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Environmental Assessment and Regulatory Aspects of Cold Ironing Planning for a Maritime Route in the Adriatic Sea

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Abstract: The technology of cold ironing (or shore-to-ship power) can meaningfully reduce greenhouse gases and air pollutant emissions from ships at the berth by powering the vessels from the electrical shore grid. While cold ironing constitutes an effective and affordable solution in northern Europe and America, economic, legal, and environmental factors still render this technology less attractive in southern Europe. This paper aims to unpack and analyze the economic, regulatory, and environmental factors that can foster cold ironing as a standard installation in the Mediterranean Sea. Based on a model design for the port of Trieste (Italy) as applied to a cluster of target ports in the Adriatic Sea (in Italy, Croatia, and Greece), this article evaluates the cold ironing payback period by comparing costs of shore side-plants with environmental externalities and O&M costs. Moreover, the paper addresses key regulatory bottlenecks arising in different European jurisdictions with regard to the setting-up and development of cold ironing, while appraising the legal and economic consequences of deploying cold ironing in light of the future inclusion of the maritime sector in the EU Emission Trading System.

Keywords: cold ironing; shore-to-ship power; port electrical grid; environmental externalities; CO_2 emissions; social cost of carbon; ETS

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1. Introduction

Air pollution and climate change pose serious risks to public health [1–4]. It is necessary to activate integrated policies aimed at combating air pollution and mitigating climate change by encouraging forms of clean-sustainable energy production [5,6]. The advantages that can be obtained are greater than the costs necessary for their implementation. The present paper wants to explore this trend towards energy transition in the context of large ship-powering. This work focuses on a possible intervention to reduce air pollution and greenhouse gas (GHG) emissions concerning maritime transportation [7–9]. The cold ironing (also known as shore connection) is a port-based emission-reduction technology that reduces emissions generated from the auxiliary engines of a ship using shore-based electric power. As the ship is supplied from the land during the cold ironing's berthing, the polluting-GHG emissions are completely avoided. When the required energy is given by renewable sources, the ship becomes sustainable, thus ready for the transition towards the green era. In particular, this paper considers the implementation of this system in the Mediterranean context, which is the second largest cruise market in the world in terms of turnover and passengers, although the implementation of this technology proceeds with difficulties. While the shipping sector plays an essential role in the EU economy and still represents one of the most energy-efficient modes of transportation, it accounts for 3–4% of all EU CO_2 emissions, totaling to around 138 million tons of CO_2 in 2018 [10]. Future outlooks project emissions from transportation to increase by 32% by 2030 if mitigation measures are not swiftly introduced, with international maritime transportation topping to 155 million tons of CO_2 in 2030 [10]. To this end, in the broader policy context of European

Green Deal, the European Commission is championing the inclusion of the shipping sector in the European Union Emission Trading System (EU ETS), which operates as the pivotal carbon pricing mechanism in the EU [11,12]. As a market-based mechanism, the ETS aims to foster investments in more energy-efficient and less GHG-intensive technologies, while posing additional economic burdens on GHG-intensive activities [13]. To embed the maritime sector in ETS, however, is all but an easy task, as it can trigger undesired feedback loops as an economic impact on shipping companies [14].

The present paper is organized in the following way. The study in Section 1 gives an overview of shore connection platforms, while Section 2 reviews the methodology followed in this study. As a first example of cold ironing, Section 3 investigates a shore connection design for the cruise port of Trieste. The same approach introduced for this first case is later applied on several ports in an Adriatic route crossing some ports in Italy, Croatia, and Greece. Then, Sections 4 and 5 introduce an advanced model for the calculation of atmospheric pollution emitted by auxiliary ship engines. The proposed model can evaluate the environmental externalities saved if the cold ironing technology is applied in the docks to replace the use of internal combustion engines for the ships supply. Section 6 adopts the procedure explored in Section 4, highlighting a database that is developed to evaluate and quantify the effect of cold ironing for the entire cluster of ports of the Adriatic route. Section 7 navigates the legal and policy context for the inclusion of shipping in the EU ETS, while pinpointing the role of cold ironing technologies for the purposes of the sound application of the same ETS. Thus, this paper also investigates the legal framework supporting the adoption and up-scaling of shore connection within the context of the future inclusion of maritime transportation in the European Union Emission Trading System. In this context, the paper elaborates on and contributes to the growing body of legal scholarship dealing with the regulation of pollutants and greenhouse gas (GHG) emissions from shipping, with specific regard to cold ironing as an emission reduction technique. Section 8 concerns the impact of CO_2 emissions and social cost of carbon. The role of cutting-edge technologies such as cold ironing should be duly appraised to ensure that the several environmental, economic, and social benefits delivered by its application are duly reflected in the application of market-based approaches to CO_2 emission mitigation in the EU. Section 9 proposes a results discussion, while the conclusions are in Section 10.

2. Methodology

The methodology is aimed at drafting a cost/benefit analysis of cold ironing in a cluster of ports. To correctly formalize the analysis, the study is based on two references: (a) the "guidelines for the preparation of cost-benefit analyzes issued by the European Commission" for the economic part and (b) the "guidebooks issued by the European Environment Agency" for the emissions estimation. The procedure identifies the benefits (e.g., avoided environmental externalities), costs (e.g., installation, O&M), and ETS contribution. To this aim, ten steps are necessary. Regarding benefits: (1) to define a cluster of cruise piers/ports along a maritime route; (2) to determine fuel consumption and hourly emissions at mooring for all cruises arriving in these ports; (3) to determine the avoided emissions in these ports due to cold ironing; and (4) to identify the avoided environmental externalities in these ports due to cold ironing. Regarding costs: (5) to size each shore connection installation; (6) to establish installation/operating costs of cold ironing based on market research regarding the best players; and (7) to quantify the cost of each platform to be installed along the route. Regarding the ETS: (8) to define different CO_2 exchange targets on the EU ETS (past, present, and future); (9) to combine the targets with the avoided CO_2 emissions; and (10) to observe/quantify how the CO_2 market can impact the shore connection feasibility in the cluster. Finally, the legal analysis carried out in Section 7 consists of desk-based research to review the main legal documents and available literature on the ETS and the shipping sector.

3. Overview of Shore Connection Platforms

In recent years, the challenge towards sustainability is becoming crucial also in the marine sector. Such a trend is not only observable in the design of large all-electric ships [15] but also in the development of port facilities [16]. If high-efficiency motors, controlled drives, and electrical propulsion can greatly reduce the onboard carbon impact, innovative solutions are also investigated to lower or even avoid the emissions during mooring [17,18]. Conventionally, a ship at berth adopts the onboard generators to feed the technical services and hotel loads, whose total power demand can reach 10–15 MW for each large vessel. As a consequence, during berthing, the ship becomes a point-source of air pollution (i.e., NOx, SOx, and particulate matter) [2] and GHG emissions [19]. To solve this matter, the so-called cold ironing can locally remove emissions by supplying the moored ship from the terrestrial electrical grid [20–22]. Although such a technique is well-known in the supply/recharge of small low-voltage (LV) ships [23,24], environmental awareness has moved the focal point to large-power demanding vessels [7–9]. In this case, the application takes the name of high-voltage shore connection (HVSC), as the supply voltage to deliver a considerable power (i.e., tens of MW) to the onboard loads during the ship berthing is high [25]. To define technical issues and solutions to enable the high-power cold ironing, not only IEEE standards [7–9] but also several scientific publications [17,18,20–22,25–30] have largely investigated the HVSC topic in the last years.

At a glance, the HVSC is quite a standard high-voltage high-power platform to feed the stationary shipboard loads, while challenges arise when considering the limitations in capacity, both in port distribution and in port supply line [25]. Secondly, galvanic corrosion [31] and high-touch voltages during phase-to-ground faults [32,33] are also important issues to be faced in a HVSC system. As the HVSC system aims to switch-off the polluting diesel–electrical generators at mooring, alternative LNG solutions [34] or even renewable sources [35] are to be taken into account when foreseeing the land electrical power production. To understand the HVSC structure [7–9], a functional scheme is presented in Figure 1. Here, several subsystems that deliver power to the berthed vessel are depicted: (1) HV input (port grid); (2) HV/MV transformer (port grid); (3) AC/AC power converter (e.g., 50/60 Hz 16 MVA); (4) MV distribution cabinet (optional); (5) Cable dispenser; and (6) ship MV cabinet. Therefore, the HV port supply (>100 kV, 132 or 220 kV in Italy) is transformed into the MV medium-voltage level (i.e., 20–40 kV, 27.5 kV in Italy) at step (2). Then, the power conversion at step (3) is necessary for interface systems with different frequencies, thus the land grid is at 50 Hz and shipboard system is at 60 Hz. This subsystem is constituted by three components: a step-down transformer (27.5/0.6 kV), an AC-DC diode rectifier in the middle, a DC-AC inverter to make available the AC voltage at 600 V, and finally a step-up transformer to provide the final voltage at 11 kV. Step (4) is the distribution cabinet for powering the cable dispenser at step (5). Finally, at step (6), the cable is connected to the shipboard power grid, usually operated at 11 kV. Evidently, different ratios characterize the electrical components when the ship presents the main distribution at 6.6 kV. During the hours in which a hypothetical cruise ship is fed by the cold ironing infrastructure, a particular crane (Figure 2) is adopted for the interconnection among land-ship grids. In order to specify all the recommendations when performing the HVSC, the IEEE standards [7–9] not only provide the online diagram (Figure 3) but also the signals whose coordination/management ensures the correct supply (Figure 4). Specific for a cruise liner, electrical cabinets are to be installed onboard to guarantee the interface towards the land grid. In this regard, Figure 5 shows the switchboard, while the control cabinet is depicted in Figure 6. Besides the standard infrastructure described so far, Figure 7 highlights the eventuality of single-phase fault at the delivery point. This case deserves attention in terms of electrical safety, as the ship behaves as a peculiar appendix of the port–earth system; thus, possible issues of touch voltages during faults can arise. To conveniently understand the overall interest in HVSC platforms, the Table 1 provides information [36–38] on worldwide cold ironing installations in the period of 2000–2017.

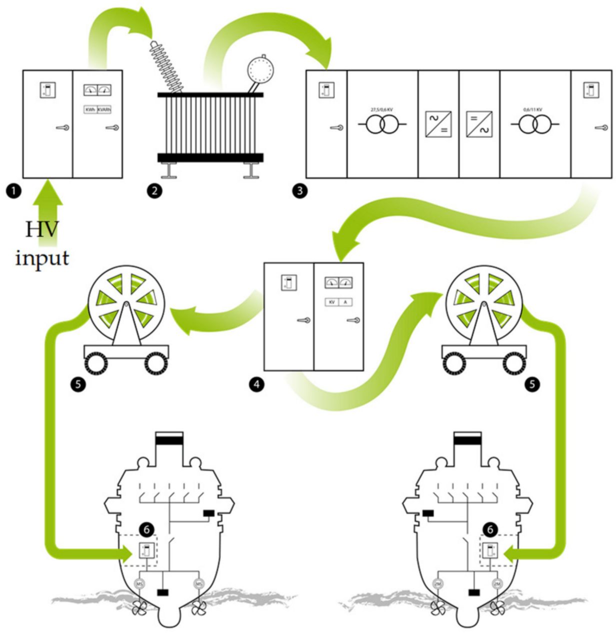

Figure 1. High-voltage shore connection system.

Figure 2. Dedicated crane [25].

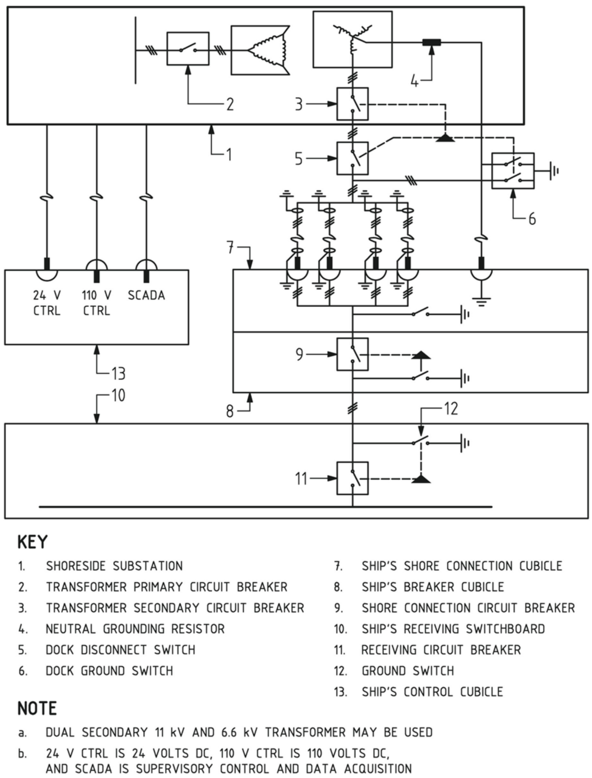

Figure 3. One-line diagram of the HVSC plant [25].

