical Industry Conference (PCIC)*, pp 1-9, New Orleans, LA, USA, 2012, https://doi.org/10.1109/PCICON.2012.6549666.
43. Paul, D. and Chavdarian, P. R., System Capacitance and its Effects on Cold Ironing Power System Grounding, in: *2006 IEEE Industrial and Commercial Power Systems Technical Conference - Conference Record*, pp 1-11, Detroit, MI, USA, 2006, https://doi.org/10.1109/ICPS.2006.1677308.
44. Glavinović, R., Krčum, M., Vukić, L. and Karin, I., Cold Ironing Implementation Overview in European Ports-Case Study-Croatian Ports, *Sustainability*, Vol. 15, No. 11, p 8472, 2023, https://doi.org/10.3390/su15118472.
45. Winkel, R., Weddige, U., Johnsen, D., Hoen, V. and Papaefthimiou, S., Shore Side Electricity in Europe: *Potential and environmental benefits*, *Energy Policy*, Vol. 88, pp 584-593, 2016, https://doi.org/10.1016/j.enpol.2015.07.013.

Paper submitted: 09.12.2025
Paper revised: 02.03.2026
Paper accepted: 11.03.2026