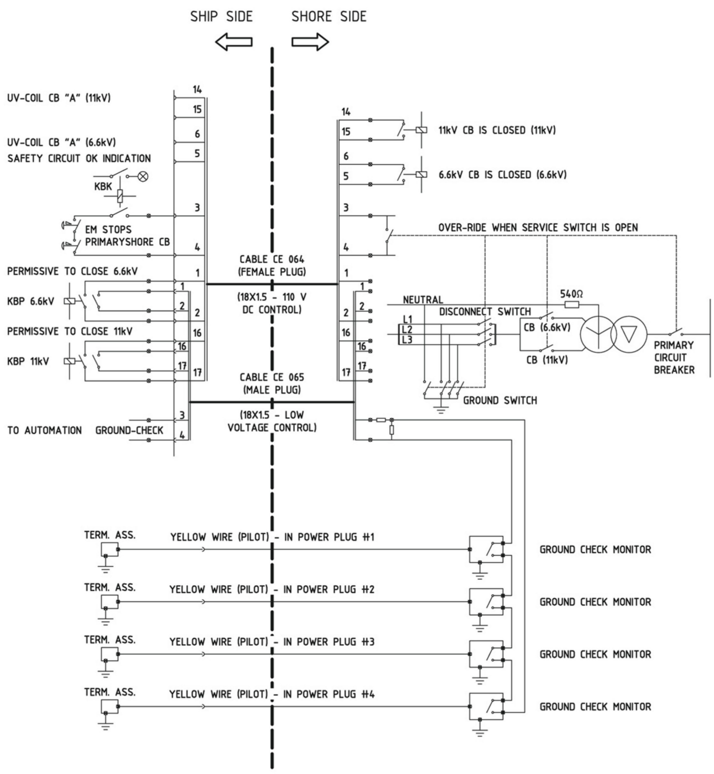

Figure 4. Signals managed by the HVSC control cabinet [25].

Figure 5. Switchboard for shore connection purposes [25].

Figure 6. Shore connection control cabinet [25].

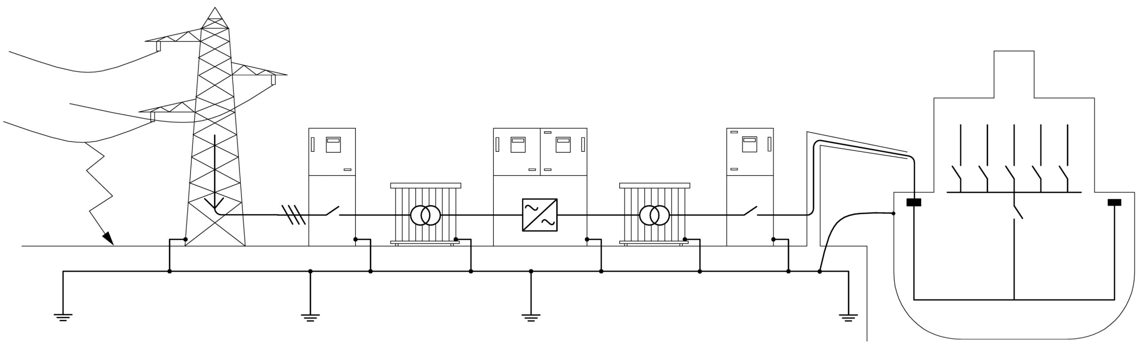

Figure 7. Port with a HVSC system supply by a HV > 100 kV primary line with a single-phase fault at delivery point [25].

Table 1. HVSC installations worldwide: 2000–2017 period [36–38].

Year	Port	Country	Capacity (MW)	Frequency	Voltage (kV)	Ship Type ^{S}
2000	Gothenburg	Sweden	1.25–2.5	50 & 60	6.6 & 11	RoRo, RoPax
2000	Zeebrugge	Belgium	1.25	50	6.6	RoRo
2001	Juneau	USA	7–9	60	6.6 & 11	Cruise
2004	Los Angeles	USA	7.5–60	60	6.6	Container, cruise
2005	Seattle	USA	12.8	60	6.6 & 11	Cruise
2006	KEMI	Finland		50	6.6	RoPax
2006	KotkaI	Finland		50	6.6	RoPax
2006	Oulu	Finland		50	6.6	RoPax

Table 1. *Cont.*

Year	Port	Country	Capacity (MW)	Frequency	Voltage (kV)	Ship Type [S]
2008	Antwerp	Belgium	0.8	50 & 60	6.6	Container
2008	Lübeck	Germany	2.2	50	6.6	RoPax
2009	Vancouver	Canada	16	60	6.6 & 11	Cruise
2010	San Diego	USA	16	60	6.6 & 11	Cruise
2010	San Francisco	USA	16	60	6.6 & 11	Cruise
2010	Karlskrona	Sweden	2.5	50	11	Cruise
2011	Long Beach	USA	16	60	6.6 & 11	Cruise
2011	Oakland	USA	7.5	60	6.6 & 11	Container
2011	Oslo	Norway	4.5	50	11	Cruise
2011	Prince Rupert	Canada	7.5	60	6.6	Container
2012	Rotterdam	Netherlands	2.8	60	11	RoPax
2012	Ystad	Sweden	6.25	50 & 60	11	Cruise
2015	Bergen	Norway	1	50 & 60	0.440/0.690	
2017	Marseille	France	4	60	11	Ferry

[S]: RoRo (i.e., Roll-on/Roll-off) and RoPax (Roll-on/roll-off Passengers).

4. Shore Connections on the Adriatic Route

To follow the global requests in system sustainability and eco-friendliness, impressive developments are expected to be applied also on port infrastructures. Here, not only are wise energy management [39], peak-shaving solutions [40], or new port cranes supply [41] day-by-day becoming a reality, but even innovative microgrid architectures play a decisive role when the overall energy management is to be improved [42–46]. Nowadays, such a modernization is foreseeable in the industrial ports with real-time measurements of energy flows [47,48], as well as in the cruise ships port, in which conversely the main goal is the emissions removal during berthing [20–25]. This work investigates the last above aspect, for which a shore connection design for the cruise port of Trieste is taken as an example to develop a methodology to be further applied on the several ports in the Adriatic route. Although the present cold ironing installations in Europe (Table 1) are mainly gathered in the north part (e.g., Finland, Norway, and Sweden), the present paper is aimed at opening a shore connections scenario also for the countries in the Mediterranean region. To do this, the expected advantages and challenges of cold ironing are to be extended to an entire route which crosses the seas of Italy, Croatia, and Greece.

4.1. The Trieste Cruise Port Case Study

Trieste is a city located in the north-eastern part of Italy. Such a position in the heart of Europe near the border to Slovenia and Croatia is crucial when concerning commercial flows, business, and tourism. Trieste has based its life and success on the industrial port, which now is the first Italian port in freight traffic [47,48]. The depth of the backdrop from up to 18 m constitutes the luck on which national/international finance and politics sectors have invested in, especially in the last years. As a matter of fact, Trieste is an intermodal hub as the EU N°1315/2013 regulation considers its port as one of the Trans-European Transport Network (TEN-T) core ports. All over Europe, the TEN-T is a wide network of railway lines, roads, inland waterways, maritime shipping routes, ports, airports, and railroad terminals. In such a context, the core network (Figure 8) includes the most important connections, then linking the most important nodes.

If the industrial port in the periphery makes Trieste an important hub for the movements of goods and oil towards northern Europe [47,48], tourism is developed in the city center's port. Here, the cruise ships find their location when mooring in front of the main square. In the following, the Trieste cruise port is an example on which to design a complete shore connection platform. Once the study methodology is developed for the single cold ironing in Trieste, it can be replicated/tailored for the other ports of the Adriatic route. The initial data/method are previously determined by some authors of this paper as part of their research activity. Whether the focus is on a single port or on a route, the goals are the following.

a. To evaluate emissions (polluting and GHG) and environmental costs pre/post the shore connection installation in the Trieste cruise terminal (Tables 2 and 3).
b. To estimate the HVSC plant costs and running costs (operation, maintenance, and employees) during the entire plant life.
c. To define costs for ship-owners.
d. To find the payback period when implementing the Trieste cold ironing.

Firstly, the analysis at point (a) rests on the following assumptions:

1. the NO_X, SO_X, NMVOC, PM_{10}, and $PM_{2.5}$ are the considered pollutants;
2. CO_2 is also taken into account as a GHG;
3. the electrical supply of the shore connection platform is assumed to be based on renewables sources, otherwise the pollutants abatement is only partial; and
4. the pollutant costs to define the externalities are reported in [49] from the EEA (European Environment Agency, 2011) and in [50] from the EEA (2014).

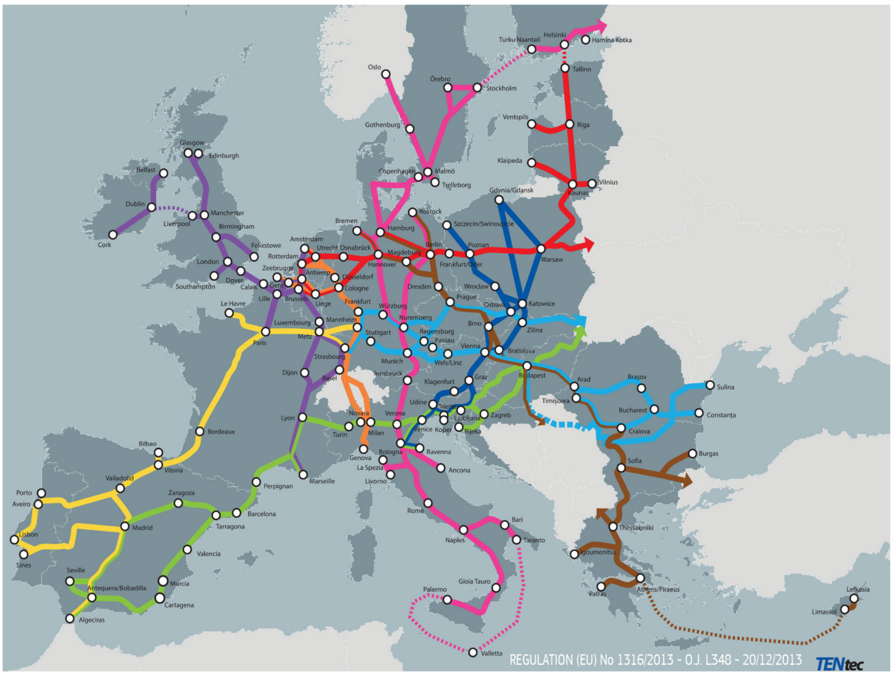

Figure 8. Core network corridors (https://ec.europa.eu/transport/themes/infrastructure/ten-t_en).

In order to identify emissions and environmental externalities, a convenient procedure follows the steps from (A) to (D). In the following, each step is explained:

A. To collect the mooring data (i.e., vessel name, gross tonnage, and day and hour of arrival and departure) for the port under study.
B. To empirically determine [51] the $C_{mooring/day}$ daily fuel consumption at berth (2) for each vessel. The gross tonnage is named *GTon*, while C_{100} is the average daily consumption with full power (100%) as in (1).

$$C_{100} = 16.904 + 0.00198 \cdot GTon \quad [\text{ton/day}] \tag{1}$$

$$C_{mooring/day} = C_{100} \cdot 0.32 \quad [\text{ton/day}] \tag{2}$$

C. To calculate the yearly emission of each pollutant (tons) for all the vessels (3), where $E_{i,p}$ means port/pollutant emission, i identifies the specific pollutant, p represents the port, and k represents the vessel. Then, $t_{k,p}$ is the mooring time of the k-th vessel in port p and Fi represents the emission factor of the i-th pollutant.

$$E_{i,p} = \sum_k C_{mooring/day} \cdot t_{k,p} \cdot F_i \quad [\text{ton/day}] \tag{3}$$

D. To determine the monetary (EUR) externalities $Q_{i,p}$ correlated to each port/pollutant (4). In the last equation, i is the pollutant, p identifies the port, and X is the cost per tons of emitted pollutant for each cruise vessel.

$$Q_{i,p} = E_{i,p} \cdot X_{i,p} \quad [\text{EUR}] \tag{4}$$

Once Equation (4) is calculated, the environmental externalities (i.e., EUR 1.58 million/year positive input in the cash flow), costs of the HVSC platform, and O&M for 25 years life (i.e., negative inputs) are to be specified. The latter are in Tables 4 and 5 for a cold ironing installation in the Trieste cruise port when the HV delivery from TSO is assumed to be available, thus its purchase is out from the study. It is important to point out that plant costs (about EUR 4 million) are obtained by cross-checking the datasheets from international electrical companies. In addition, the assessment of O&M costs (about EUR 6 million) is based on an evaluation with the local DSO and historical price data in the past 25 years. When the inputs are ready, the cash flow of Figure 9 can establish a remarkable payback period of 3 years. The investment sustainability is thus evident.

Table 2. Emissions abatement with cold ironing in Trieste (2015).

	Δ NO_X	Δ 2.7% [1] SO_X	Δ 1.5% [1] SO_X	Δ 0.5% [1] SO_X	Δ CO_2	Δ VOC	Δ PM_{10}	Δ $PM_{2.5}$
Location	ton	ton	ton	Ton	ton	ton	ton	ton
Trieste	52.9	67.8	37.7	12.6	4019.5	7.3	11.5	11.5

[1] The study considered the SO_X abatement with different sulfur tenor, assuming possible regulatory restrictions (i.e., SECA areas).

Table 3. Environmental externalities per year reduced by adopting cold ironing in Trieste.

	Case 2.7% SO_X		**Case 1.5% SO_X**		**Case 0.5% SO_X**	
	Δ min [1]	**Δ max [1]**	**Δ min [1]**	**Δ max [1]**	**Δ min [1]**	**Δ max [1]**
Location	Million euros	Million euros	Million euros	Million euros	Million euros	Million euros
Trieste	2.39	7.40	1.95	6.08	1.58	4.90

[1] Minimum and maximum values are due to different evaluation methods to determine the environmental costs.

Table 4. HVSC plant costs (hypothesis for Trieste, 2015).

Element	Cost (EUR)
MT switchgears	32.00 k
Converter 16 MVA 11 kV 60 Hz	3450.00 k
Cable dispenser	150.00 k
Design and construction (20%)	726.40 k
Total	**4358.40 k**

Table 5. HVSC O&M costs (hypothesis of 25 years of life).

Element	Cost (EUR)
MV substation	1111.80 k
Converters and cable dispenser	4512.50 k
Total	**5624.30 k**

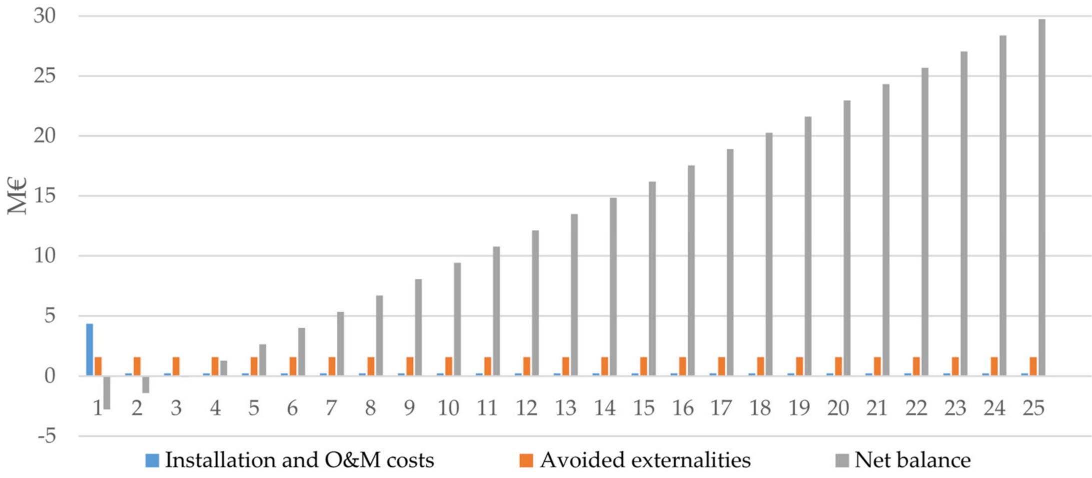

Figure 9. Avoided externalities vs. installation and O&M costs (Trieste cold ironing, 25 years of plant life).

4.2. The Three EU Countries' Adriatic Route

As a matter of fact, the cold ironing infrastructures are mainly installed in the northern seas [26–28]. The reasons of this trend include the high energy costs, which, in southern Europe, penalize the ship supply from land at berth. Secondly, environmental regulation [2] may also not be able to effectively force this technology in the Mediterranean Sea, albeit the enchanting natural beauty. To overcome this issue, one possibility is the clustering, thus a practical way to extend risks but also benefits towards different countries. Concerning the Adriatic Sea, a first idea can consider three EU European countries, namely Italy, Croatia, and Greece. The choice of the cruise terminals to be included in the cluster considers a route for which Trieste (Italy) plays as a home-port. Then, Split and Dubrovnik are the stops in Croatia, while Corfù, Argostoli, and Piraeus are the terminals for Greece, and the final stop is in Bari (Italy) before the way back to Trieste. The cluster is surely a key factor to foster cold ironing as a standard technology also in southern Europe seas. Indeed, when several are electrified terminals, the onboard implementation becomes economically viable for ship-owners due to the increased utilization factor. On one hand, the coordinated implementation of shore connections in a cluster needs to develop common strategies, but on the other hand, it allows to speed up the cold ironing spread. From a perspective of a fully integrated European energy market, massive purchasing of energy to power the cold ironing's cluster can allow for energy price reduction, pushing up the HVSC penetration.

5. Model for Evaluating the Environmental Externalities

Without cold ironing technology, cruise ships must keep auxiliary engines turned on during berthing in order to feed, among others, the HVAC services. The consequent negative effects of pollution (e.g., health effects, crop losses, material/building damages, and biodiversity loss) are impressive [1,2,25], while the new iniative to cut GHG emissions [3] additionally forces a change in the energy paradigm. Since these negative effects are not reimbursed by ship-owners, ship emissions directly have an impact on collectivity as externalities [25]. In such a regard, national/international best practices [52,53] recognize these externalities as key factors when assessing the HVSC feasibility. In general, the estimation of environmental cost is not an easy activity to be performed. In the case of those related to transports, the European Commission has provided procedures to evaluate the "user pays-polluter pays" in EU states [54], as well as the marginal external costs of all transportation modes. The costs in Table 6 are express the 2016 price levels, hence updated to the 2019 year by the HICP (Harmonized Index of Consumer Price) as in (5).

To calculate the P_{2019} environmental cost of 2019, the HICP_{2019} is to be subdivided by the HICP_{2016}. The result is then multiplied by the P_{2016} cost in order to finally harmonize the calculus. In (5), both HICP are obtained from the EU-28 Eurostat database, in which

$HICP_{2016}$ = 100.25 and $HICP_{2019}$ = 105.42. As to the countries in the Adriatic route (CR-GR-IT), the initial data (2016) are reported in Table 6, whereas the values updated by (5) are in Table 7. In both tables, the environmental costs are referred to as NO_X, NMVOC, SO_2, $PM_{2.5}$, PM_{10}, and CO_2. The vessel damage (i.e., environmental externalities) is finally found by multiplying the cost parameters (Table 7) by the polluting-GHG emissions from a specific source (e.g., cruise ships). The following step-by-step procedure provides all the information to precisely quantify the negative factors to be avoided by the HVSC.

$$P_{2019} = HICP_{2019}/HICP_{2016} \cdot P_{2016} \quad [\text{EUR/ton}] \tag{5}$$

Table 6. Environmental costs for CR-GR-IT (2016, $PM_{2.5}$ referred to urban areas) [54].

	EUR/ton NO_X	EUR/ton NMVOC	EUR/ton SO_2	EUR/ton $PM_{2.5}$	EUR/ton PM_{10}	EUR/ton CO_2eq
EU-28 Aggregate	21,300.00	1200.00	10,900.00	123,000.00	22,300.00	100.00
Croatia (CR)	18,500.00	900.00	8000.00	95,000.00	8200.00	100.00
Greece (GR)	5100.00	300.00	5900.00	86,000.00	24,800.00	100.00
Italy (IT)	25,400.00	1100.00	12,700.00	132,000.00	19,000.00	100.00

Table 7. Environmental costs for CR-GR-IT (2019, data used in this paper).

	EUR/ton NOx	EUR/ton NMVOC	EUR/ton SO_2	EUR/ton $PM_{2.5}$	EUR/ton PM_{10}	EUR/ton CO_2eq
EU-28 Aggregate	22,398.46	1261.89	23,450.03	129,343.24	11,462.12	105.16
Croatia (CR)	19,454.06	946.41	8622.88	99,899.25	8412.57	105.16
Greece (GR)	5363.01	315.47	26,078.96	90,435.11	6204.27	105.16
Italy (IT)	26,709.91	1156.73	19,979.85	138,807.38	13,354.95	105.16

Step-by-Step Procedure to Quantify the Cluster Emissions and Environmental Costs

A. Select the ports forming the cluster. Here, the cruise ships are supposed to be stopped for the time at which they produce polluting-GHG emissions.

B. Collect the available data [55–62] on cruise moorings for each cluster's port in the reference year (2019, the last before COVID-19). The necessary information are in Table 8, for which the cold ironing time is obtained by Equation (6). The latter takes into account the time at which the ship is supposed to be fed by the HVSC system. In Equation (6), one hour is generally considered the standard time for plug-in and plug-out operations. Without the HVSC infrastructure, the time in Equation (6) is spent powering the ship by fuel (i.e., marine diesel oil), thus increasing the polluting-GHG emission outcome.

$$t_{cold\ ironing} = t_{departure} - t_{arrival} - 1 \quad [\text{hour}] \tag{6}$$

C. Determine the emission factor of each undesired substance (NO_X, NMVOC, PM_{10}, $PM_{2.5}$, and CO_2), which reflects the quantity emitted when burning a ton of fuel. Evidently, the factors are strictly dependent on the engine type, fuel type, and navigation phase (cruise, maneuvering, and hoteling). As these data are not completely available for all the vessels (Table 8), weighted average emission factors are calculated to simplify the analysis. For the considered substances, the average in Equation (7) weighs the emission factors for every engine type depending on the incidence of that engine in respect to the cruise world fleet [63]. In Equation (7), each *i*-th undesired substance is quantified by the Fi emission factor, a dimensionless term (i.e., g emissions/ton fuel), whereas the index e represents the engine type and w_e is the percentage of the e engine type in respect to the world cruise fleet (Table 9). When "fuel" is not reported in the mass unit of measure, the related quantity is to be intended as a polluting-GHG emission. Conversely with "fuel".

$$F_i = \sum_e F_{i,e} \cdot w_e \Big/ \sum w_e \qquad [\text{g/tonfuel}] \tag{7}$$

D. To increase the comprehension, it is important to observe that the method in Equation (7) follows the same methodology commonly used when determining C_{spec} (i.e., specific fuel consumption of the cruise fleet). Indeed, in Equation (8), the term w_e has the same meaning already observed in Equation (7), while C_e is the specific fuel consumption. Evidently, the calculus in Equation (8) is fundamental when seeking the specific fuel consumption at the mooring.

$$C_{spec} = \sum_e C_e \cdot w_e \Big/ \sum w_e \qquad [\text{gfuel/kWh}] \tag{8}$$

E. Only the emission factor for sulfur oxides (SOx) is assessed by a different approach. As it depends on only the fuel, in Equation (9), the undesired substance is weighed by adopting the S percentage of the sulfur content in the fuel. In our case, the last number is equal to 0.1 as in the European moorings' regulations.

$$F_{su} = 20 \cdot \text{S} \qquad [\text{kg/tonfuel}]. \tag{9}$$

F. For the five substances under consideration, Table 10 provides the emission factors of the main/auxiliary engines. As all this data have a sensitive margin of error, the results take into account the "rated" value, but also "minimum-maximum" values correlated to uncertainties (Table 11).

Table 8. Dataset for each port of the cluster.

Date	Vessel	Time of Arrival	Time of Departure	Mooring Time	Cold Ironing Time

Table 9. Statistical distribution of engine and fuel types for the Mediterranean cruise fleet.

GT BFO	GT MDO	HSD BFO	HSD MDO	MSD BFO	MSD MDO	SSD BFO	SSD MDO	ST BFO	ST MDO
3.29%	4.79%	1.76%	3.68%	76.98%	5.68%	3.81%	0.00%	0.02%	0.00%

Table 10. Emission factors for the different undesired substances (main/auxiliary engines).

Pollutant-GHG	Unit	Main Engines	Auxiliary Engines
NO_X	g/kWh	9.80	13.45
NMVOC	g/kWh	1.38	0.40
$PM_{10–2.5}$	g/kWh	2.14	0.75
SO_X	kg/ton fuel	2.00	2.00
CO_2	g/kWh	750.00	750.00

Table 11. Estimated uncertainties given as a percentage related to the emission factors.

Pollutant-GHG	At Sea	Maneuvering	Mooring
NO_X	±20%	±40%	±30%
SO_X	±10%	±30%	±20%
NMVOC	±25%	±50%	±40%
$PM_{10–2.5}$	±25%	±50%	±40%
CO_2	±10%	±30%	±20%
[Fuel Consumption]	±10%	±30%	±20%

G. Build the vessel database, whose structure is reported in Tables 12 and 13. This database plays a crucial part in this work as it contains all the data regarding consumption, power, and emission for the considered ships. This information is used to estimate the abatement due to the cold ironing implementation. When $P_{main,100\%}$ and $P_{aus,100\%}$ are not directly available from literature, Table 12 can be completed by using Equations (10) and (11) from [63].

$$P_{main,100\%} = 42.966 \cdot GT^{0.6035} \quad [\text{MW}] \tag{10}$$

$$P_{aux,100\%} = 0.27 \cdot P_{main,\ 100\%} \quad [\text{MW}] \tag{11}$$

Conversely, the berth values $P_{main,mooring}$ and $P_{aux,mooring}$ are 20% and 40% of the rated values, respectively [63]. As the main engines operate for only 5% of the mooring time, the specific fuel consumption at the berth results as in Equation (12). Equation (13) is needed to verify the units of measurement:

$$C_{mooring} = C_{spec} \cdot (P_{main,100\%} \cdot 0.05 + P_{aux,100\%})/10^3 \quad [\text{ton/h}] \tag{12}$$

$$\left[\frac{\text{gfuel}}{\text{kWh}} \frac{1}{10^6}\right] \cdot \left[\text{MW} \cdot 10^3\right] = \left[\frac{\text{tonfuel}}{\text{h}}\right] \tag{13}$$

H. The use of the HVSC platform can abstain the emissions of undesired substances (Tables 14 and 15). For the ones whose emission factor is found at step F., the *Ei,p* avoided emissions are given by Equation (14), while Equation (15) checks the units of measurement. The avoided sulfur is weighted in Equation (16), whereas the units verification is conducted in Equation (17).

$$E_{i,p} = \left(P_{main,100\%} 10^3 \cdot 0.05 \cdot F_{i,main} + P_{aus,100\%} 10^3 \cdot F_{i,aus}\right) \frac{1}{10^6} \cdot t_{cold\ ironing} \quad [\text{ton}] \tag{14}$$

$$\left(\left[\text{MW} \cdot 10^3\right] \cdot \left[\frac{\text{g}}{\text{kWh}}\right] + \left[\text{MW} \cdot 10^3\right] \cdot \left[\frac{\text{g}}{\text{kWh}}\right]\right) \cdot \frac{1}{10^6} \cdot [\text{h}] = [\text{ton}] \tag{15}$$

$$E_{i,su} = F_{su} \cdot \frac{1}{10^3} \cdot C_{mooring} \cdot t_{cold\ ironing} \quad [\text{ton}] \tag{16}$$

$$\left[\frac{\text{kg}}{\text{ton fuel}} \frac{1}{10^3}\right] \cdot \left[\frac{\text{tonfuel}}{\text{h}}\right] \cdot [\text{h}] = [\text{ton}] \tag{17}$$

I. The last step is the external costs determination, obtained by multiplying each emission by the relative cost as reported in Table 7.

Table 12. Vessel database structure—part 1.

							Rated Values					
Vessel	**GT**	**$P_{main,100\%}$**	**$P_{aus,100\%}$**	**$P_{aus,\ mooring}$**	**$P_{main,\ mooring}$**	**$C_{moor.}$**	**NO_x**	**NMVOC**	**PM_{10}**	**$PM_{2.5}$**	**SO_x**	**CO_2**
name	ton	MW	MW	MW	MW	ton/h	ton/h	ton/h	ton/h	ton/h	ton/h	ton/h

Table 13. Vessel database structure—part 2.

Minimum Values							Maximum Values						
$C_{moor.}$	**NO_x**	**NMVOC**	**PM_{10}**	**$PM_{2.5}$**	**SO_x**	**CO_2**	**$C_{moor.}$**	**NO_x**	**NMVOC**	**PM_{10}**	**$PM_{2.5}$**	**SO_x**	**CO_2**
ton/h	ton/h	ton/h	ton/h	ton/h	ton/h	ton/h	ton/h	ton/h	ton/h	ton/h	ton/h	ton/h	ton/h

Table 14. Database of the substance emitted (for each port)—part 1.

						Rated Values						
Ship	Date	Arrive	Departure	Mooring Time	HVSC Time	$C_{moor.}$	NO_x	NMVOC	PM_{10}	$PM_{2.5}$	SO_x	CO_2
		h	h	h	h	ton	ton	Ton	ton	ton	ton	ton

Table 15. Database of the substance emitted (for each port)—part 2.

Minimum Values							Maximum Values						
$C_{moor.}$	NO_x	NMVOC	PM_{10}	$PM_{2.5}$	SO_x	CO_2	$C_{moor.}$	NO_x	NMVOC	PM_{10}	$PM_{2.5}$	SO_x	CO_2
ton	ton	ton	ton	ton	ton	ton	ton	ton	Ton	ton	ton	ton	ton

6. Evaluation of Environmental Externalities and HVSC Feasibility in the Adriatic Route

By adopting the step-by-step procedure already explored, a consequent database is developed to evaluate and quantify the effect of cold ironing for the entire cluster of ports. To match all the possible combinations and intersections between the input data, the database is constituted by 15 sheets and about 58,500 elements. Along the selected Adriatic route from Italy to Croatia and Greece (Figure 10), a database is capable of weighing the emissions that are saved due to the HVSC platforms in the ports. In Figure 11, a representation of the database is provided to explain both the potentiality and complexity. Emissions indicate externalities for the collectivity, thus representing the positive incomes to be pondered in the cash flow. Once all the cruise ships in the Adriatic route (more than one hundred) are selected, the database can give the specific hourly consumptions and emissions (i.e., polluting substances and GHG) by applying Equations (6)–(9). This result is noteworthy as it precisely represents the emission contribution of each vessel. Hence, by combining this information with the mooring data and arrival–departure hour of each ship, the database gives the global emissions/externalities in each port, as disclosed by the procedure. It is then possible to query the database in order to check the feasibility of each HVSC installation. The Adriatic route's outcome is summarized in Tables 16–21, presenting diverse rated, minimum, and maximum values.

Figure 10. Adriatic route (Trieste, Split, Dubrovnik, Corfù, Argostoli, Piraeus, and Bari).

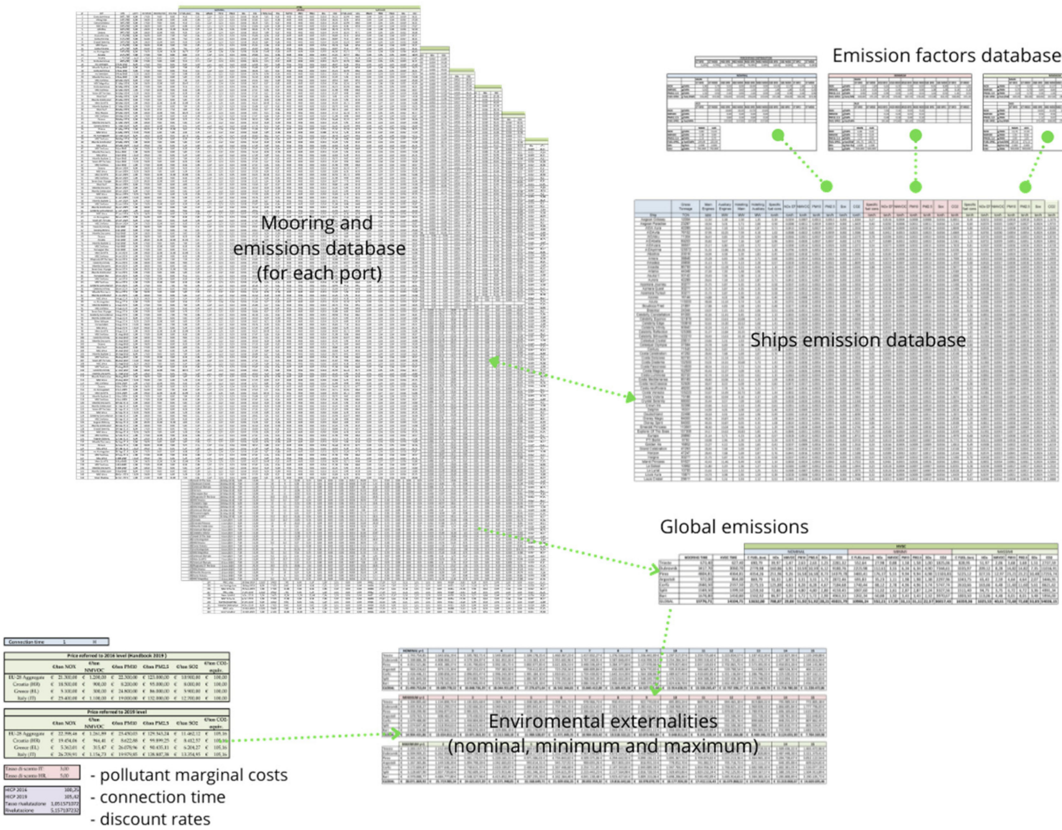

Figure 11. Database structure and correlations (15 sheets, about 58,500 elements).

Table 16. Avoided emissions in the cluster with cold ironing (yearly rated values).

Port	Mooring Time	HVSC Time	Rated Values (tons Emitted)						
			C Fuel	NO_X	NMVOC	PM_{10}	$PM_{2.5}$	SO_X	CO_2
Trieste	673.40	627.40	690.79	39.97	1.47	2.63	2.63	1.38	2281.32
Dubrovnik	3417.70	3060.70	2779.98	160.86	5.91	10.59	10.59	5.56	9180.76
Piraeus	4804.81	4364.81	4354.26	251.96	9.26	16.58	16.58	8.71	1,4379.78
Argostoli	972.00	864.00	869.79	50.33	1.85	3.31	3.31	1.74	2872.46
Corfù	2660.50	2337.50	2175.55	125.89	4.63	8.28	8.28	4.35	7184.68
Split	1569.50	1399.50	1259.50	72.88	2.68	4.80	4.80	2.52	4159.45
Bari	1678.80	1450.80	1501.21	86.87	3.19	5.72	5.72	3.01	4957.68
GLOBAL	**15,776.71**	**14,104.71**	**13,632.80**	**788.87**	**29.00**	**51.92**	**51.92**	**27.27**	**45,021.79**

Table 17. Avoided emissions in the cluster with cold ironing (yearly minimum values).

Port	Minimum Values (tons Emitted)						
	C Fuel	NO_X	NMVOC	PM_{10}	$PM_{2.5}$	SO_X	CO_2
Trieste	552.64	27.98	0.88	1.58	1.58	0.88	1825.06
Dubrovnik	2223.98	112.61	3.55	6.34	6.34	3.56	7344.61
Piraeus	3483.41	176.37	5.55	9.94	9.94	5.57	11,503.83
Argostoli	695.83	35.23	1.11	1.98	1.98	1.11	2297.96
Corfù	1740.44	88.12	2.78	4.96	4.96	2.78	5747.74
Split	1007.60	51.02	1.61	2.87	2.87	1.61	3327.56
Bari	1200.97	60.81	1.92	3.43	3.43	1.92	3966.15
GLOBAL	**10,906.24**	**552.21**	**17.39**	**31.11**	**31.11**	**17.45**	**36,017.43**

Table 18. Avoided emissions in the cluster with cold ironing (yearly maximum values).

Port	Maximum Values (tons Emitted)						
	C Fuel	NO_X	NMVOC	PM_{10}	$PM_{2.5}$	SO_X	CO_2
Trieste	828.95	51.97	2.06	3.68	3.68	1.99	2737.59
Dubrovnik	3335.97	209.12	8.28	14.82	14.82	8.01	11,016.91
Piraeus	5225.12	327.55	12.97	23.21	23.21	12.54	17,255.74
Argostoli	1043.75	65.43	2.59	4.64	4.64	2.51	3446.95
Corfù	2610.66	163.66	6.48	11.60	11.60	6.27	8621.62
Split	1511.40	94.75	3.75	6.72	6.72	3.63	4991.34
Bari	1801.45	112.93	4.47	8.00	8.00	4.33	5949.22
GLOBAL	**16,359.36**	**1025.53**	**40.61**	**72.68**	**72.68**	**39.26**	**54,026.15**

Table 19. Avoided environmental costs in the cluster per polluting-GHG substance (yearly rated values).

Port	Rated Values (Values in EUR)					
	NO_X	NMVOC	PM_{10}	$PM_{2.5}$	SO_X	CO_2
Trieste	1,067,680.88	1700.04	52,560.67	365,158.34	18,451.05	239,897.12
Dubrovnik	3,129,477.30	5597.59	91,287.96	1,057,604.36	46,773.47	965,422.37
Piraeus	1,351,275.53	2922.49	432,439.11	1,499,587.24	54,030.0	1,512,136.57
Argostoli	269,926.03	583.79	86,382.51	299,552.25	10,792.8	302,059.06
Corfù	675,147.98	1460.19	216,062.81	749,250.08	26,995.4	755,520.19
Split	1,417,845.97	2536.05	41,359.07	479,159.91	21,191.2	437,395.80
Bari	2,322,889.87	3698.68	114,353.13	794,453.32	40,142.8	521,929.91
GLOBAL	**10,234,243.56**	**18,498.83**	**1,034,445.26**	**5,244,765.51**	**218,376.9**	**4,734,361.03**

Table 20. Avoided environmental costs in the cluster per polluting-GHG substance (yearly minimum values).

Port	Minimum Values (Values in EUR)					
	NO_X	NMVOC	PM_{10}	$PM_{2.5}$	SO_X	CO_2
Trieste	747,376.62	1019.39	31,492.90	218,792.76	11,808.67	191,917.69
Dubrovnik	2,190,634.11	3356.48	54,697.21	633,687.21	29,935.02	772,337.90
Piraeus	945,892.87	1752.41	259,105.53	898,511.10	34,579.22	1209.709.26
Argostoli	188,948.22	350.06	51,758.01	179,483.41	6907.42	241,647.25
Corfù	472,603.59	875.57	129,458.85	448,929.87	17,277.08	604,416.16
Split	992,492.18	1520.69	24,781.21	287,099.34	13,562.41	349,916.64
Bari	1,626,022.91	2217.84	68,517.22	476,014.40	25,691.42	417,543.93
GLOBAL	**7,163,970.49**	**11,092.45**	**619,810.92**	**3142,518.09**	**139,761.25**	**3,787,488.82**

Table 21. Avoided environmental costs in the cluster per polluting-GHG substance (yearly maximum values).

Port	Maximum Values (Values in EUR)					
	NO_X	NMVOC	PM_{10}	$PM_{2.5}$	SO_X	CO_2
Trieste	1,387,985.15	2380.06	73,584.94	511,221.68	26,569.51	287,876.54
Dubrovnik	4,068,320.49	7836.63	127,803.14	1,480,646.10	67,353.80	1,158,506.85
Piraeus	1,756,658.19	4091.49	605,414.76	2,099,422.14	77,803.26	1,814,563.89
Argostoli	350,903.84	817.30	120,935.51	419,373.15	15,541.70	362,470.88
Corfù	877,692.37	2044.26	302,487.94	1,048,950.11	38,873.43	906,624.23
Split	1,843,199.76	3550.48	57,902.69	670,823.88	30,515.42	524,874.96
Bari	3,019,756.83	5178.15	160,094.38	1,112,234.65	57,805.70	626,315.89
GLOBAL	**13,304,516.63**	**25,898.37**	**1,448,223.36**	**7,342,671.71**	**314,462.81**	**5,681,233.24**

By multiplying the last results by the cost shown in Table 7, the yearly environment costs are finally found. Then, to prove the profitability of the HVSC in the cluster, the yearly avoided costs are to be evaluated by taking into account the entire service life of the installation. To this aim (Tables 22 and 23), a reference period of 15 years is used by following the provisions in Annex I of commission delegated regulation (EU) n. 480/2014 of 3 March 2014. When performing the economic analysis, Equation (18) provides $C_{life,p}$, which is the cost of emission in port p during the entire lifetime. To find such a value, the cost of emission in port p in the 2019 reference year (i.e., $C_{1,p}$) is adopted, as well as the t year of reference, the i polluting/GHG substance, and the r discount rate. For the discount rate, the commission implementing regulation EU 2015/207 of 20 January 2015 suggests 3% for Italy and 5% for Greece and Croatia as beneficiaries of the cohesion funds.

$$C_{life,\,p} = \sum_{t=1}^{15} C_{1,p} \Big/ (1 + r/100)^t \qquad [\text{EUR}] \tag{18}$$

Table 22. First year avoided externalities: overall summary.

Port	Rated (EUR)	Minimum (EUR)	Maximum (EUR)
Trieste	1,745,448.10	1,202,408.03	2,289,617.87
Dubrovnik	5,296,163.05	3,684,647.94	6,910,467.01
Piraeus	4,852,390.99	3,349,550.40	6,357,953.72
Argostoli	969,296.50	669,094.36	1,270,042.39
Corfù	2,424,436.69	1,673,561.11	3,176,672.34
Split	2,399,488.07	1,669,372.46	3,130,867.19
Bari	3,797,467.75	2,616,007.72	4,981,385.59
GLOBAL	**21,484,691.14**	**14,864,642.02**	**28,117,006.11**

Table 23. Lifetime discounted avoided externalities (15 years): overall summary.

Port	Rated (EUR)	Minimum (EUR)	Maximum (EUR)
Trieste	20,887,884.43	14,389,290.60	27,399,997.43
Dubrovnik	55,224,559.64	38,420,845.00	72,057,354.27
Piraeus	50,597,225.36	34,926,690.10	66,296,145.10
Argostoli	10,107,123.13	6,976,832.33	13,243,083.92
Corfù	25,280,273.11	17,450,685.46	33,124,042.72
Split	25,020,126.94	17,407,009.22	32,646,419.68
Bari	45,444,529.30	31,305,924.75	59,612,546.71
GLOBAL	**232,561,721.90**	**160,877,277.46**	**304,379,589.84**

To precisely testify the HVSC economic feasibility, the avoided environmental externalities (i.e., benefits from cold ironing) are to be compared with the construction and O&M costs of implementing the HVSC infrastructure. With reference to the plant costs, the first hypothesis is the availability of a high-voltage connection in the harbor area. As a matter of fact, this assumption is mostly satisfied as the ports usually host energy-intensive utilities. By observing Figure 1, the system under study is therefore constituted by the elements from step 3 to step 5. A detailed market research between several producers finally produces the present quote for a single HVSC installation (Table 24) whose values actually update the previous ones (2015 as the reference year) discussed in Table 4. As the number of stops in moorings has a large variability in the considered ports for the Adriatic route, the HVSC supplying points to be installed are decided on a case-by-case basis (Table 25). From the daily medium mooring, the actual stops are consequently rounded.

Table 24. Shore connection costs (single plant).

Element	Cost (EUR)
MT switchgears	32,000.00
Converter 16 MVA 11 kV 50–60 Hz	4,500,000.00
Cable dispenser	1,200,000.00
Design and construction (25%)	1,433,000.00
Total	**7,165,000.00**

Table 25. Number of assumed cold ironing points and related costs.

Port	Daily Medium Mooring	Assumed Plants	Cost of HVSC (EUR)
Trieste	1.14	1	7,165,000.00
Dubrovnik	1.82	2	1,4330,000.00
Piraeus	2.05	2	14,330,000.00
Argostoli	1.25	1	7,165,000.00
Corfù	2.25	2	14,330,000.00
Split	1.28	1	7,165,000.00
Bari	1.55	2	14,330,000.00
GLOBAL	**15.00**	**11**	**78,815,000.00**

Secondly, O&M costs are examined to complete the analysis. In terms of the plant costs, also the assessment of O&M (Tables 26 and 27) is based on market research and historical/standard price data in a period of 15 years. These costs include the maintenance for low/medium voltage switchgears, costs of remote control, air conditioning, inspection, earth measurements, costs for new staff, UPS battery replacement, cleaning, cable dispenser, and so on. By combining the avoided externalities (i.e., rated, minimum, and maximum scenarios) and plant/O&M costs, the economic feasibility of the HVSC Adriatic cluster is estimable. For the sake of clarity, this comparison among externalities/costs is based on the discounted cash flow, a methodology in which the only incoming/outgoing cash flows are examined, thus without amortization, provision, VAT, taxes and subsides, etc. As in Figure 12, the payback time for the cluster is only 5 years in the rated case, while 3.5 years in the maximum and 8 years in the minimum scenarios. In contrast, the economic feasibility is case-dependent. For example, the Argostoli cruise terminal (Figure 13) has a payback time of 15 years (i.e., technical life) in the rated case, thus the economic feasibility is not reached in the minimum case. Although this can appear odd based on the high mooring hours (more than Trieste in Tables 16–18), the discrepancy depends on the marginal costs of each emission/country (Table 7). In order to encourage ship-owners to adopt the onboard HVSC infrastructure, incentives are to be put in place to ensure the payback also in the underdog ports. Trieste in Figure 14 is the benchmark, while the Dubrovnik case is depicted in Figure 15 as the most profitable solution.

Table 26. Operation and maintenance costs (values for first year).

Element	Amount (EUR)
MT substation	42,402.00
Power converter	90,000.00
Cable dispenser	60,000.00
Staff	46,339.00
GLOBAL	**238,741.00**

Table 27. Lifetime discounted O&M costs (15 years): global summary.

Port	Plants Assumed	O&M Costs (EUR)
Trieste	1	2,857,028.18
Dubrovnik	2	5,714,056.36
Piraeus	2	5,714,056.36
Argostoli	1	2,857,028.18
Corfù	2	5,714,056.36
Split	1	2,857,028.18
Bari	2	5,714,056.36
GLOBAL	**11**	**31,427,310.00**

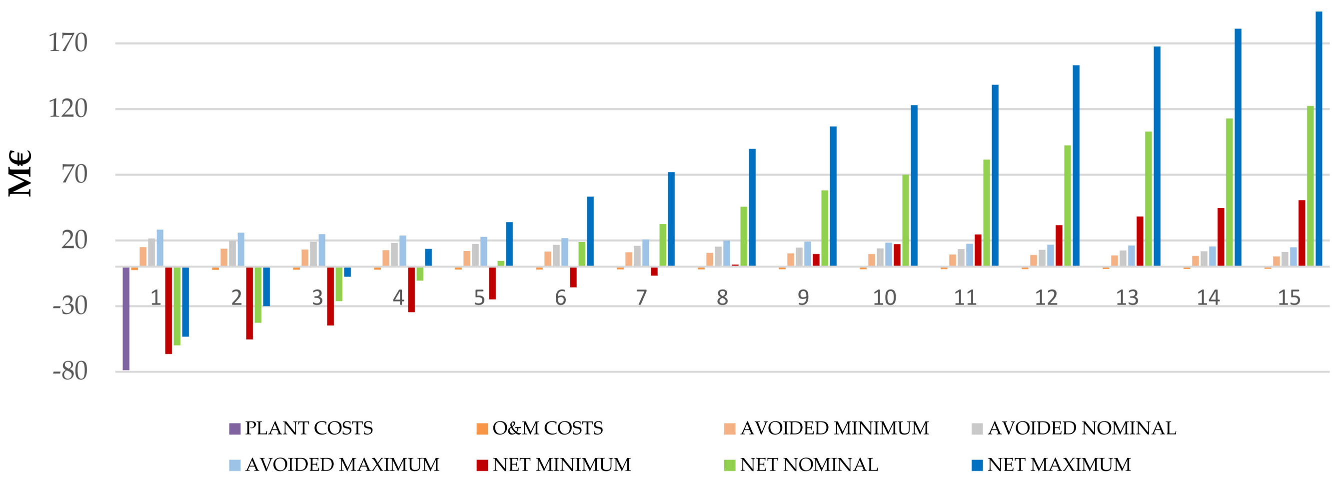

Figure 12. Cash flow in rated, minimum, and maximum scenarios for all ports.

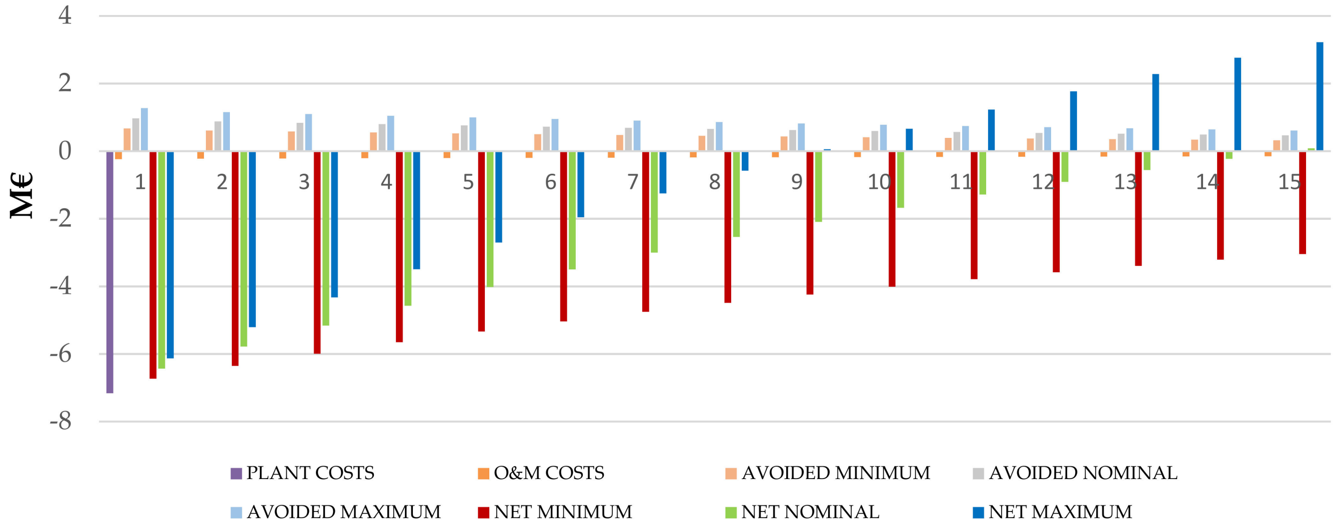

Figure 13. Cash flow in rated, minimum, and maximum scenarios in Argostoli (GR).

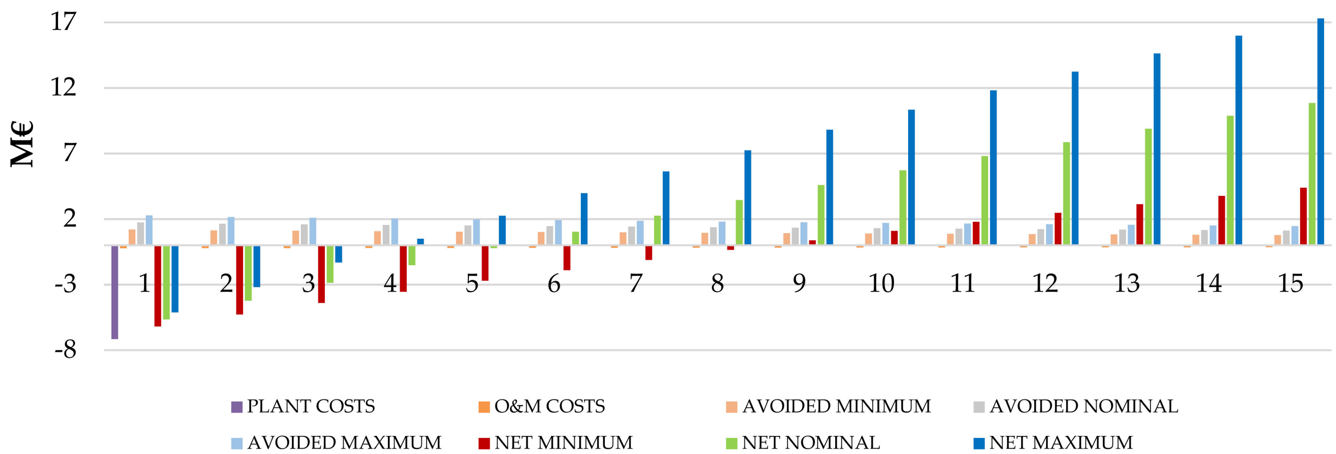

Figure 14. Cash flow in rated, minimum, and maximum scenarios in Trieste (IT).

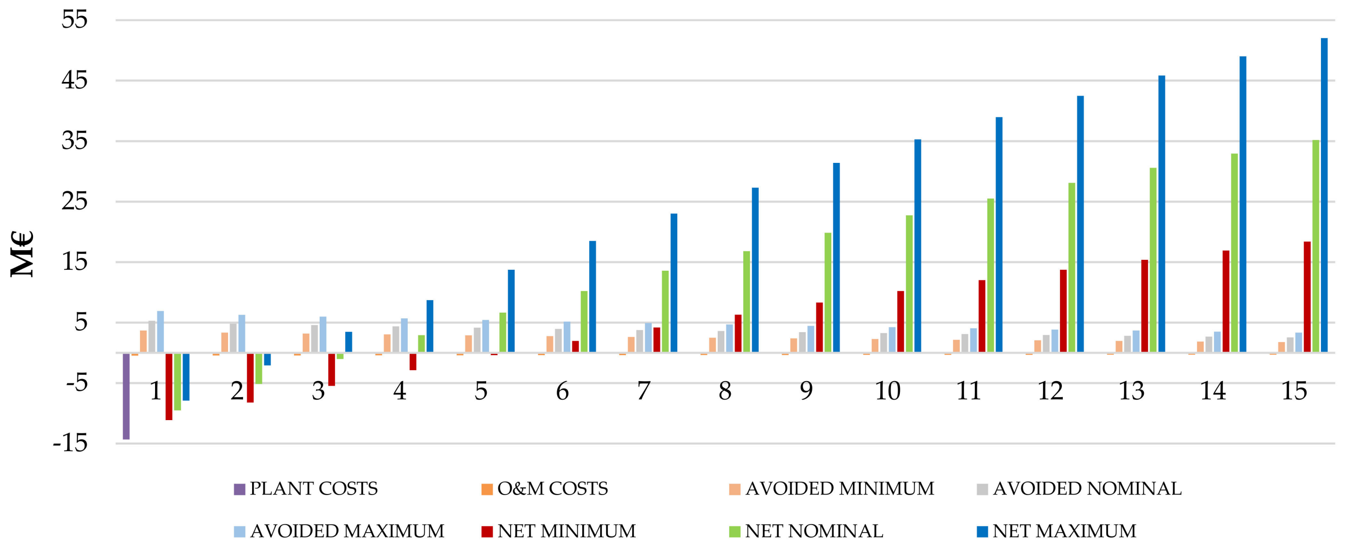

Figure 15. Cash flow in rated, minimum, and maximum scenarios in Dubrovnik (CR).

7. Embedding Cold Ironing in the Context of the EU Emission Trading System for Maritime Transport

Within the broader policy context of the European Green Deal, the abatement of GHG emissions from the shipping sector stands out as one of the main priorities of the European Commission. As this paper has explained, the maritime sector has a significant abatement potential and therefore can deliver substantial environmental and climate change benefits. Due to the global nature of international shipping and the difficulty to allocate GHG emissions amongst countries, maritime GHG emissions are not tackled in the international climate change regime, although the International Maritime Organization (IMO) has also been deemed as the ideal forum to this end [11]. Over the past decade, an increasing debate has lingered on the opportunity to adopt market-based instruments to the maritime sector [12,64]. At the international level, efforts have been pursued by the International Maritime Organization (IMO) to both address GHG emissions and set carbon efficiency targets. In 2011, the IMO adopted a new regulatory framework on energy efficiency. Since then, the IMO adopted in April 2018 an initial strategy on the reduction of greenhouse gas emissions from ships, albeit without support from all States. It sets a greenhouse gas emission reduction objective of at least 50% by 2050 compared to 2008 levels, coupled with a vision for the full decarbonization of the sector as soon as possible in this century. It also sets an objective to reduce carbon intensity, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050 as compared to 2008. In November 2020, the IMO approved a technical and operational measure for existing ships with a view to implement the IMO strategy and complement existing energy efficiency policies. Despite such progress being made, however, the above measures are not deemed sufficient to achieve a decarbonization of international shipping consistent with the pathway envisaged under the pivotal Paris agreement objectives.

In the EU, the flagship of carbon pricing is the EU Emission Trading System (EU ETS). Established through Directive no. 2003/87/EC (henceforth called the ETS Directive), the EU ETS is the second cap-and-trade system worldwide, comprised of more than 15,000 stationary installations operating in energy and GHG-intensive sectors as well as (from 2008) 1500 aircraft operators. After a long journey of consultations and internal appraisal, and also in light of the inadequate efforts at the international level, the European Commission adopted on 14 July 2021 a proposal for an amendment of the EU ETS Directive to fully include the maritime sector into the scheme (COM (2021) 551 final), which will be discussed below.

The economic impact on the maritime sector from its inclusion in the EU ETS is deeply influenced by the design elements of the system. The EU ETS as a cap-and-trade mechanism relies on the concept of scarcity to leverage market forces towards adequate market prices for ETS allowances, with a view to induce investments at a lower marginal cost to reduce GHG emissions [13]. In this respect, to adopt a pricing mechanism for GHG emissions from the maritime sector is likely to result in higher shipping costs and lower shipping speeds as the GHG emissions cap decreases over time [14]. The overall increase of logistic costs for ship-owners (as comprising net transportation costs and time at sea) as a result of the application of market-based schemes such as the EU ETS may range from 1.7% to 7.2% depending on different scenarios [65]. In contrast small-sized vessels running short-sea shipping routes have been found to be more negatively affected as compared to larger ships travelling longer distances [65]. As shown by previous research on the aviation sector, in assuming the constant increase of ETS allowance prices, shipping companies will be forced to develop a long-term sustainability strategy to maintain their competitiveness through investments in clean technologies, including the use of alternative fuels and energy sources [66]. This will allow for flexibility regarding the choice of technical and operational measures to improve vessels' performance in terms of energy consumption and GHG emissions. Thus, the cost-effectiveness rationale behind different CO_2-abatement options for the shipping industry will rationally equal the emission allowance price, as ship operators will seek to minimize the additional cost from CO_2 emissions.

In particular, the following ETS design elements are relevant for the maritime sector, as addressed by the recent European Commission's proposal to amend the ETS Directive:

- emission cap setting;
- material and geographical scope of application;
- method of allocation of EU ETS allowances to vessels owners; and
- monitoring, reporting, and verification (MRV).

As for the emission cap setting, the European Commission is proposing that emissions from the current EU ETS sectors (including the maritime sector) be reduced by 61% by 2030, compared to 2005 levels (as compared to the current -43% contribution from the system to the EU's climate target). To this end, the Commission envisages a steeper annual emissions reduction cap of 4.2% (as compared to the current 2.2%/year), following a one-off reduction of the overall emissions cap by 117 million allowances (s.c. "re-basing").

As for the material scope of application, the envisaged EU ETS reform applies to CO_2 emissions from all maritime transportation activities of ships above 5000 gross tonnage-performing voyages with the purpose of transporting passengers or cargo for commercial purposes; this is with the exception of warships, naval auxiliaries, fish-catching or fish-processing ships, wooden ships of a primitive build, ships not propelled by mechanical means, or government ships used for non-commercial purposes pursuant to Regulation 2015/757/EU. As emphasized by [67], an important parameter to be considered in relation to extending the EU ETS to include shipping is the heterogeneity of the maritime industry, which is composed of maritime segments that present large differentiations at their technical and operational features, at the market structure, and in terms of the elasticity of demand. The implementation of an ETS for the abatement of CO_2 emissions from shipping will have a differential impact on the various maritime segments due to their distinct characteristics [12]. Two consequences must be stressed in this respect. First, given the fairly high elasticity of demand for short sea shipping services in comparison to deep sea segments, for example, this could lead to a modal shift from sea to land-based modes of transportation if the transportation cost of these services would increase due to the additional cost of CO_2 emissions for shipping. The situation is remarkably different for deep sea shipping, which cannot easily be replaced by road transport. Second, the increased operational cost for vessels operating or crossing EU territorial waters resulting from the application of the EU ETS could lead to the distortion of competition [68].

As for the geographical scope of application, the EU ETS shall apply, in respect of 50% of the CO_2 emissions from ships departing from a port under the jurisdiction of a Member State and arriving at a port outside the jurisdiction of a Member State, 50% of the CO_2 emissions from ships running voyages departing from a port outside a Member

State and arriving at a port under the jurisdiction of a Member State. In addition, the EU ETS shall apply 100% of the CO_2 emissions from ships running voyages departing from and arriving to ports under the jurisdiction of a Member State; arriving at a port under the jurisdiction of a Member State; and from ships at berth in a port located in a EU Member State (Article 3g).

Next comes the issue of the method of allowances allocation. The EU ETS traditionally allocates allowances based on auctioning or free allocation (Article 9–10 ETS Directive). According to the European Commission's proposal, all ETS allowances shall be allocated to the maritime sector by auctioning. As underscored by previous research, the existing notable differences among the vessels covered by the EU ETS as to the fuel consumption could result in a disproportionate economic burden as even a full auctioning allocation system would be based on the type of fuel used and consumption thereof [14]. The envisaged ETS reform endorses a step-wise approach to the obligation, imposed on ship-owners, to surrender ETS allowances. Accordingly, ship-owners are obliged to surrender allowances equaling 20% of verified CO_2 emissions reported for 2023; 45% of verified CO_2 emissions reported for 2024; 70% of verified CO_2 emissions reported for 2025; and 100% of verified CO_2 emissions reported for 2026 and each year thereafter (Article 3 ga). In the case of non-compliance, in addition to the general EU ETS rules on penalties, ships can be denied entry to EU ports where the responsible shipping company failed to surrender the necessary allowances for two or more consecutive years.

Last on MRV, a proposal is tabled to amend Regulation 1757/2015/EU in order to oblige shipping companies to report aggregated emissions data at the company level and submit for approval their verified monitoring plans and aggregated emissions data at the company level to the responsible administering authority. Under the current European Commission's proposal, all data monitored, reported, and verified under Regulation 2015/757/EU should be submitted to and verified by a national competent authority (Article 3gb of the proposal).

Given the above context, it is important hence to position the adoption of cold ironing technologies in such a regulatory and policy framework. It is noteworthy in this respect that that the application of cold ironing technologies would deliver immediate CO_2 reductions considering the application of electricity to replace fuel engines for ships. As demonstrated in Section 6, the application of cold ironing throughout the selected passenger route would deliver 36,017.43–54,026.15 tCO_2-eq emission reductions (Tables 17 and 18), moreover resulting in EUR 3787,488.82–5681,233.24 avoided costs only from CO_2 emissions (Tables 20 and 21). Under the current ETS setup, particular importance is posed on the role of technologies and activities that provide net GHG emission reductions and more broadly contribute to mitigating climate change [69]. Therefore, economic and environmental benefits generated by cold ironing as applied by shipping companies should be integrated and duly remunerated within the EU ETS, in particular as embedded in the market price of ETS allowances, in order to both mitigate the increased operational costs for ship-owners and ensure compliance with the scheme (see Section 8 below).

Second, cold ironing technology should be financed through the revenues accrued through the ETS. The ETS-driven Innovation and Modernisation funds come into play in this respect (as introduced by Directive no. 2018/410/EU).

Regarding the Innovation Fund, according to Article 10a, paragraph 2 of the ETS Directive, at least 50% of the revenues generated by the auctioning of ETS allowances should be directed to a set of activities contributing to the EU's mitigation action, including, among others:

- to encourage a shift to low-emission and public forms of transportation (Article 10a, paragraph 2, let. f ETS Directive), and
- to finance research and development in energy efficiency and clean technologies in the sectors covered by this Directive (Article 10a, paragraph 2, let. g ETS Directive).

Pursuant to Article 10a, paragraph 8 of the ETS Directive, the financial flow stemming from the auction of more than 450 million allowances (from 2020 to 2030) will support innovative and cross-cutting projects in low-carbon solutions in all ETS sectors, thus including the shipping of goods and passengers. From this standpoint, projects eligible under the Innovation Fund comprise both small and large-scale projects, which are deemed to contribute substantially to mitigating climate change, as well as products substituting carbon intensive ones produced in the sectors listed in Annex I of the ETS Directive, and will help stimulate the construction and operation of low-carbon projects. Innovation Fund projects will be assessed against a multiple set of criteria including effectiveness, efficiency, and scalability in order to appraise their GHG-abatement potential, level of innovation, economic viability, potential for wider application and replication, cost of abatement, and project maturity in terms of technological and business readiness. Given the above environmental and GHG benefits, cold ironing projects (both undertaken by shipping companies and Member States' ports) should be included under the Innovation Fund as they will contribute to the attainment of the ETS targets from the maritime sector.

Regarding the Modernisation Fund, established under Article 10d of the ETS Directive, it is directed to support the ten lower-income EU Member States (namely Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, and Slovakia) to attain the EU's climate and energy targets, enhance the financing of renewable energy sources, and promote best practices among them and other Member States. The Modernisation Fund builds on the 2% of the total allowances (for 2021–2030) auctioned under the ETS. Notably, the Modernisation Fund should be channeled to support investments in the generation and use of electricity from renewable sources, the improvement of energy efficiency, energy storage, and the modernization of energy networks (at least 70%), as well as investments in energy efficiency technology in transport. Notably, projects financed under the Modernisation Fund contribute to the development and embedding of renewable energy generation for the purposes of cold ironing at berth, thus reducing the overall GHG emissions' impacts of cold ironing and maximizing its environmental and CO_2 benefits [22].

8. Impact of CO_2 Emissions and Benefits of Shore Connections under EU ETS Application to Maritime Transport

The inclusion of the shipping industry in the EU Emission Trading Systems [12–14,65–69] offers an interesting point of view in respect to the implementation of cold ironing technology. Thus, this aspect can additionally force the installation of HVSC facilities to supply ships during berthing. To additionally motivate the adoption of cold ironing, a comparison between the cost of fuel and cost of energy during shore-to-ship feeding is proposed in this section. To perform such an evaluation, the costs of LSMGO (low-sulfur marine gas oil) are provided in Table 28 based on [70], whereas the costs of electricity are in Table 29 as in [71]. In the last costs, all taxes and levies are included to evaluate economic costs or the benefit for ship-owners.

Table 28. Low-sulfur marine gas oil (0.1%) average price on Piraeus [70].

Reference number	Price Per Ton (EUR)	Data Reference
1	556.81	24 May 2019 to 21 September 2019

Table 29. Electricity price (2019) (non-householder consumer), 2–20 GWh consumption [71].

Country	I Sem. 2019 (EUR)	II Sem. 2019 (EUR)	2019 (Average, in EUR)
Italy (IT)	0.1575	0.1587	0.1581
Croatia (CR)	0.1075	0.1052	0.1064
Greece (GR)	0.0994	0.1006	0.1000

The annual fuel consumption in a p port is the first information to be acquired from the database in Section 4. Then, the annual total cost of the fuel is calculated by Equation (19), where p represents the considered port, $C_{mooring}$ is the specific consumption for a single ship as in Equation (12), the time to supply by the HVSC is named $t_{cold\ ironing}$, and $LSMGO$ is the fuel price from Table 28. Furthermore, the energy cost must be identified to assess the HVSC investment. The latter represents the money paid by the ship-owner to ensure the no-emissions electrical supply of the ship from land during HVSC mooring. As in Equation (21), such a cost is given by multiplying the power values in (10)–(11) at berth (i.e., $P_{main,mooring}$ and $P_{aux,mooring}$), the $t_{cold\ ironing}$ time in which the ship is fed from the HVSC, and the ε_p, which is the electricity price, for the p port as in Table 30. Units of measure are checked in Equations (20) and (22).

$$Cost\ fuel_{\ p} = \left(\sum_{ships,p} C_{mooring} \cdot t_{cold\ ironing} \right) \cdot LSMGO\ price \tag{19}$$

$$[€] = \left[\frac{\text{ton}}{\text{h}} \cdot \text{h} \right] \cdot \left[\frac{€}{\text{ton}} \right]. \tag{20}$$

$$Cost\ electricity_{\ p} = \left(\sum_{ships,p} (P_{main,100\%} \cdot 0.05 + P_{aux,100\%}) \cdot t_{cold\ ironing} \right) \cdot \varepsilon_p \tag{21}$$

$$[€] = [\text{kW} \cdot \text{h}] \cdot \left[\frac{€}{\text{kWh}} \right] \tag{22}$$

The calculation based on Equations (19) and (21) is performed to contrast the two costs for each port. The results are shown in Table 30 in which the cold ironing economic convenience appears evident in the countries where the energy cost is low (i.e., GR and CR). Conversely, in Italy, where the energy is more expensive (Table 29), the positive differential Δ suggests that the classical powering from marine fuel is more convenient (i.e., 80% the cost of the electrical supply from the HVSC platform). Although such an evaluation is obtained by excluding the cost to install the HVSC cabinet on the ship, the hypothetical ship-owner can find the interest in adopting the HVSC when observing the entire route as the saved money is approximately EUR 1 million (i.e., EUR −913,760.30 in Table 30). In the countries in which the energy cost makes the HVSC unaffordable (i.e., Italy), the ship-owners are evidently discouraged in adopting the cold ironing during berthing.

In such a case, the ETS mechanism can be the correct tool for ensuring the reimbursement of expenses incurred, i.e., the operational cost when buying the electrical energy. To explore the ETS possibility, three different examples are next examined. Each scenario is based on a particular CO_2 price (Table 31) when this avoided environmental emission is supposed to be traded on the EU ETS market. In the table, the CO_2 price is referred to verified values in 2019 and 2021 [72,73], while the evaluation for the future (2030 year) is obtained from some forecasts [74,75]. The last values identify three profiles in which the monetary volumes related to the saved CO_2 emissions are calculated. Such volumes are convertible by the ship-owners who take part in the EU ETS market. In such a context, Equation (23) can quantify the economic return. In last equation, $m_{CO2,p}$ is the CO_2 mass that annually is avoided in the p port assuming the rated scenario, while $\varepsilon_{CO2,Ref}$ is the CO_2 price in the three examples of interest (Table 31). The performed analysis gives the results in Table 32, whose graphical representation is in Figure 16. In our opinion, the conclusions are impressive. In the current case nowadays (Reference number 2) and even the ports with a high energy price (i.e., Trieste and Bari in Italy), the EU ETS mechanism can strongly foster the HVSC implementation. Indeed, the money flux for saved CO_2 emissions can practically compensate for the negative differential between the fuel costs and energy costs (i.e., the green bar minus the light-blue bar practically corresponds to the grey bar). In other words, this means that the idea of EU ETS repayment makes the HVSC affordable in every port along the Adriatic route, even in the underdog cases. In contrast, when taking into account a possible future scenario in which the CO_2 price is EUR 100/ton (Reference number 3), the monetary savings for ship-owners are undeniable. The last value (EUR 100/ton) is to be considered as plausible at the end of 2030, similarly to what is expected in several outlooks [74,75]. Again, Equation (24) is only a final verification of units of measure.

$$Value\ of\ CO2_p = m_{CO2,p} \cdot \varepsilon_{CO2,\ Ref} \tag{23}$$

$$[€] = [\text{ton}] \cdot \left[\frac{€}{\text{ton}}\right] \tag{24}$$

Table 30. Cost of mooring (1 year considered), supplied by fuel and electricity (cold ironing).

Port	Fuel Consumption (ton)	Cost of Fuel (EUR)	Energy (kWh)	Cost of Energy (EUR)	Δ Cost (EUR)
Trieste (IT)	690.79	384,638.75	3,041,761.3	480,902.47	96,263.72
Dubrovnik (CR)	2779.98	1,547,908.76	12,241,016.0	1301,832.05	−246,076.71
Piraeus (GR)	4354.26	2,424,482.30	19,173,046.4	1,917,304.64	−507,177.65
Argostoli (GR)	869.79	484,306.03	3,829,940.1	382,994.01	−101,312.02
Corfù (GR)	2175.55	1,211,362.37	9,579,573.7	957,957.37	−253,404.99
Split (CR)	1259.50	701,298.01	5,545,934.2	589,810.10	−111,487.91
Bari (IT)	1502.92	836,835.67	6,617,779.5	1,046,270.93	209,435.26
GLOBAL	**13,632.8**	**7,590,831.87**	**60,029,051.2**	**6,677,071.58**	**−913,760.30**

Table 31. CO_2 price on EU ETS considered.

Reference Number	Price	Data Reference
1	EUR 24.72/ton	Average price in 2019 [72]
2	EUR 57.65/ton	1 July 2021 [73]
3	EUR 100.00/ton	Forecast for 2030 [74,75]

Table 32. Value of avoided CO_2 on EU ETS (1 year considered).

Port	Avoided CO_2 ton	Ref Number 1 CO_2 Price (EUR)	Ref Number 2 CO_2 Price (EUR)	Ref Number 3 CO_2 Price (EUR)
Trieste (IT)	2281.32	56,394.26	131,518.16	228,132.10
Dubrovnik (CR)	9180.76	226,948.44	529,270.93	918,076.20
Piraeus (GR)	14,379.78	355,468.28	828,994.59	1,437,978.48
Argostoli (GR)	2872.46	71,007.09	165,597.03	28,245.51
Corfù (GR)	7184.68	177,605.30	414,196.82	718,468,03
Split (CR)	4159.45	102,821.62	239,792.33	415,945,06
Bari (IT)	4963.33	122,693.63	286,136.24	496,333.46
GLOBAL	**45,021.79**	**1,112,938.61**	**2,595,506.10**	**4,502,178.84**

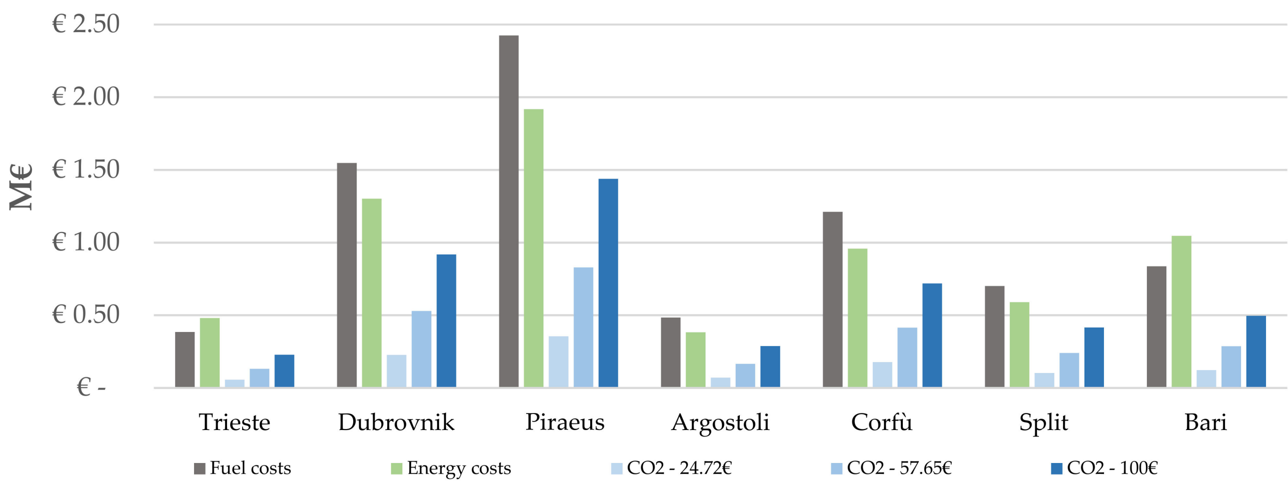

Figure 16. Overview on costs/revenues for the Adriatic route.

9. Results Discussion

Some additional considerations on the results are provided next. In regard to the avoided emissions in the cluster, Table 33 summarizes the yearly results already observed on Tables 16–18. From the initial goal of assessing the environmental–economic factors, the analysis of the results over the useful life of the plant starts from grouping the environmental benefit and cost data (plant and O&M), as in Table 34. Evidently, by summing up the numbers in Table 34, the final result in Table 35 can be obtained. These data show that over the life considered for the plant (15 years as suggested by the guidelines), most of the plants are able to abundantly cover the initial investment, even in the pejorative (MIN) case.

Table 33. Avoided emissions in the cluster with cold ironing (yearly values of tons emitted).

	C FUEL	NO_X	NMVOC	PM_{10}	$PM_{2.5}$	SO_X	CO_2
RATED	13,632.80	788.87	29.00	51.92	51.92	27.27	45,021.79
MIN	10,906.24	552.21	17.39	31.11	31.11	17.45	36,017.43
MAX	16,359.36	1025.53	40.61	72.68	72.68	39.26	54,026.15

Table 34. Comparison of costs and benefits obtained in Sections 5 and 6.

Port	Avoided Externalities Rated (EUR)	Avoided Externalities Minimum (EUR)	Avoided Externalities Maximum (EUR)	Cost of HVSC (EUR)	O&M Costs (EUR)
Trieste (IT)	20,887,884.43	14,389,290.60	27,399,997.43	7,165,000.00	2,856,429.83
Dubrovnik (CR)	55,224,559.64	38,420,845.00	72,057,354.27	14,330,000.00	5,712,936.30
Piraeus (GR)	50,597,225.36	34,926,690.10	66,296,145.10	14,330,000.00	5,712,936.30
Argostoli (GR)	10,107,123.13	6,976,832.33	13,243,083.92	7,165,000.00	2,856,468.15
Corfù (GR)	25,280,273.11	17,450,685.46	33,124,042.72	14,330,000.00	5,712,936.30
Split (CR)	25,020,126.94	17,407,009.22	32,646,419.68	7,165,000.00	2,856,468.15
Bari (IT)	45,444,529.30	31,305,924.75	59,612,546.71	14,330,000.00	5,712,936.30
GLOBAL	**232,561,721.90**	**160,877,277.46**	**304,379,589.84**	**78,815,000.00**	**31,421,111.33**

Table 35. Net profit (or loss) after lifetime for the cluster in the three scenarios.

Port	Rated (EUR)	Minimum (EUR)	Maximum (EUR)
Trieste	10,865,856.25	4,367,262.41	17,377,969.25
Dubrovnik	35,180,503.27	18,376,788.64	52,013,297.91
Piraeus	30,553,168.99	14,882,633.74	46,252,088.74
Argostoli	85,094.95	-3,045,195.86	3,221,055.74
Corfù	5,236,216.75	-2,593,370.91	13,079,986.36
Split	14,998,098.75	7,384,981.04	22,624,391.50
Bari	25,400,472.93	11,261,868.38	39,568,490.34
GLOBAL	**122,319,411.90**	**50,634,967.45**	**194,137,279.84**

The performed study has also developed important conclusions for policy-makers. In order to guarantee the sustainability of the investment and simultaneously the environmental benefits, the A and B solutions appear the most convenient.

A. Consider the cluster as a whole also from the point of view of economic return, thus helping the underdog ports for which the single investment is not repaid within the useful life. Equalization or financing mechanisms could be additionally developed to support the installation of the systems with long payback time.
B. Exclude the ports with reduced visits/mooring time or even the countries not able to monetize the environmental benefits.

The A option is desirable to maximize the presence of such plants on routes with similar characteristics, limiting downtime and increasing the spread of the same technology among ship-owners. In contrast, the option B foresees the possible removal of some plants from the cluster. This inevitably reduces the propensity of ship-owners to adapt their ships with cold ironing systems, with possible negative repercussions in terms of the use of plants also on the remaining ports equipped with shore connection. The need for attention when approaching the dissemination of this technology is evident.

From the annual data in Section 8, it is finally possible to complete Table 36. Here, an important index represents the incidence of the CO_2 values exchanged on the EU ETS with respect to the net balance obtained from the cost–benefit analysis in the "Maximum" case. Although the incidence does not formally play a defined role, it highlights the weight that the CO_2 valorization on the ETS assumes with respect to the plant net. In particular, it is possible to observe how the non-return on investment in the ports of Argostoli and Corfu is offset by the total amount of the quotas relating to the CO_2 produced in these ports, which are then traded on the EU ETS. For the port of Argostoli, there is even an overrun of the share traded on the EU ETS compared to the net balance in the most favorable case. Therefore, from the perspective of the global solution, the EU ETS has an evident beneficial effect on cold ironing development.

Table 36. CO_2 quotas traded on the ETS and incidence with respect to the net balance in the "Maximum" case.

Port	Net profit-Maximum (EUR)	15Y (2019 price) (EUR)	Incidence	15Y (2021 Price) (EUR)	Incidence	15Y (100€ Price) (EUR)	Incidence
Trieste	17,377,969.25	845,913.83	4.87	1,972,772.34	11.35	3,421,981.52	19.69
Dubrovnik	52,013,297.91	3,404,226.55	6.54	7,939,063.93	15.26	13,771,142.99	26.48
Piraeus	46,252,088.74	5332,024.21	11.53	12,434,918.92	26.89	21,569,677.22	46.64
Argostoli	3,221,055.74	1,065,106.33	33.07	2,483,955.51	77.12	4,308,682.58	133.77
Corfù	13,079,986.36	2,664,079.45	20.37	6,212,952.27	47.50	10,777,020.42	82.39
Split	22,624,391.50	1,542,324.30	6.82	3,596,884.95	15.90	6,239,175.97	27.58
Bari	39,568,490.34	1,840,404.47	4.65	4,292,043.60	10.85	7,445,001.90	18.82
GLOBAL	**194,137,279.84**	**16,694,079.14**	**8.60**	**38,932,591.52**	**20.05**	**67,532,682.61**	**34.79**

In general terms, as explained in Section 7, the large-scale use of cold ironing technology represents a solution in line with the policy developments of the European Union and in particular with the recent proposal for the inclusion of maritime transportation within the EU ETS. In particular, cold ironing technology can be an important compliance tool and simultaneously should fall under the category of projects financed/supported by the Members' revenues from the ETS market. This would favor the creation of economies of scale, while significantly reducing the costs for ship-owners and maritime operators. At the same time, this generates a significant benefit from the environmental/climatic point of view with reference to the reductions in polluting emissions and CO_2. Further research is necessary to quantify, in broader terms, the correct balance between the benefits and costs generated by the use of cold ironing against the social costs and benefits resulting from the reduction of greenhouse gases [76] when moving towards the application of EU ETS to shipping.

10. Conclusions

The present paper has proposed a technical, environmental, and regulatory analysis to show the feasibility of cold ironing in a particular Adriatic route crossing the coastlines of Italy, Croatia, and Greece. Such a technology has its major implementation in the northern American and northern European contexts, where low energy costs or stringent environmental policies force nations towards the no-emission supply of ships in ports. Conversely, the high cost of energy from land in the Adriatic Sea penalizes the high-voltage shore connection technology, despite the many cruise liners to be fed during the periodical mooring. To overcome this issue in southern Europe, a possible solution is represented by the clustering idea: rather than a sporadic/localized cold ironing arrangement, the coordinated installation across a specific route is a key factor to leverage on both ship-owners and port facilities towards the technology's implementation. Based on this, the paper has considered a set of consequential ports to define a specific Adriatic route (i.e., Trieste, Split, Dubrovnik, Argostoli, Corfu, Piraeus, and Bari), where the frequent touches of the same ships can increase the exploitation, while reducing pollutant emissions and the payback time.

From the models, standards, and guidelines stated at European community level, a complex database has been developed in the paper to weigh the avoided emissions during the shore-to-ship supply in the Adriatic cluster of ports. As prevented emissions means a localized reduction in social costs, the cold ironing utilization finally provides an economic profit. The monetization is obtained from the missing social costs of each avoided emission; in other words, the several substances (i.e., NO_x, SO_x, $PM_{2.5}$, PM_{10}, NMVOC, and also CO_2) not emitted thereafter from the combustion of marine fuel during the port berthing. The database has demonstrated its capability in studying a particular scenario of ports but it also can be easily updated to include additional ports, ships, and touches. In such a way, it can be a useful tool to help the policy makers in the ports clustering and in the direct funding of particular ports/plants. By following a market research program, the cost of each HVSC plant has been estimated in some millions of euros mainly due to the high-power components and frequency converter. Conversely, the return time from the investment not only depends on the exploitable mooring hours but also on the value that each social cost assumes in a given country. For example, the port of Trieste has a return time that is significantly shorter than of the Argostoli port, despite the smaller number of touches (i.e., less than the 30%) and consequently lower hours of mooring.

Usually the development of cold ironing collides with the hesitation of ship-owners who do not amortize the costs for adapting the ship. To overcome this assumption, an additional comparison between electricity costs and average costs of low sulfur bunker oil at mooring has been performed in this work. In the countries in which the kWh price is reduced, the switching towards cold ironing supplying already appears convenient when observing the operating costs. Meanwhile, the countries with a high-energy price have to take into account additional measures to foster the shore-to-ship adoption. Indeed, the entrance of the European shipbuilding industry into the Emission Trading System can revolutionize the debate on cold ironing. By studying the scenarios of CO_2 price dynamics (i.e., years 2019, 2021, and 2030) on the EU ETS market, cold ironing can finally play the role of a powerful technology to reduce the costs for powering ships during mooring. When approaching the EU ETS market, a sort of balance is ensured in the high-energy price countries, while the entire cluster can benefit from the ports located in the countries with low kWh prices. This conclusion finally corroborates the future of cold ironing development.

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